ANALYTICAL COMPARISON BETWEEN LASER BEAM AND ELECTRON BEAM WELDING

A Thesis

Submitted to the College of Engineering of

Nahrain University in Partial Fulfillment of the

Requirements for the Degree of Master of Science in

Laser and Optoelectronics Engineering

by

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February 2007

Certification

I certify that this thesis titled **"Analytical Comparison between Laser Beam and Electron Beam Welding"** was prepared by **Rasha Khaled Mohammed Al-Dabbagh**, under my supervision at Nahrain University, College of Engineering, in partial fulfillment of the requirements for the degree of Master of Science in Laser and Optoelectronics Engineering.

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Date : / / 2007

Certificate

We certify, as an examination committee, that we have read the thesis titled **"Analytical Comparison between Laser Beam and Electron Beam Welding"**, examined the student **Rasha Khaled Mohammed Al-Dabbagh** in its contents, and found that the thesis meets the standard for the degree of Master of Science in Laser and Optoelectronics Engineering.

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Abstract

Laser and electron beams are presently widely applied to many fields of material processing. Laser and electron beams produce the highest heat sources intensities used in welding process.

This work investigates analytical comparison which discusses the differences and similarities between laser and electron beam welding.

These comparisons have been made in three aspects. The first explains the main physical characteristics of laser and electron beams as heat sources used for welding process, and shows the most important points of differences between the laser and electron beam in the generation and manipulation of the beams. The second aspect is the technological comparison that presents the performance of the two beams in the fields of welding, and shows the power capability and efficiency, technical performances of beams, mathematical models applied and application fields. The third aspect is the economical comparison which shows the process economics such as; cost of machines, tooling, maintenance, infrastructure and preparation of workpieces.

The results obtained from these comparisons have been presented in two methods. The first method includes explanations supported by graphical illustrations, while the second one includes comparison tables.

The results show that the electron beam have power efficiency and depth of penetration higher than that of laser, but electron beam needs vacuum environment and protection against x-ray production in most cases. Laser beam is excellent in welding magnetic and non metallic materials (plastics) while electron beam welding is impossible to be used for these materials.

These beams have fundamentally different physical natures so that laser beam has special characteristics which is important for welding like the possibility of beam splitting, beam mobility, controllability and low beam distortion.

The results also show that nearly similar capital cost is incurred for both laser and electron beam welding up to 5kW, while laser capital cost increases rapidly above the 5kW level.

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List of Symbols and Abbreviations

A	Radius of the laser beam, (m^2).
a	Thermal diffusivity of the material, (m^2/s).
$\boldsymbol{B}$	Magnetic field, (Webers/m^2).
c_p	Specific heat of the material, (J/kg. ^{0}C).
d	Beam diameter, (m).
E	The beam energy, (J).
$\boldsymbol{E_f}$	Electric field, (V/m).
e	Charge of the electron, (C).
f_0	Focal length, (m).
$\boldsymbol{f_e}$	Electric force, (Newton).
$\boldsymbol{f_m}$	Magnetic or Lorentz force, (Newton).
h	Penetration depth of heat, (m).
I	Electron beam current, (A).
I_0	Incident laser beam intensity, (W/cm^2).
J_0	Bessel function of the first kind and zero order.
J_1	Bessel function of the first kind and one order.
j	Cathode emission current density, (A/cm^2).
t_p	Pulse duration of the laser, (s).
K	Thermal conductivity of the material, (W/m.^{0}C).
$\acute{K}$	Point overlap ratio for pulsed electron beam.
K_0	Modified Bessel function of an imaginary argument of second kind of order zero.
k	Boltzmann's constant, (J/K).
k_0	Concentration coefficient, (cm^2).
m	Atomic mass, (kg).
P	Power of the laser beam, (W).
Q	Power density of electron beam, (W/cm^2).
R	Reflectivity of the surface.

s	Constant of the electron optical system.
T_m	Melting temperature of the material, (^{0}C).
T_v	Vaporization temperature of the material, (^{0}C).
V	Accelerating voltage, (V).
Z	Atomic number of an element.
α	Absorption coefficient, (cm^{-1}).
γ	Density of the material, (kg/m^3).
ε	Absorptivity of the surface.
η	Efficiency coefficient.
ξ	Integration variable.
τ_p	Pulse length of electron beam, (s).
τ_w	Pulse space width of electron beam (s).
υ	Welding speed, (m/s).
CNC	Computer numerical control.
EBW	Electron beam welding.
HAZ	Heat affected zone.
HEDB	High energy density beam.
LBW	Laser beam welding.

Analytical Comparison Between Laser Beam And Electron Beam Welding

Aim of the Project

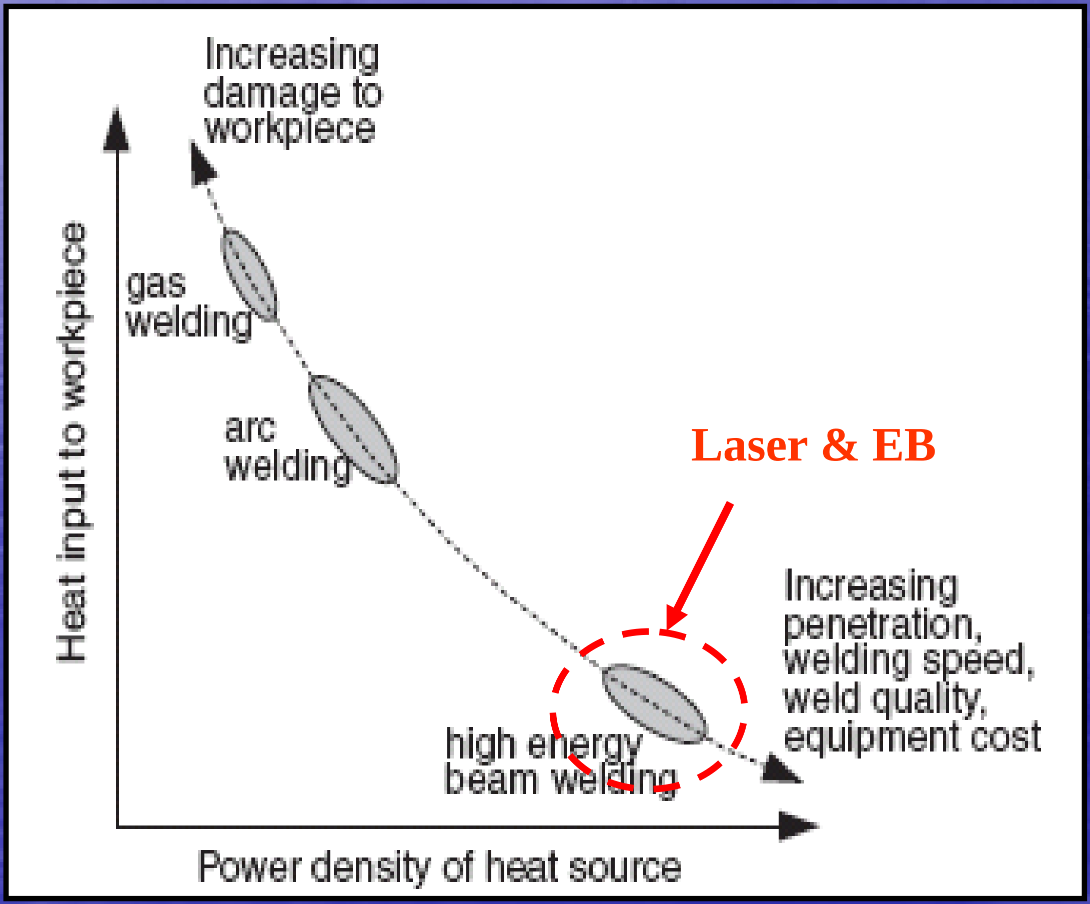
The main goal is to make a technical and economical comparison between

Laser beam and Electron beam welding

This is achieved through:

- Presenting the characteristics of these heat sources.
- Analyzing the application of the process and the design of the laser and electron beam sources.
- Discussing the differences between laser and electron beam welding.

Laser and electron beam produce the highest heat source intensity used in welding process



The advantages of increasing the power density of the heat source are:

- Deeper weld penetration
- Higher welding speeds
- Better weld quality with less damage to the workpiece

Criteria for the Comparative Study

- **Physical Comparison**
- **Technological Comparison**
- **Economical Comparison**

The results obtained have been presented in two methods

- Explanations supported by graphical illustrations
- Comparison tables

COMPARISON RESULTS

Physical Comparison

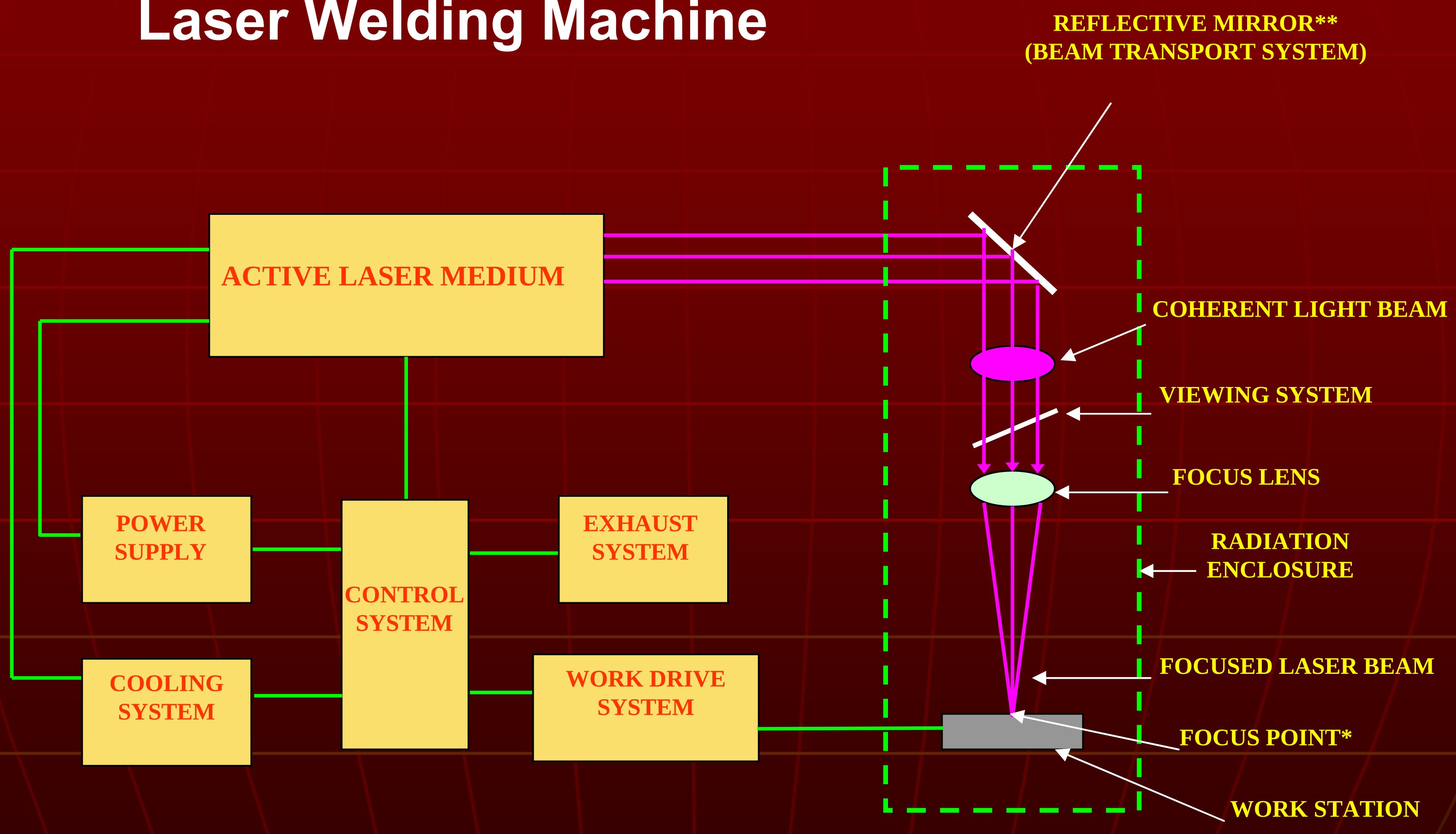
➢ **Generation and Manipulation of Beams**

The following parts have been discussed:

- **Beam generators**
- **Beam transportation to the workpiece**
- **Beam concentration**
- **Variation of the focus distance**

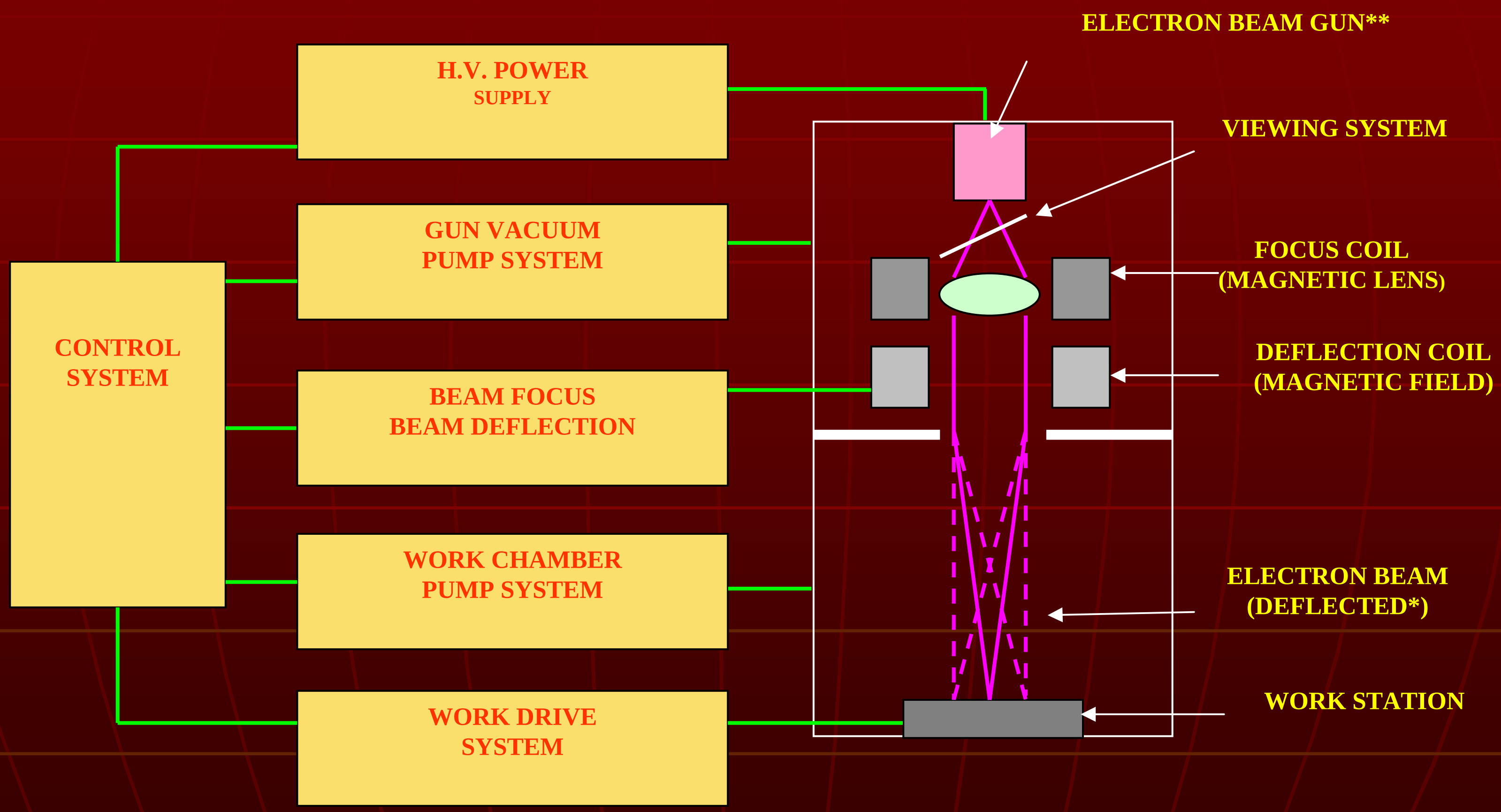
Physical Comparison

Laser Welding Machine



Physical Comparison

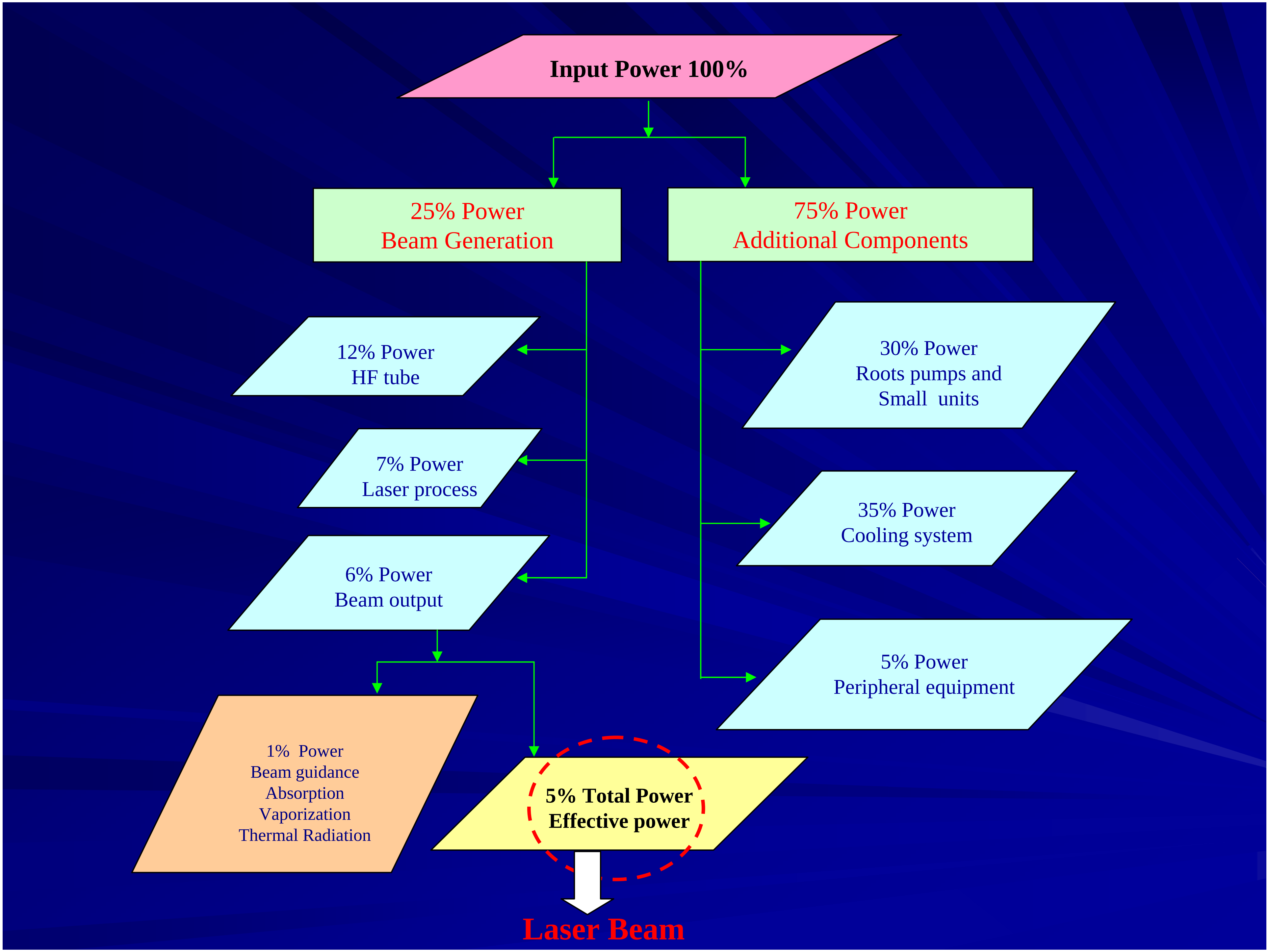
Electron Beam Welding Machine

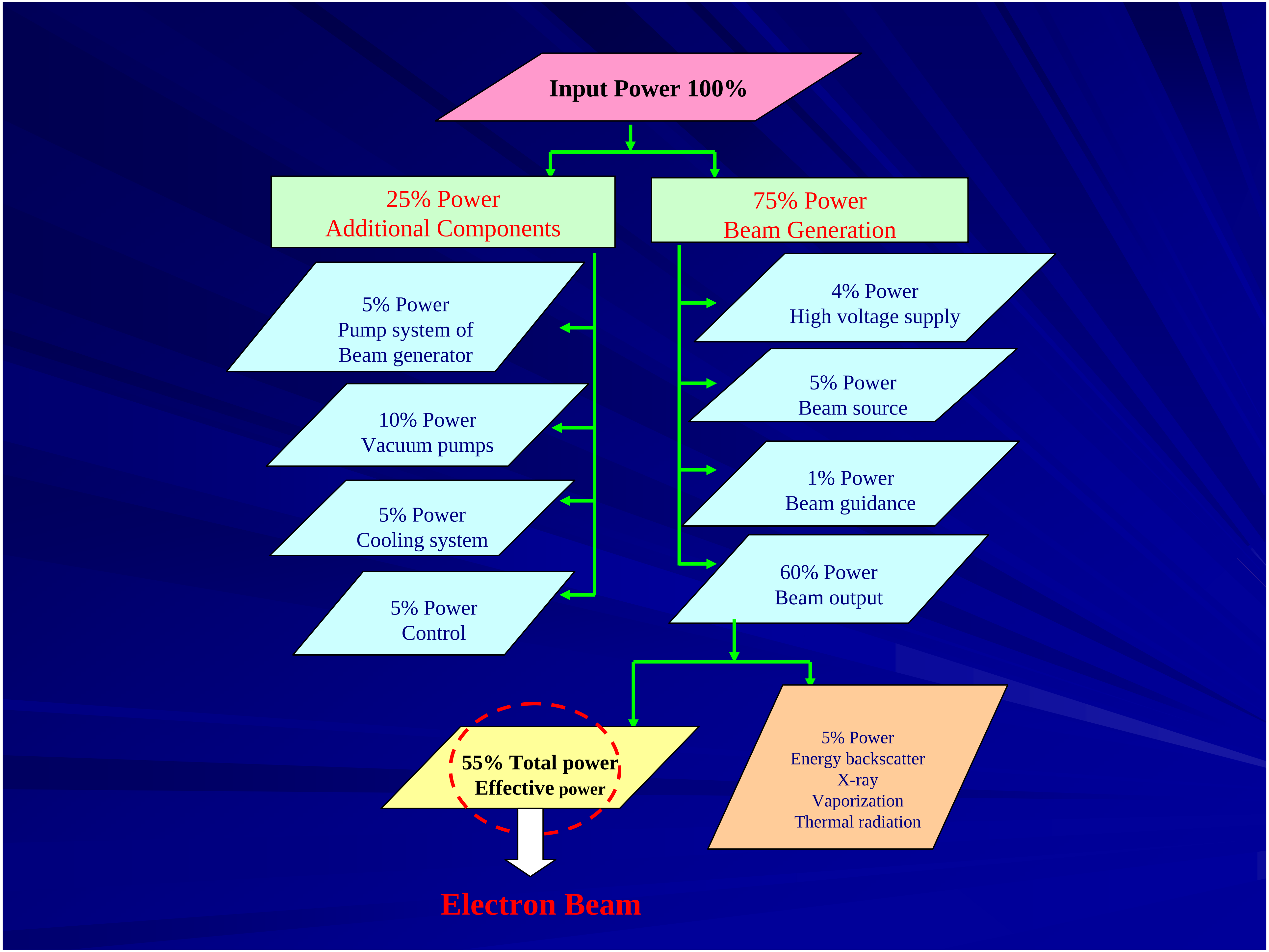


Technological Comparison

- **Power Capability and Efficiency**

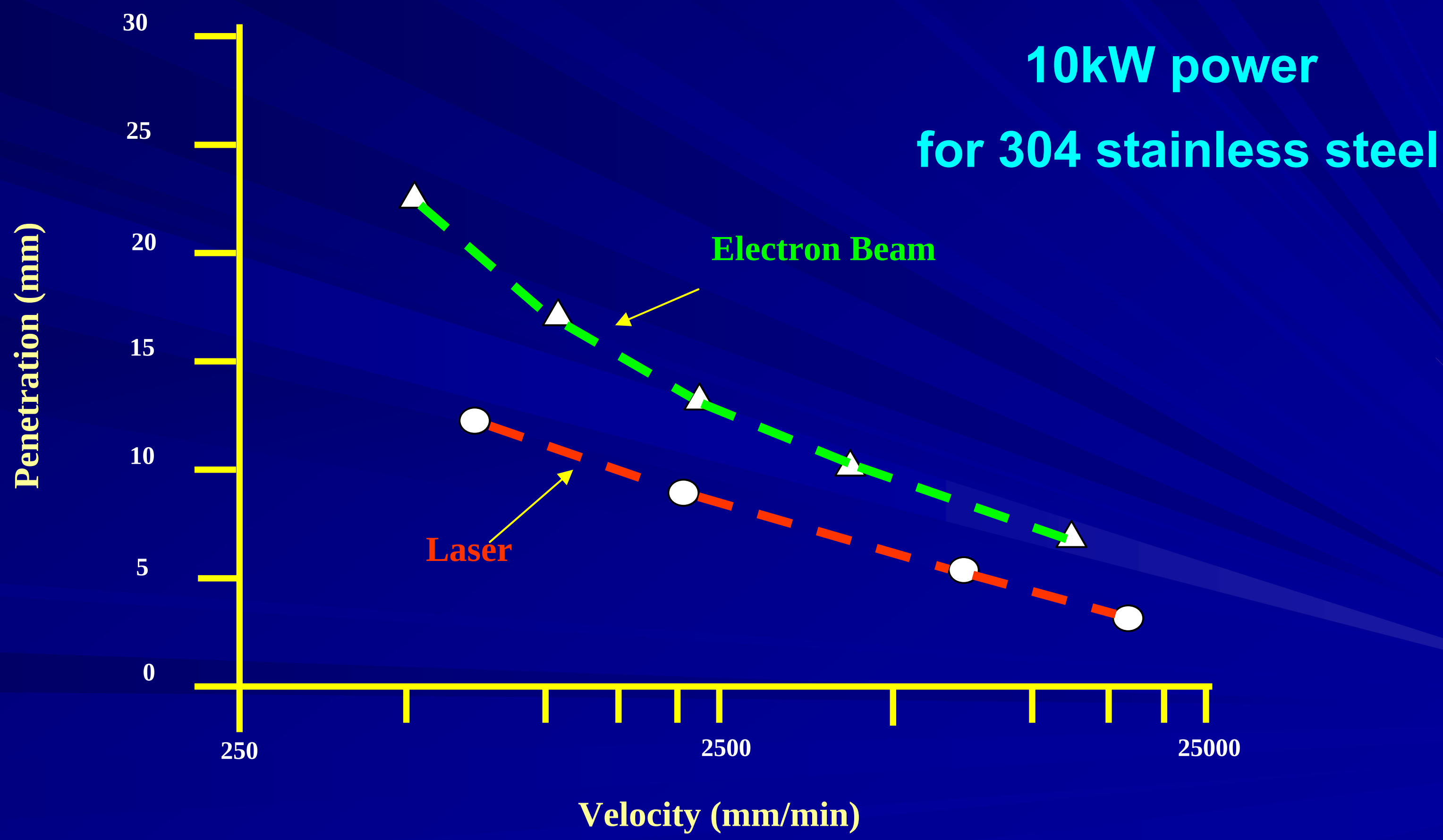
- **The electron beam offers relatively higher output and the greatest ease of generation**
- **The electron beam having power capability and efficiency higher than the laser**


Input Power 100%
25% Power
Beam Generation
75% Power
Additional Components
12% Power
HF tube
7% Power
Laser process
6% Power
Beam output
30% Power
Roots pumps and
Small units
35% Power
Cooling system
5% Power
Peripheral equipment
1% Power
Beam guidance
Absorption
Vaporization
Thermal Radiation
5% Total Power
Effective power
Laser Beam


Input Power 100%
25% Power
Additional Components
75% Power
Beam Generation
5% Power
Pump system of
Beam generator
10% Power
Vacuum pumps
5% Power
Cooling system
5% Power
Control
4% Power
High voltage supply
5% Power
Beam source
1% Power
Beam guidance
60% Power
Beam output
55% Total power
Effective power
5% Power
Energy backscatter
X-ray
Vaporization
Thermal radiation
Electron Beam

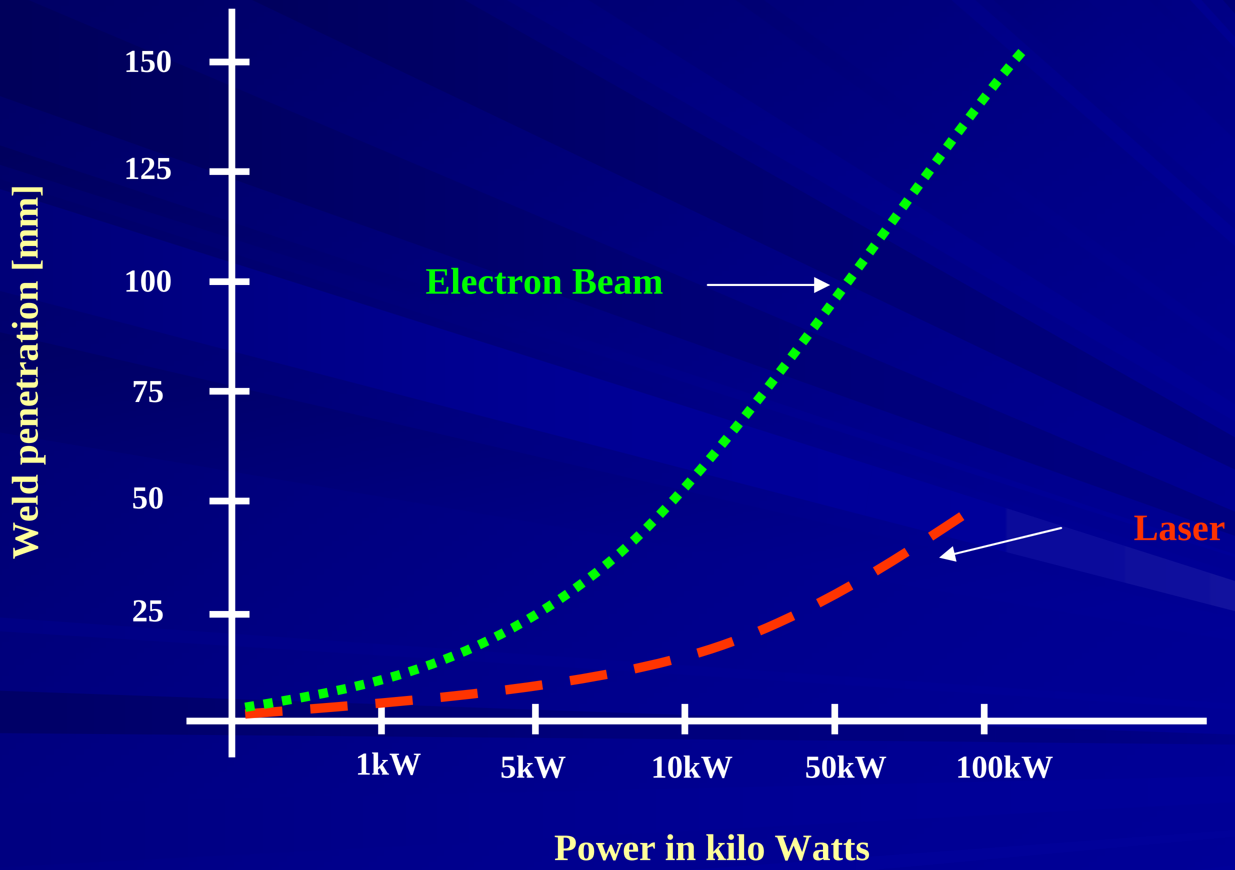
Technological Comparison

➢ Technical Performance of Laser and Electron Beam



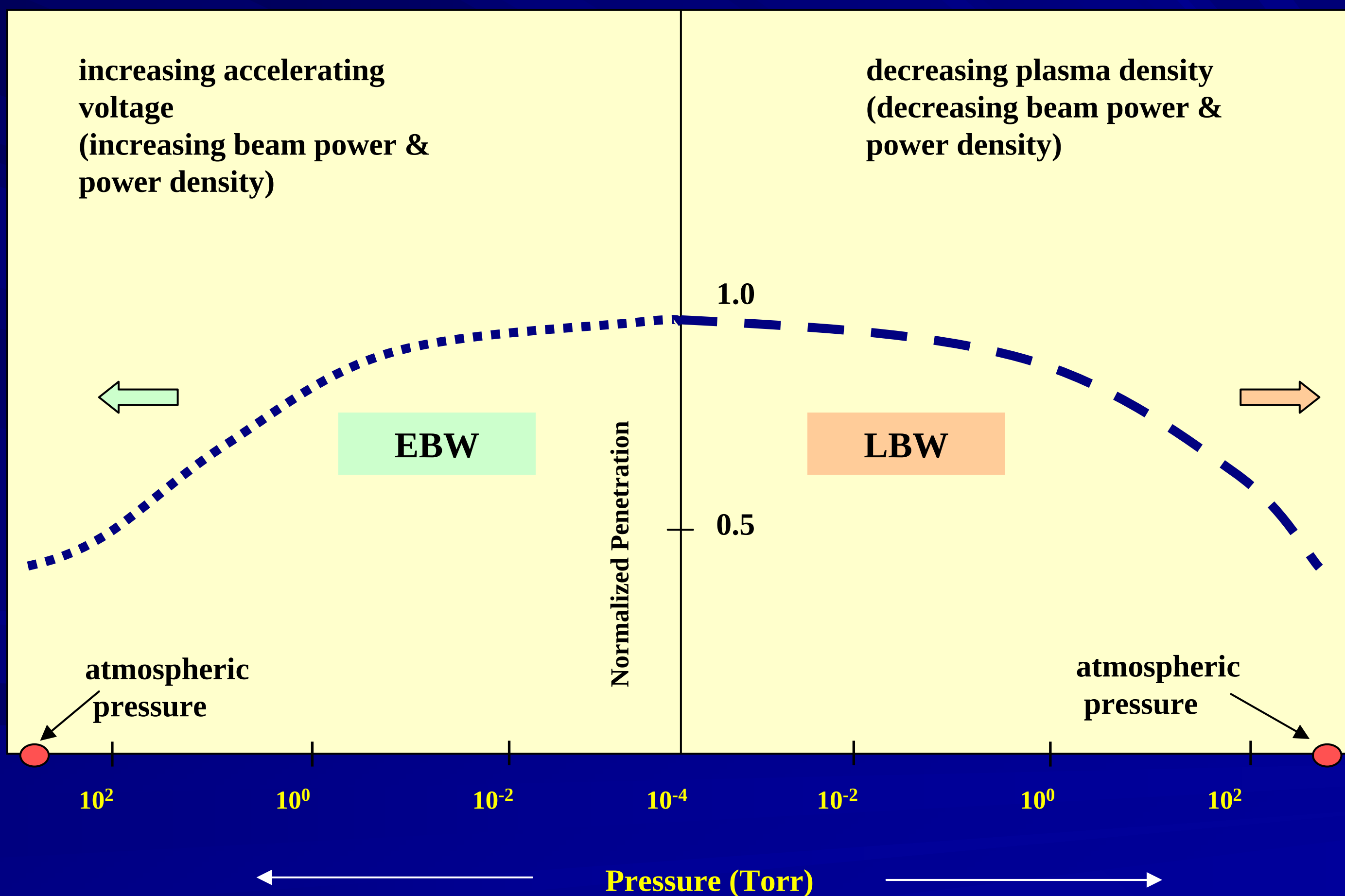
Technological Comparison

A weld penetration comparison, electron beam vs. CO_2 laser



Technological Comparison

Comparison of pressure dependences of penetration depth between laser and electron beam welding



Technological Comparison

➢ **Analytical Models**

The mathematical model which has been selected to suit laser beam welding is the

circular surface source on semi-infinite half-space

$$T(r,z,t) = \frac{P\varepsilon}{2\pi AK} \int_0^\infty J_0(m'.r).J_1(m'.A).\Big\{ e^{(-m'z)}.erfc[\tfrac{z}{2(a.t)^{1/2}} - m'(at)^{1/2}]$$
$$- e^{(m'.z)}.erfc[\tfrac{z}{2(a.t)^{1/2}} + m'.(a.t)^{1/2}] \Big\}.\frac{dm'}{m'}$$

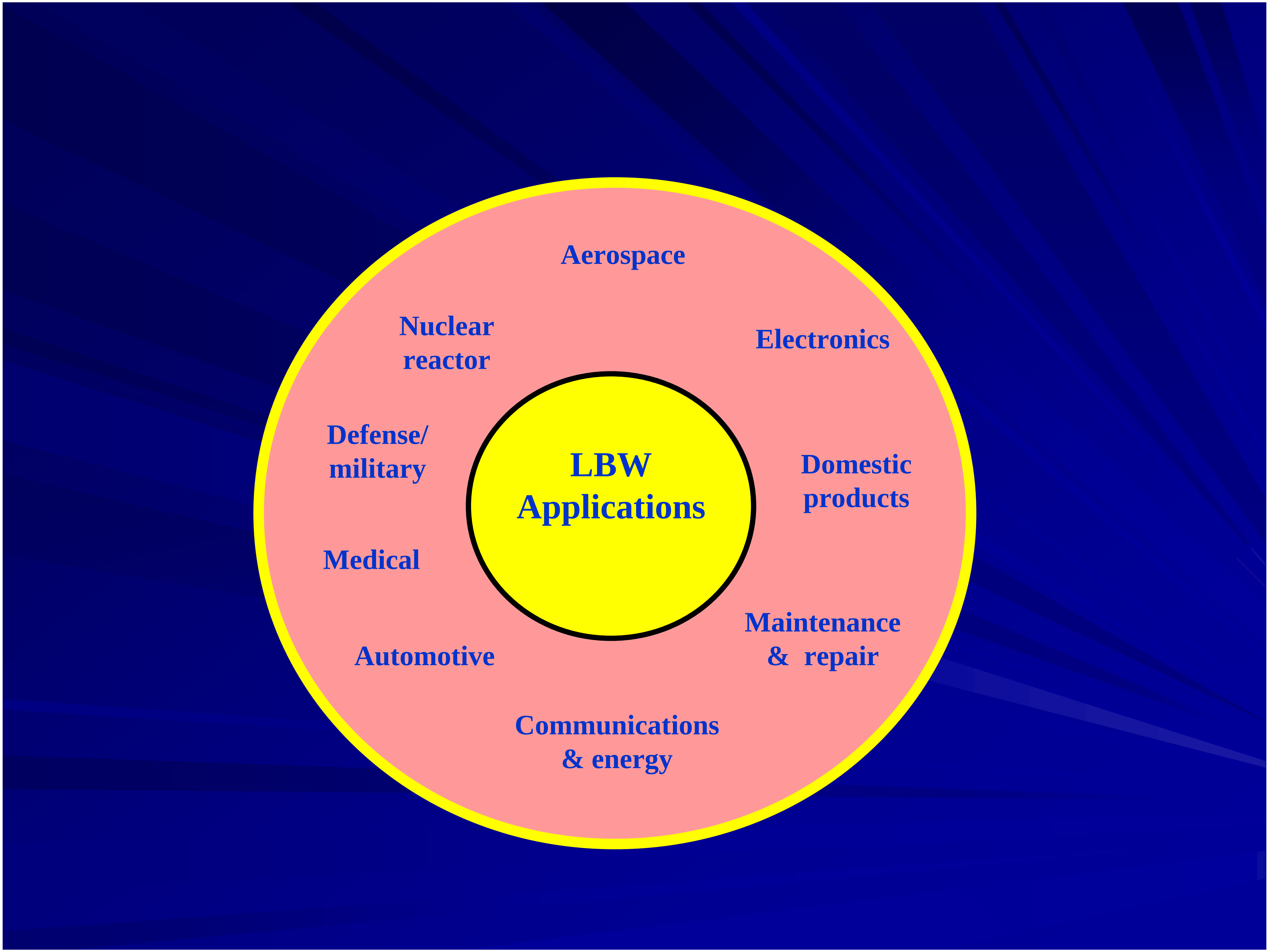
For electron beam welding the Gaussian source has been selected. The Gaussian distribution allows uniform high intensity energy application.

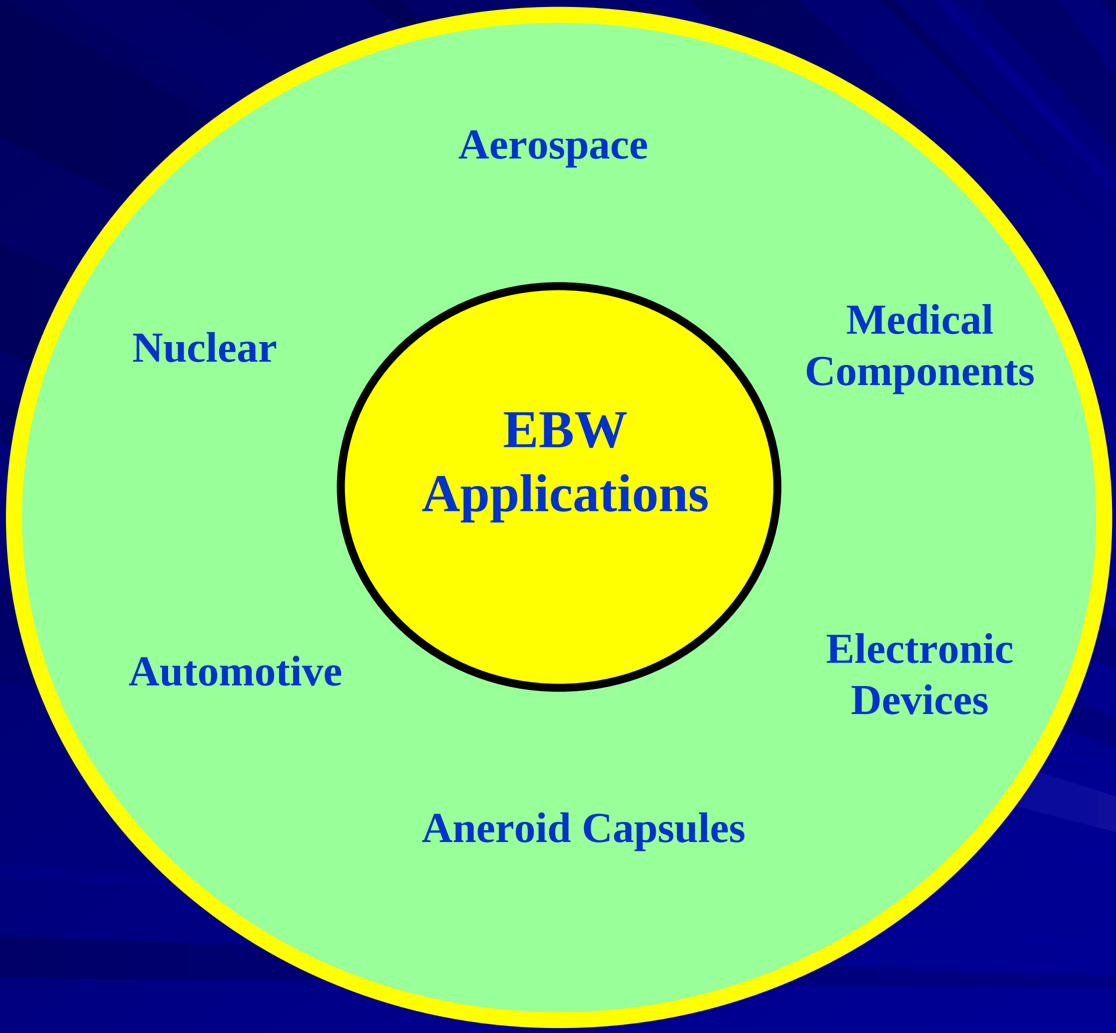
$$T(r,z,t) = \frac{2P_0}{c_p \gamma (4\pi a)^{3/2}} \times \int_0^t \frac{d\xi \exp\{-(4a)^{-1}[z^2/\xi + r^2/(t_0+\xi)]\}}{\sqrt{\xi}(t_0+\xi)}$$

Technological Comparison

➢ **Application Fields**

Applications of laser and electron beam welding cover today a wide range of industries


LBW
Applications
Aerospace
Nuclear
reactor
Electronics
Defense/
military
Domestic
products
Medical
Maintenance
& repair
Automotive
Communications
& energy


EBW
Applications
Aerospace
Nuclear
Medical
Components
Automotive
Electronic
Devices
Aneroid Capsules

MATERIAL	*THICKNESS	EBW	LBW
Carbon Steel	S	✓	✓
	I	✓	✓
	M	✓	✓
	T	✓	-
low-alloy steel	S	✓	✓
	I	✓	✓
	M	✓	✓
	T	✓	-
Stainless Steel	S	✓	✓
	I	✓	✓
	M	✓	✓
	T	✓	-
Cast Iron	I	-	-
	M	-	-
	T	-	-
Nickel and alloys	S	✓	✓
	I	✓	✓
	M	✓	✓
	T	✓	-
Aluminum and alloys	S	✓	✓
	I	✓	✓
	M	✓	-
	T	✓	-

Technological Comparison

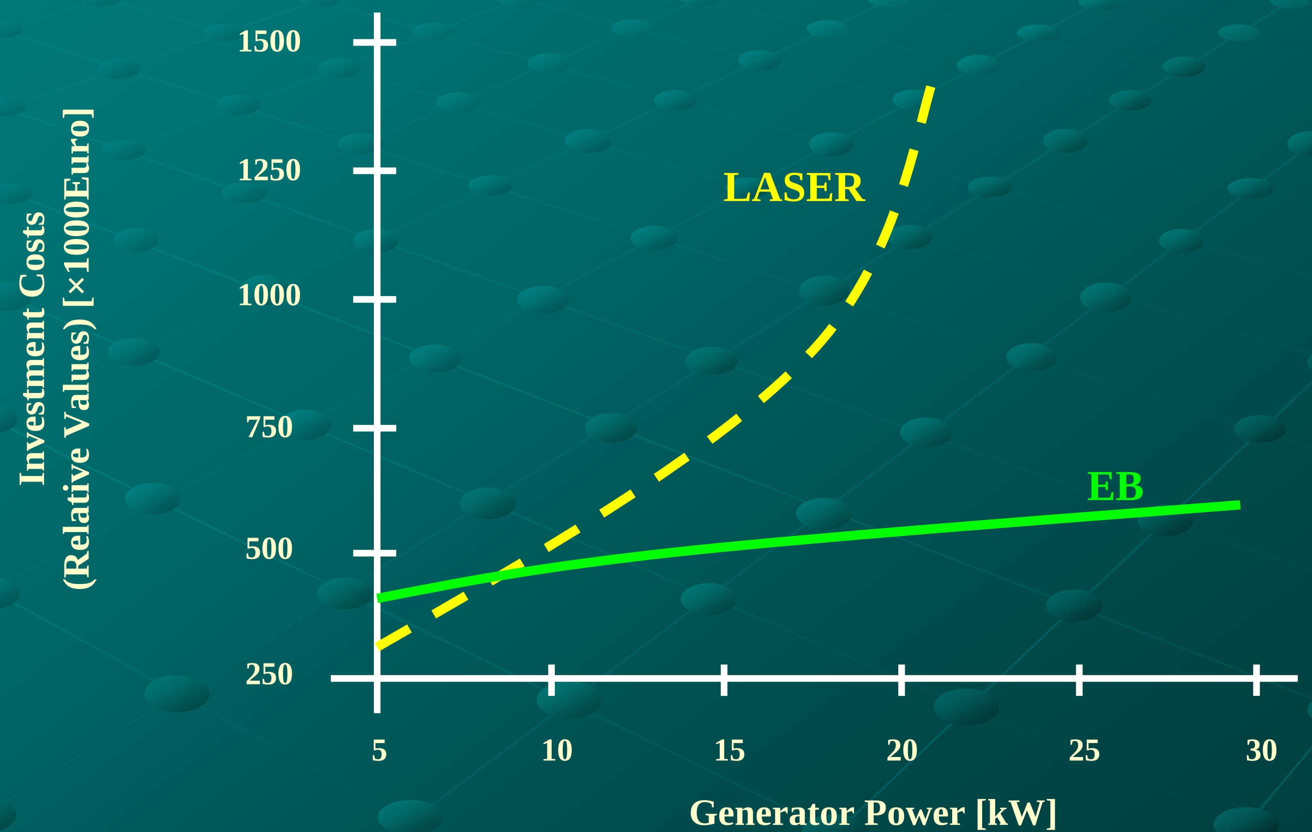
- Process Environment
- Safety Implications
- Reliability and Reproducibility of the Welding Results

Economical Comparison

- Investment Costs for the Welding Machines and Tooling
- Investment Costs for the Infrastructure and Maintenance
- Automation and Costs for Preparation of Workpieces

Economical Comparison

A diagram of the investment cost for equipment comparison .



Tables of Summarized Comparison Results

Comparison between laser and EB in the field of power and generation of beams.

COMPARING PARAMETER	LASER BEAM	ELECTRON BEAM
Power and Efficiency Comparisons		
Maximum power achieved in research devices	up to 25kW	up to 300kW
Maximum beam energy of equipment usually used in industry	6kW	60kW
Power stability	(1-3)%	1%
Power efficiency	(1-10)%	75%
Loss of efficiency due to plasma affect and reflection of the beam	yes	no

COMPARING PARAMETER	LASER BEAM	ELECTRON BEAM
Generation and Manipulation of Beams Comparisons		
Beam generation	photons issue from an optical cavity	electrons produced by an cathode (emissive surface)
Possibility of CW and pulsed mode	available	available
Beam profile	high point density small depth of focus	high point density long depth of focus
Beam concentration	lens(transmission optics)	electromagnetic axisymmetric fields
Variation of focal distance	difficult	easy
Beam splitting	possible	not possible
Beam deflection/redirection	mechanical -electro metallic mirrors	magnetic -electro (coils, condenser plates)
Distortion	very small	small
Beam mobility	good	difficult
Spot size	100 µm-1mm	50µm-1mm
Controllability	very good	good

Technological comparison between laser and electron beam welding.

COMPARING PARAMETER	LASER BEAM	ELECTRON BEAM
Technological Comparisons		
Speed of energy transport between the center of beam generation and workpieces	c (speed of light)	2/3 c (2/3 speed of light)
Heat generation	low	moderate
Processes for high energy density beam welding	CO_2, Nd-YAG, direct diode, hybrid processes	high vacuum, partial vacuum-vacuum, non
Process temperature	locally high	locally high
Maximum fused zone thickness	20mm	150mm
Welding speed	moderate	high
Heat affected zone	very small	small
Metallurgical changes	precipitation hardening & cold worked alloys soften in heat affected zone	precipitation hardening & cold worked alloys soften in heat affected zone
Surface preparation	all material must be clean	surfaces must be clean
Possibility of welding magnetic materials	yes	conditional /no
Possibility of welding non-ferrous metals	difficult	good

COMPARING PARAMETER	LASER BEAM	ELECTRON BEAM
Possibility of welding non-metallic materials (plastics)	yes	no
Weld quality	excellent	more excellent
Joint design	special care to overcome reflectivity	butt or lap
Weld bead geometry	good very	excellent
Flux required	no	no
Joint strength	high	high
Seamrate	high	high
Welding atmosphere	shielding gas /air	vacuum
Effect of energy absorption	depending on material and beam intensity	depending on material (Z-number) and fused zone thickness
Effect of focus diameter and focus position on beam energy	low	very high
Multistation operation (time sharing) possibility	yes	no
Approximate joining efficiency mm2/kJ	15-25	20-30
Fit up tolerance	very close	close

Economical comparison between laser and electron beam welding.

COMPARING PARAMETER	LASER BEAM	ELECTRON BEAM
Economical Comparisons		
Capital cost (based on 5kW)	high	high
Capital cost (above 5 kW)	high	very high
Equipment costs	very high	very high
Fixturing costs	low	high
Consumables cost	very low	very low
Infrastructure cost	very high	high
Market projection	(20-30)% growth per year in welding application	10% growth per year in welding application
Manual skill	low	low
Automation	semi or fully automatic	semi or fully automatic

CONCLUSIONS

- ✓ For applications on material thickness ≤ 5mm, laser beam must be used. On the case of thick material (≥ 5mm) the electron beam welding must be used.

- ✓ When the aspect ratio of the molten zone > 10, electron beam welding must be used.

- ✓ For applications of welding insulator materials the laser must be used in welding.
- ✓ Laser welding is advantageous with “problem free” material which are not subject to crack or porosity.
- ✓ To get ultra clean welds, high vacuum electron beam welding must be used.

- ✓ **For aerospace, today electron beam is established and will continue to progress during the coming years. The availability of new laser sources in the future could modify the situation.**

Recommendations for Future Work

- Theoretical study to discuss economical comparison between laser and EB welding.
- Theoretical research in welding using high energy density beams to focus on the high performance welding.

- Studying the place of laser and electron beam in mass production area.

- Studying and analyzing of fundamental phenomena and the development of new processes in high energy density beams material processing and their applications.


THANK YOU

مقارنة تحليلية بين

لحام حزمة الليزر ولحام الحزمة الالكترونية

رسالة

مقدمة إلى كلية الهندسة في جامعة النهرين وهي جزء من متطلبات نيل

درجة ماجستير علوم في هندسة الليزر والالكترونيات البصرية

من قبل

رشا خالد محمد الدباغ

(بكالوريوس في هندسة الليزر و الالكترونيات البصرية ٢٠٠٤)

شوال **١٤٢٧ هـ**

شباط **٢٠٠٧م**

شكر وتقدير

الحمد لله الذي يسر لي أمري، ومكنني من إتمام هذه الرسالة التي لم يكن من السهل إعدادها. واشكر من أعماق قلبي أستاذي الفاضل ومشرفي الدكتور محمد عبد الأمير حسين الذي ساعدني بعلمه ومعرفته وآرائه القيمة، فله مني جزيل الشكر.

أود أيضا أن أشكر السيد رئيس القسم و كل أساتذة و منتسبي قسم هندسة الليزر و الإلكترونيات البصرية لتعاونهم أثناء فترة البحث.

والشكر الجزيل لوالدي ووالدتي وأخوتي الأعزاء وأصدقائي لما قدموه لي من مساعدة وتشجيع ودعاء طوال فترة البحث.

رشا خالد محمد الدباغ

تشرين الثاني ٢٠٠٦

الخلاصة

تُستخدم حزمة الليزر والحزمة الالكترونية في الوقت الحاضر على نحو واسع في العديد من مجالات معالجة المواد. ُتنتج كل من حزمة الليزر والحزمة الالكترونية مصادر الحرارة الأعلى شدة المستخدمة في عمليات اللحام.

يَتحرّى هذا العمل المقارنة التحليلية لمناقشة الاختلافات والتشابهات بين حزمة الليزر والحزمة الالكترونية في عمليات اللحام.

جُعلت هذه المقارنات في ثلاث سمات. الأولى تُوضّح الخصائص الطبيعية الرئيسية لحزمة الليزر والحزمة الالكترونية كمصادر حرارية استخدمت في عملية اللحام، وتعرض النقاط الأكثر أهمية للاختلافات بين حزمة الليزر والحزمة الالكترونية في توليد وتداول الحزم. إنّ السمة الثانية هي المقارنة التقنية التي تُبين أداء الحزمتين في حقول اللحام، وتعرض القابلية والكفاءة الكهربائية والأداء التقني للحزم والنماذج الرياضية المطبقة ومجالات التطبيقات. إنّ السمة الثالثة هي المقارنة الاقتصادية التي تُبين اقتصادية العملية مثل: الكلف الاقتصادية للمكائن والأدوات والصيانة والبنية التحتية وتحضير قطع العمل.

تم عرض نتائج المقارنات بطريقتين. تتضمن الطريقة الأولى الشروحات المدعومة بالرسوم التوضيحية ، بينما تتضمن الثانية جداول المقارنة.

تُظهر النتائج أنّ الحزمة الالكترونية لها كفاءة كهربائية وعمق اختراق أعلى من حزمة الليزر، لكن الحزمة الالكترونية تحتاج الى بيئة مفرغة من الهواء والاحتماء من تولد الأشعة السينية في أكثر الحالات.

حزمة الليزر ممتازة في لحام المواد المغناطيسية وغير المعدنية (البلاستيك) بينما الحزمة الالكترونية يستحيل استخدامها في لحام هذه المواد.

إن هذه الحزم لها طبائع فيزيائية مختلفة أساسا، لذلك تمتاز حزمة الليزر على الحزمة الالكترونية بخصائص لها أهمية في اللحام مثل إمكانية شطر الحزمة وقابلية تحريك الحزمة وقابلية التحكم وتقليل تشويه الحزمة.

تُبين النتائج أيضا بأنّ كلفة رأس المال المستندة على ٥ كيلوواط متساوية تقريبا لحزمة الليزر والحزمة الالكترونية، بينما تزداد كلفة رأس المال لحزمة الليزر بسرعة فوق مستوى ٥ كيلوواط.

Chapter One

INTRODUCTION

1.1 Introduction

High energy density beams such as electron beams and laser beams have brought many benefits to material processing which can not be achieved by conventional heat sources, and presently they are widely applied to many fields of material processing [1]. Laser and electron beams are used as tools for welding, cutting, drilling, melting, tempering or vaporizing in many machining tasks [2]. The use of these beams offers the possibility of a relatively simple automation and programming of a wide variety of industrial processes [3, 4].

Development of the electron beam and laser beam process started at about the same time (around 1960) and remained primarily in laboratory use for several years [5]. Laser and electron beams produce the highest heat source intensities used in welding. Although intensities of $10^9 W/cm^2$ are possible, only levels of 10^6 or 10^7 are useful for welding. Above this level, vaporization of the metal is so intense that holes are drilled rather than welds being formed. Laser and electron beam processes have many similarities and many differences and hence they cannot always be used interchangeably [6]. When viewing the application of each of these high energy beam systems (electron beam or laser) numerous comparisons have to be made to fully understand and then select the energy source which best affords complete economical and application success [5].

1.2 Welding

Welding is a micro metallurgical operation consisting of producing a molten bead connecting the edges of two pieces; the process is said to involve similar metals when these two pieces, as well as the joint filler metal, have an identical or similar chemical composition, and dissimilar metals when this is not the case. It constitutes a joining method of choice for all construction involving metals. It is also employed, more recently and to a lesser extent, with thermoplastics. Welding requires the application of heat. All energy sources can be employed: chemical (flame), light (laser), electrical or mechanical [7].

The process of welding is an integral manufacturing procedure in many engineering and structural components, having a direct influence on the integrity of the components and their thermal and mechanical behavior during service [8]. New discoveries and the availability of electric energy in the nineteenth century pushed the development of modern welding with an ever-accelerating rate (figure 1.1) [6].

The different welding processes can be ordered by the intensity of the heat source used for fusion (figure 1.2). This order reveals many important trends among them. The penetration is measured as the ratio of depth to width of the weld cross section which increases dramatically with the intensity of the heat source. This makes the welding process more efficient and allows for higher welding speeds. A more efficient process requires less heat input for the same joint, resulting in a stronger weld. A smaller heat source moving at a faster speed also implies a much reduced dwell time at any particular point. If the dwell time is too short, the process cannot be manually controlled and must be automated. Welding processes with a more concentrated heat source create a smaller heat affected zone (HAZ) and lower post-weld distortions. The benefits brought by a more concentrated heat source come at a price: the capital cost of the equipment is roughly proportional to the intensity of the heat source [6].

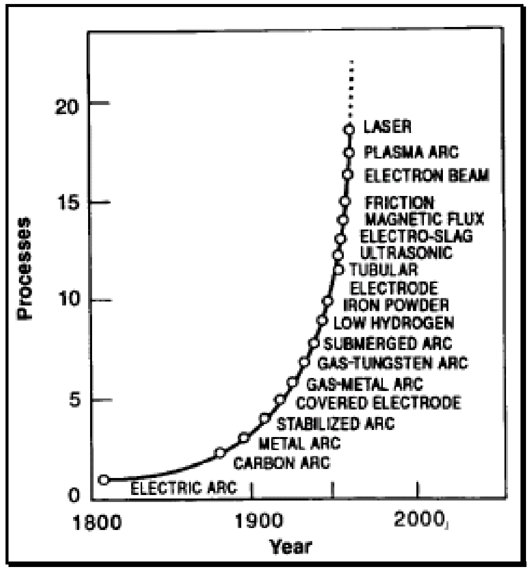


Figure 1.1: Growth of welding processes since electrical energy became readily available [6].

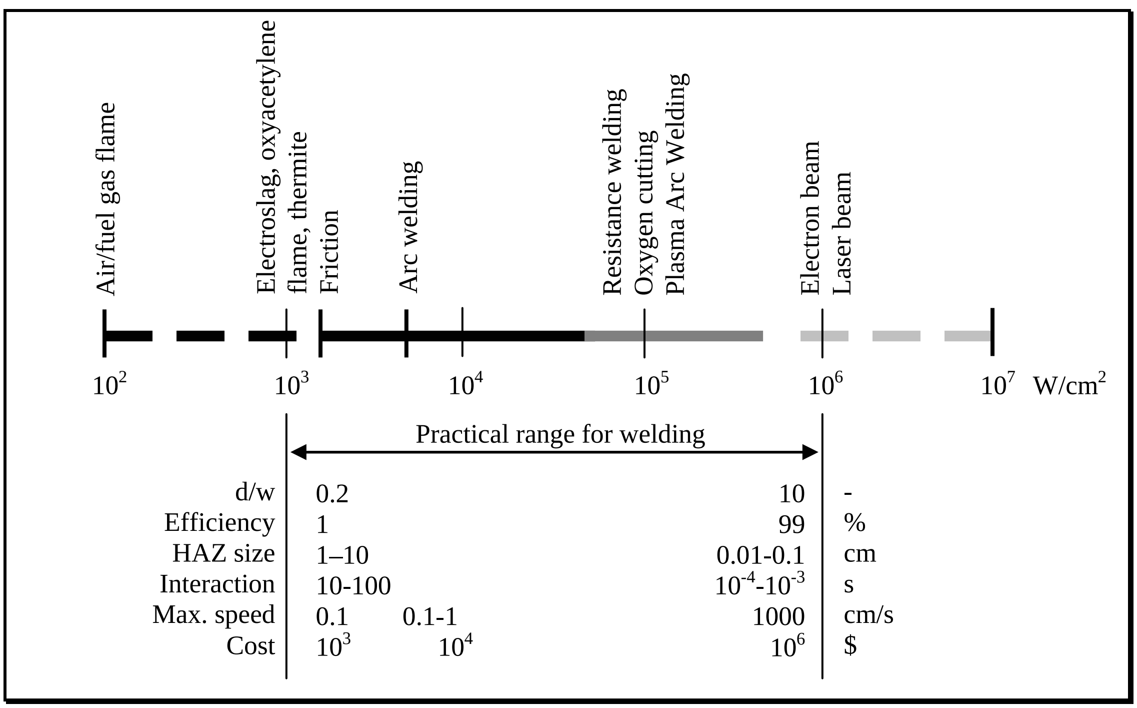


Figure 1.2 : Welding processes ordered according to heat source intensity [6].

The heat sources for the gas, arc, and high-energy beam welding processes are a gas flame, an electric arc, and a high-energy beam, respectively. The power density increases from a gas flame to an electric arc and a high-energy beam. As shown in figure 1.3, as the power density of the heat source increases, the heat input to the workpiece that is required for welding decreases. The portion of the workpiece material exposed to a gas flame heats up so slowly that, before any melting occurs, a large amount of heat is already conducted away into the bulk of the workpiece. Excessive heating can cause damage to the workpiece, including weakening and distortion. On the contrary, the same material exposed to a sharply focused electron or laser beam can melt or even vaporize to form a deep keyhole instantaneously, and before much heat is conducted away into the bulk of the workpiece, welding is completed [9].

Therefore, the advantages of increasing the power density of the heat source are deeper weld penetration, higher welding speeds, and better weld quality with less damage to the workpiece [10], as indicated in figure 1.3.

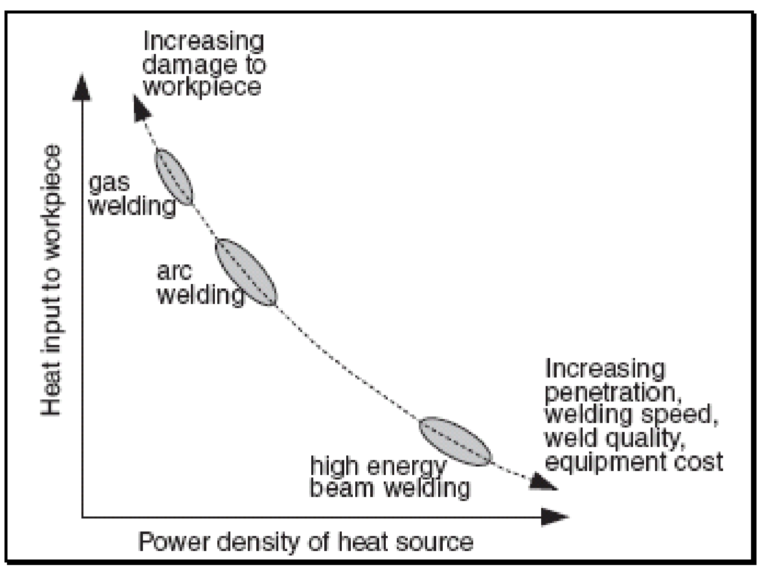


Figure 1.3: Variation of heat input to the workpiece with power density of the heat source [9].

1.3 Advantages and Limitations of Welding

The advantages of welding processes include [7, 10, 11]:

- Welding is usually a cheaper process than riveting for any particular joint, and the joint can often be made much more quickly.
- A good weld is as strong as the base metal.
- It provides metallic continuity in the piece, thus conferring properties in the joint that are equivalent to those of the metal being joined (mechanical, thermal, chemical, electrical, leak tightness, durability, etc.).
- General welding equipment is not very costly.
- Portable welding equipment are available.
- Welding permits considerable freedom in design.
- Welding is not as noisy as riveting, and permits building and alterations to proceed with the least disturbance to occupants.
- A large number of metals/alloys both similar and dissimilar can be joined by welding.
- Welding can join workpieces through spots, as continuous pressure tight seams, end-to-end and in a number of other configurations.
- Welding can be mechanized.

The limitations of welding processes are [7, 10, 11]:

- Welding gives out harmful radiations (light), fumes and spatter.
- Welding results in residual stresses and distortion of the workpieces therefore the welded joint needs stress relief heat treatment.
- Jigs and fixtures are generally required to hold and position the parts to be welded.
- Edge preparation of the workpieces is generally required before welding them.
- A skilled welder is a must to produce a good welding job.
- Welding heat produces metallurgical changes. The structure of the welded joint is not same as that of the parent metal.

1.4 Fusion Welding Processes

There are about 35 different welding and brazing processes and several soldering methods in use by industry today [10]. Fusion welding is a joining process that uses fusion of the base metal to make the weld. Figure 1.4 shows the main type of fusion welding processes.

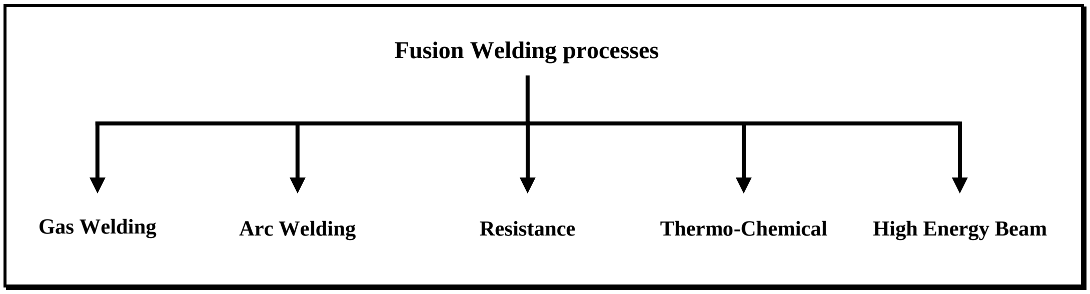


Figure 1.4: Fusion welding processes [adapted from ref. 12].

The major types of fusion welding processes are as follows:

i. Gas welding

Gas welding is a welding process that melts and joins metals by heating them with a flame caused by the reaction between a fuel gas and oxygen. Oxyacetylene welding is the most commonly used gas welding process because of its high flame temperature. A flux may be used to deoxidize and cleanse the weld metal. The flux melts, solidifies, and forms a slag skin on the resultant weld metal [12].

ii. Arc welding

Arc welding is a fusion welding process in which coalescence of the metals is achieved by the heat from an electric arc between an electrode and the work [13]. The types of arc welding are:

- Carbon arc welding
- Shielded metal arc welding (SMAW)
- Gas–tungsten arc welding (GTAW)
- Plasma arc welding (PAW)

- Gas–metal arc welding (GMAW)
- Flux-cored arc welding (FCAW)
- Submerged arc welding (SAW)
- Electroslag welding (ESW)
- Stud arc welding

iii. Resistance Welding

Achieves coalescence using heat from electrical resistance to the flow of a current passing between the faying surfaces of the two parts held together under pressure [13]. The types of resistance welding are:

- Spot welding (RSW)
- Seam welding (RSEW)
- Projection welding (PW)
- Resistance butt welding
- Flash butt welding (FW)
- Percussion welding
- High frequency resistance welding

iv. Thermo-Chemical Welding Processes

Thermo-chemical welding is a group of welding processes. It is used for most metals and alloys and for surfacing dies and tools. The types of Thermo-chemical welding are: thermit welding and atomic hydrogen welding.

Thermit welding is a welding process wherein coalescence is produced by heating with superheated liquid and slag resulting from chemical reaction between metal oxide and aluminum, with or without the application of pressure, the liquid metal acts as filler metal too.

Atomic hydrogen welding is a welding process wherein coalescence (fusion) is produced by heating the job with an electric arc maintained between two tungsten electrodes in an atmosphere of hydrogen, which also acts as a shielding gas, filler rod and pressure may or may not be applied depending up on job conditions [6].

v. **High-energy beam welding**

- Electron beam welding (EBW)
- Laser beam welding (LBW)

1.5 High Energy Density Beam Welding

No other welding process has created so much scientific and technical interest as the high energy density beams (HEDB); that is, Electron Beam (EB) and Laser Beam (LB). The wide variety of industrial techniques involved in these processes interests many branches of physics; indeed, these processes involve specialist in electron-optics and quantum physics, electronics and electrotechnics, high voltage and vacuum, robotics and computer sciences; and last but not least, metallurgists to whom new horizons have been opened. It is not surprising therefore to see that HEDB occupy a prime place in the research and development of welding processes [14]. Of course the commercial turnover with these processes remains quite low when compared to conventional welding processes; but their potential prospects appear very promising, especially when considering flexible production and rational utilization of energy. The application of HEDB covers various fields: from television to telemetry, cyclotrons to telecommunications, nuclear fusion of metal to isotope separation, surgery to armament, etc [1].

Although both processes (EBW and LBW) employ a high concentration of beam energy at the work surface, the method of establishing the energy beam is quite different. The electron beam is established by the direct or indirect heating of an emitter element (tantalum or tungsten) which allows electrons to become free particles of matter which are negative in electrical charge. The electrons are accelerated in free space (vacuum environment) by applying a positive attractive charge to the anode element. The electrons, now accelerated close to the speed of light, are directed and focused by a magnetic lens to a converging point at the work surface.

The laser beam (Light Amplification by Stimulated Emission of Radiation) is generated in a much different manner than EB. In a lasing medium, solid, liquid, or gas, a laser beam is generated by spontaneous collisions of molecules which stimulate emission of photons. The photons are emitted in precisely the same direction and at the same frequency. This cascade of identical photons (having a fixed wavelength) becomes the output, or a coherent beam of light energy which has been amplified in a resonant cavity by continuous stimulated emission. The coherent beam of light is then brought (by means of mirrors) to the focus lens which converges the energy to a point at the work surface [5].

1.6 Literature Review

- In 1986, Schuler, [2], studied and discussed the differences between electron beam and laser beam in welding and surface treatment. His study's conclusions explained that the primary area of application for electron beam technology is welding. The necessity for working in a vacuum strongly limits application possibilities. Lasers can only be used for welding depths up to 15mm. With electron beam devices deep welding over 100mm can be carried out without difficulty. With welding depth under 5-10mm, economic and technological considerations determine whether concrete problem can be better solved with laser or electron beams.

- Also in 1986, Arata and Sayegh, [1], reviewed current trends in the development of welding and its allied processes using electron beams and laser beams. They contrasted them with conventional welding processes, most particularly by arc heat source. In addition various problems in HEDB material processing and their solutions were discussed with researches of fundamental phenomena of HEDB material processing. Their study's conclusions summarized that the characteristics of the heat source created by these processes give joint qualities. Metallurgical problems associated with HEDB welding result from the high thermal gradient during welding as well as from the relatively rapid cooling rate and from the absence of filler metal.

- In 1987, Hanson, [5], made an overview comparison of high energy beam (EB/laser), primarily as used for metalworking applications. The equipment development of laser and electron beam welding processes has been studied including monitoring and quality control of the beam parameters. He considered each process (electron beam and laser beam) provided adaptive considerations for a wide spectrum of welding automation cell application needs.

- In 1988, Rykalin, et al. [3], described the ways of application of laser and electron beams to various industrial processes and the interaction of these beams with materials. The basic processes and phenomena of laser and electron beam has been described in many potential applications and industrial techniques, namely, laser and electron beam welding, cutting, heat treatment, annealing, alloying, and hole piercing.

- In 1993, Dave, et al. [15], made a study about laser and conventional electron beam welding processes. His study summarized that the laser and electron beam processes have many similarities and many differences. They provide some unique advantages such as low distortion and extremely rapid processing; however, they can be extremely costly except in high volume applications.

- In 2005, Levi, [16], made a short review about high energy density fusion welding processes describing electron beam and laser beam welding. He explained the advantages and limitations, similarities and differences such as: high power density, unique repair capabilities, narrow and deep welds, different materials combination allowable, favorable costs for special applications, high quality welds, no contamination, vacuum sealing, etc. He concluded that laser and EB welding permit to weld deeper welds with narrower melt volume, and much lower heat input influencing a thinner heat affected zone (HAZ) which is a quality ensuring quite better weld properties.

1.7 The Aim of the Project

The main goal of this research is to make a technical and economical comparison of welding by electron beam and laser beam to enable the most appropriate field of application to be selected for each process. This is achieved through:

i. Presenting the special characteristics of heat sources produced by high energy density beams (electron beams and laser beams), and the consequences for welding of the physical and metallurgical aspects.
ii. Analyzing the application of the process and the equipment specifications of the laser and electron beam techniques.
iii. Discussing the differences between electron and laser beam welding, the advantages and limitations of these technologies.

1.8 Thesis Layout

This thesis consists of five chapters:

- *Chapter One*: contains a brief description about the welding processes, advantages and limitations and high energy density beam welding (laser and electron beam). The related literature survey and the main aim of the work is given. Finally, the thesis is overviewed through the thesis layout.
- *Chapter Two*: gives a main description of the laser beam welding process, the mechanisms of the process, interaction phases between laser beam and materials, applications and analytical models.
- *Chapter Three*: gives a main description of the electron beam welding process, the mechanisms of the process, interaction phases between electron beam and materials, applications and analytical models.
- *Chapter Four*: gives the project results which presented as comparisons.
- *Chapter Five*: gives the present work conclusions, and the future work recommendation.

Chapter Two

LASER BEAM WELDING

2.1 Introduction

The focused laser beam is one of the highest power density sources available to industry today. It is similar in power density to an electron beam. Together these two processes represent part of the new technology of high energy density processing [17]. Laser beams have the ability to deliver very high power intensities to localized regions, lasers are now considered practical and economical tools for several industrial material processing applications. One of the important applications of the laser in industry is the use of the laser in metalworking. Laser applications in metal processing include: welding, cutting, and surface treatment; as in heat treatment, melting, alloying, cladding, machining, microlithography, bending, texturing, engraving and marking [18]. Laser beam welding is defined as a fusion welding process wherein coalescence is produced by the heat obtained from the application of a concentrated coherent light beam impinging upon the surfaces to be joined [10]. It is relatively easy to focus the beam from an industrial laser to a sub-millimeter diameter on a metal surface. With laser output in the kilowatt range, the resulting irradiance melts the workpiece in a few microseconds. When the beam is shut off or travels away from the heated area, the molten material solidifies, forming a weld. Such processes produce three distinct regions as shown in figure 2.1: the *base metal*, which is material that has not been altered by the welding process, the *fusion zone*, composed of material that was melted during welding, and the *heat affected zone* (HAZ) composed of base metal that has been changed in some measurable way by heat associated with welding [19].

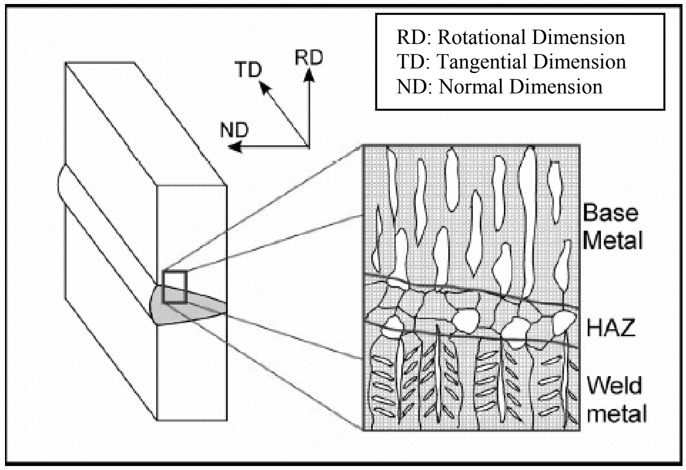


Figure 2.1 : Schematic diagram of a weld structure [20].

Compared with conventional processing technologies, laser welding offers a number of advantageous features [3, 21, 22]:

- Laser welding is a high energy density process, so that the heating is very localized.
- Small heat affected zone (HAZ).
- Low deformation of weldment.
- Laser welding may be performed in the atmosphere or with a simple shielding gas; there is no need to move parts into and out of vacuum.
- High weld rate, so that the processing can be economical.
- Access to only one side of the material is required.
- Laser welding gives consistent quality.
- No filler material is needed in most cases.
- A large number of different materials can be welded together.
- An easily automated process.

There are some limitations to laser processing [21, 23]:

- The initial capital cost is usually high.
- The depth of penetration in laser welding is limited, except for multikilowatt lasers.

- In laser welding, careful control of the process is required to avoid surface vaporization.
- Sensitivity to the surface condition.

Often, the advantages outweigh the limitations. In fact, laser processing has often been used to solve problems that were difficult for conventional processing. Of the many different types of lasers that have been developed, only a relatively small number are useful for material processing [21]. The leading contenders are listed in table 2.1 [23].

Table 2.1 : Characteristics of several industrial lasers [23].

Lasers	**Power Range (W)**	**Wave Length (µm)**	**Typical Industrial Applications**
CO_2-Flowing gas(CW & pulsed)	500-45,000	10.6	Cutting, welding, cladding, free forming , and hardening
CO_2-Sealed (Pulsed)	10-1,000	10.6	Micro-welding, cutting, scribing, and drilling
Nd-YAG (CW)	1,000-5,000	1.06	Welding, cutting, cladding, and hardening.
Nd-YAG (Pulsed)	10-2,000	0.53,1.06	Micro-welding, cutting, Drilling, Scribing, and marking
Nd-YAG-Diode Pumped (pulsed)	10-500	1.06	Cutting, drilling, scribing, Marking, and micro-machining
Excimer (pulsed)	0.001-400	0.157,0.351	Micro-machining, marking, and photolithography

2.2 Laser Beam Welding Mechanisms

A typical laser welding system includes a laser beam generator, beam-directing optics to transport the beam to the work and focus it to the required spot size and power density, and a workstation containing workpiece handling equipment that may feature manual or automatic loading and unloading [24].

It is possible to weld with most laser systems, even those designed for cutting. In many cases, a system comprising a laser, positioning tables, and computer numeric control (CNC) can be used for short run welding along gross defects, but attempts to tie small variations in the signal to variations in weld penetration have not been successful because the normal variations in plume emission are too great [19].

There are two modes of welding with laser: conduction welding and keyhole welding illustrated in figure 2.2 , [23, 25].

For laser conduction welding the laser energy deposited on the surface of piece and is transported to inside by means of heat conduction for lower power density [24]. In this method surface melting only occurs because of the power is insufficient. This method is much less efficient than keyhole welding. The primary loss of energy in conduction welding is by reflection, molten metals have a reflectivity around 50%, so half the power does not even get into the work [19].

Keyhole welding is efficient because the vapor channel traps the laser beam, reducing loss of energy by reflection, and because the keyhole acts as a cylindrical heat source extending below the surface of the work, reducing loss of energy by thermal conduction of the fusion zone [19, 26].

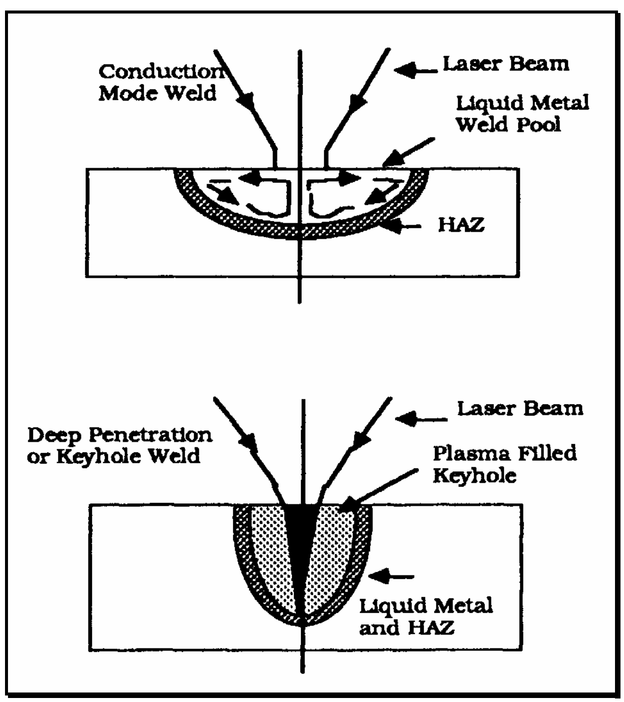


Figure 2.2 : Conduction limited and “Keyhole” type welds [23].

The most distinguishing characteristic of the laser beam for welding in comparison to the arc, resistance, or other common heat sources is its high power density. For most industrial laser welding applications in which keyhole (deep penetration) welding is required, a laser beam of several kW is focused onto the material surface with a focus spot diameter of approximately 0.1mm or larger. This results in power density in the range of 10^6 to $10^7 W/cm^2$ at the beam focus, which is similar to focused electron beams for welding. At this power density, pressure generated by beam-material interaction creates a keyhole in the material, as shown in figure 2.3. The keyhole is filled with metal vapor and surrounded by a thin cylinder of molten metal. As relative motion between the beam centerline and workpiece occurs, the molten metal flows around from the front of the keyhole and solidifies at the back, forming a laser weld [24, 25].

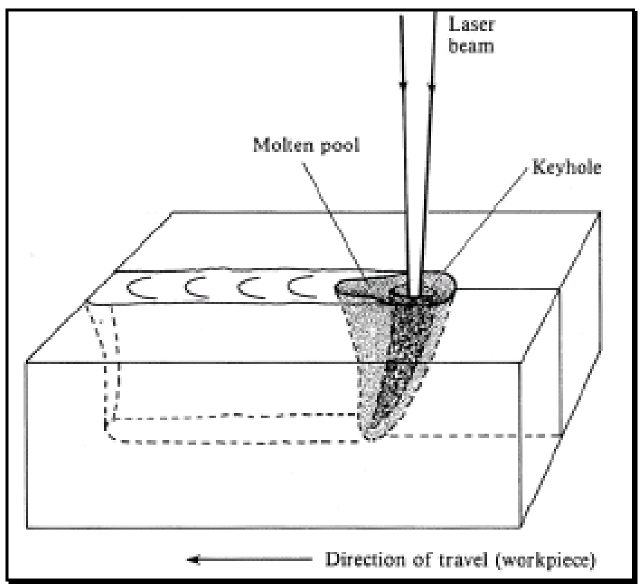


Figure 2.3 : Formation of keyhole during high power laser welding [23].

2.3 Laser Beam Material Interaction

When laser radiation strikes a target surface, the beam will be partially reflected, partially absorbed. If the laser beam hits a metallic surface, almost all the light will be reflected, a little will be absorbed, and non will be transmitted [27]. The energy that absorbed begins to heat the surface. There are several regimes of parameters that should be considered, depending on the time scale and on the irradiance. For example, losses due to thermal conduction are small if the pulse duration is very short, but they can be important for longer pulses. Under some conditions, there can be important effects due to absorption of energy in the plasma formed by vaporized material above the target surface. The losses due to thermal radiation from the target surface are usually insignificant [17, 21, 28].

To heat the material, it needs a lot of light to be absorbed. One way to do this is to cover the highly reflective metal surface with an absorbing dielectric coating that heats up and transfers the heat to the metal. This work except that the coating tend to change their properties at heat-treating temperatures, affecting the coupling. Another approach is to use a plane-polarized beam that is incident on the surface at Brewster's angle, maximizing the coupling. This eliminates the need for, and variability of, coatings but makes it difficult to treat curved surfaces. Whatever method is used, lasers heat only the surface of metals. All subsurface heating is accomplished by conduction. This makes it easy to model, since the mechanism is easily defined, although the values for thermal properties as a function of temperature are not [29].

High-power laser radiation incident on metals gives rise to the following processes [3]:

a) Electron and ion emission due to heating effects.
b) Melting, vaporization, and ejection of the droplets of melt from the interaction region.
c) Thermal radiation and x-radiation of up to 2keV.
d) Ultrasonic vibrations in metal due to the periodicity of heating and thermal expansion in the interaction of pulses whose substructure consists of spikes.

If the heating process continues, the solid being heated will change its state. Most materials will melt. A molten metal surface interacts with light much like a solid one. Absorption for metals increases when they melt because the degree of disorder in the material has increased, causing more interaction between atomic vibrations and electrons. Reflectivity drops from over 90% to about 50% for common metals [19].

The heating effects due to absorption of high-power beam can occur very rapidly, according to the absorption law [21] :-

$$I_{(z)} = I_0 e^{-\alpha z} \tag{2.1}$$

were $I_{(z)}$ is the light intensity penetrating to a depth (z). The incident light intensity is I_0 , α is the absorption coefficient of the metal. Figure 2.4 indicates the physical phenomena involved in the interaction of laser with material. For the purpose of this figure, the fraction of the light that is reflected is neglected. For metals the absorption coefficient are in the order of 10^5 cm^{-1}.Thus the absorbed energy is deposited in a layer of about 10^{-5}cm thick. It penetrates into the material by thermal conduction, thus the top part of the figure indicates heating of the material. When the surface reaches the melting temperature a liquid interface propagates into the material as indicated in figure 2.4.b. With continued irradiation the surface begins to vaporize as shown in figure 2.4.c and hole begins to be drilled. If the laser light is intense enough, absorption in the below off material leads to high-temperature opaque plasma. The plasma can grow back along the beam toward the laser supported absorption (LSA) wave. The plasma absorbs the incident light and shields the surface as shown in figure 2.4.d [21].

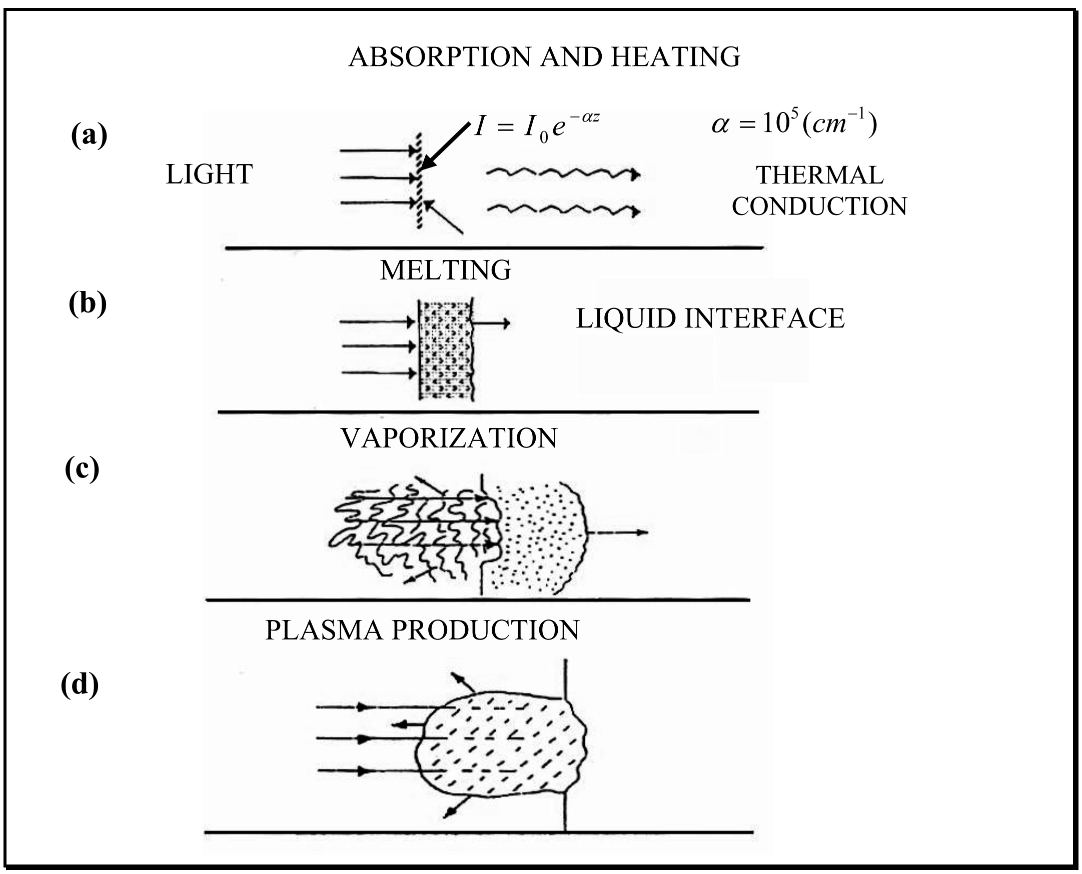


Figure 2.4 : Schematic diagrams of physical processes occurring when a high-power laser beam strikes an absorbing surface [21]

2.4 Laser Beam Profile

An ideal (Gaussian) radial power density distribution in the beam can be achieved only in a TEM_{00} mode. High power laser beams usually have a multi mode characteristic [2]. TEM_{00} modes produce deep, narrow welds, but are not the best mode for all laser welding. In many cases, the small focal spot and high peak power density of a fundamental mode are inappropriate. A high-order, and multiple modes output are all used, especially in a high-power laser, can be more stable than TEM_{00} mode. High order modes are less sensitive to resonator distortion and put less thermal load on the laser optics. Both of these properties increase the reliability of the laser [19]. In industrial laser applications most high-power Nd:YAG lasers and some CO_2 lasers run multimode. The cutting, welding, and drilling efficiencies of these lasers are directly related to the beam profile. For example an Nd:YAG laser with a double peak can cause one cut width in the X direction, and a different cut width in the Y direction. Also, a beam with a poor profile can result in hole drilling of a different size than expected, and welding that is not as strong as necessary [30].

Additions asymmetries are caused by polarization of the beam. However, the deviations can be made within limits and do not essentially affect the machining results [2].

The lasers have the possibility to beam split by semi transparent mirrors. One can direct the beam parts to different locations and in this manner increases the versatility or the through put of the system [2]. Beam splitting is useful for welding larger parts. A single higher-power laser beam can be split into two beams each at half the power of the original beam, and may be divided again if need be. This allows for multiple-part production from a single motion source. Cost-per-unit-power drops as laser size increases, so beam-splitting is a good option for welding large parts quickly [31].

The laser beam is commonly focused by means of lenses or lens systems with focal lengths ranging from 25 to 300mm and working diameters from 10-20mm. In use are also mirrors, reflector lenses, sets of varifocal and interchangeable lenses, and rotational lenses. Lasers operating in visible and in the near infrared employ glass lenses, and infrared lasers use lenses from NaCl, KCl, Ge, GaAs, ZnSe, etc., which can provide power densities of around 10^6-10^{10}W/cm^2 and above the focal spots of optical systems.

Depending on the parameters of laser radiation and the performance of optical systems, the diameters of focused laser beams range from 100μm to 1mm [3]. The focused spot size influences the weld size and shape and the amount of vaporization of the metal. The focal length of the lens that focuses the laser beam onto the weld joint is a key factor [32].

Industrial lasers are available with the capacity to provide pulsed output, continuous output (CW) or both. For pulsed lasers, the pulsing characteristics vary by laser design from low frequency, high peak power pulses to high frequency, square and sine wave pulses [32].

The laser beam may be pulsed (in milliseconds) for applications such as spot welding of thin materials, with power levels up to 100kW. Continuous multi-kW laser systems are used for deep welds on thick sections [33].

The pulsed mode is used to maximize heating and cooling rates in welding. The CW mode on the other hand, is used to maximize welding speed and reduce heat and cooling rates. CW generally provides the highest welding speed. Pulses with high peak power spikes on the leading edge are used to overcome the reflective nature of materials such as aluminum and copper [32].

2.5 Factors Affecting Laser Beam Welding Processes

Laser welding is a relatively straightforward process. If the workpiece is made of weldable material, all that is required is to hit the weld joint with the right amount of power. In most instances, the most difficult part of laser welding is constructing proper fixturing to hold the work. There are, however, a lot of variables that must be specified to generate the desired weld. Control of laser welding means having control of these parameters [19].

2.5.1 Laser Beam Related Parameters

i. Power

Lasers with beam power up to 15kW are sold by several companies. The welding depth of such machines go up to 15mm at reasonable welding speeds. Higher beam power does not lead to higher penetration depth, because of the power absorption of the laser plume. However, more than 90% of lasers used for material processing have a beam power of less than 1kW. Typical values of the power stability are 1% to 3%, which is enough for most applications [3, 34].

- *Effect of continuous power*

Important parameter is the power in watts between 100W and 20kW for materials processing [19]. There are two main problems in welding: lack of penetration or the inverse, "drop out". The maximum welding speed rises with increase in power. The drop out at the higher power levels of 2kW is almost certainly due to the poorer mode structure given by most lasers when working at their peak power. However, for higher power levels up to 5kW, the drop out may now be due to the same cause and also plasma effects. For high speeds the effects of sideways conduction during melting are slight. Penetration is inversely proportional to the speed for a mode, focal spot size and power [23, 35].

- *Effect of pulsed power*

Important parameters are joules per pulse and number of pulses per second, energy per pulse (1mJ-1kJ), pulse length (1ms-1ns), pulse repetition rate (0.1/s to 1000/s) [19]. The use of pulsed power allows two more variables: pulse repetition frequency (PRF), and percentage overlap to be considered. The welding speed is decided by (the spot size diameter×PRF×(1-%overlap)). In fact speed is independent of power. Penetration is a function of power and likewise the weld bead quality. Too much power causes vaporization and material ejection as in drilling. Thus for welding the pulse is usually longer than for drilling and shaped to have a smaller initial peak [23].

ii. Wavelength

Due to the high absorptivity within the "keyhole" there is little operational difference when welding with long or short wavelengths. When welding with a conduction limited weld then the surface reflectivity becomes paramount and the lower reflectivity with the shorter wavelengths gives a distinct advantage to Excimer, YAG or CO lasers over the CO_2 laser [19]. Wavelength affects absorption and reflection characteristics, and spot size and mode structure affect average irradiance and irradiance distribution in the spot [36, 37].

2.5.2 Transport Parameters

i. Speed

The speed of welding is proportional to the amount of power supplied but also depends on the type and thickness of the workpieces. Welding speed is also influenced by the optimum temperature distribution within the weld and HAZs for the material being welded. For pulse welding, speed is also influenced by the pulse rate available from the laser. For continuous welds with pulsed laser, speed is influenced by the amount of pulse overlap required to give the desired weld finish [32, 38].

- *Effect of Speed on the Weld Pool and Weld Bead Shape*

As the speed increases so will the pool flow pattern and size change. At slow speeds the pool is large and wide and may result in drop out, figure 2.5.d. In this case the ferrostatic head is too large for the surface tension to keep the pool in place and so it drops out of the weld leaving a hole or depression. At higher speeds, the strong flow towards the centre of the weld in the wake of the keyhole has no time to redistribute and is hence frozen as an undercut at the sides of the weld, diagrammatically shown in figure 2.5.b. If the power is high enough and the pool is large enough then the same undercut proceeds and edge freezing occurs leaving a slight undercut but the thread of the pool in the centre has a pressure which is a function of the surface tension and the curvature. This leads to pressure instability causing the "pinch" effect in which those regions of high curvature flow to regions of lower curvature resulting in large humps, figure 2.5.c. There is an intermediate region in which there is a partial undercutting and central string. All this has been mapped for certain alloys as shown in figure 2.6.a,b [17].

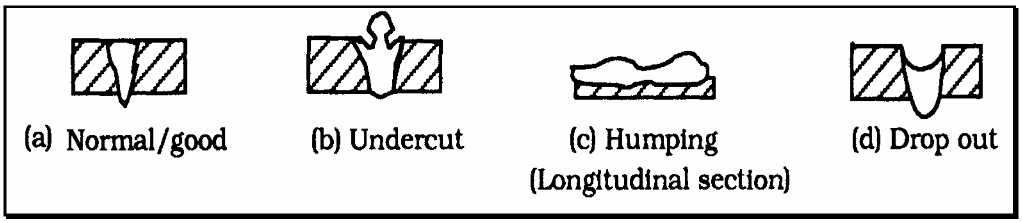


Figure 2.5: Range of weld shapes varying usually with speed [17].

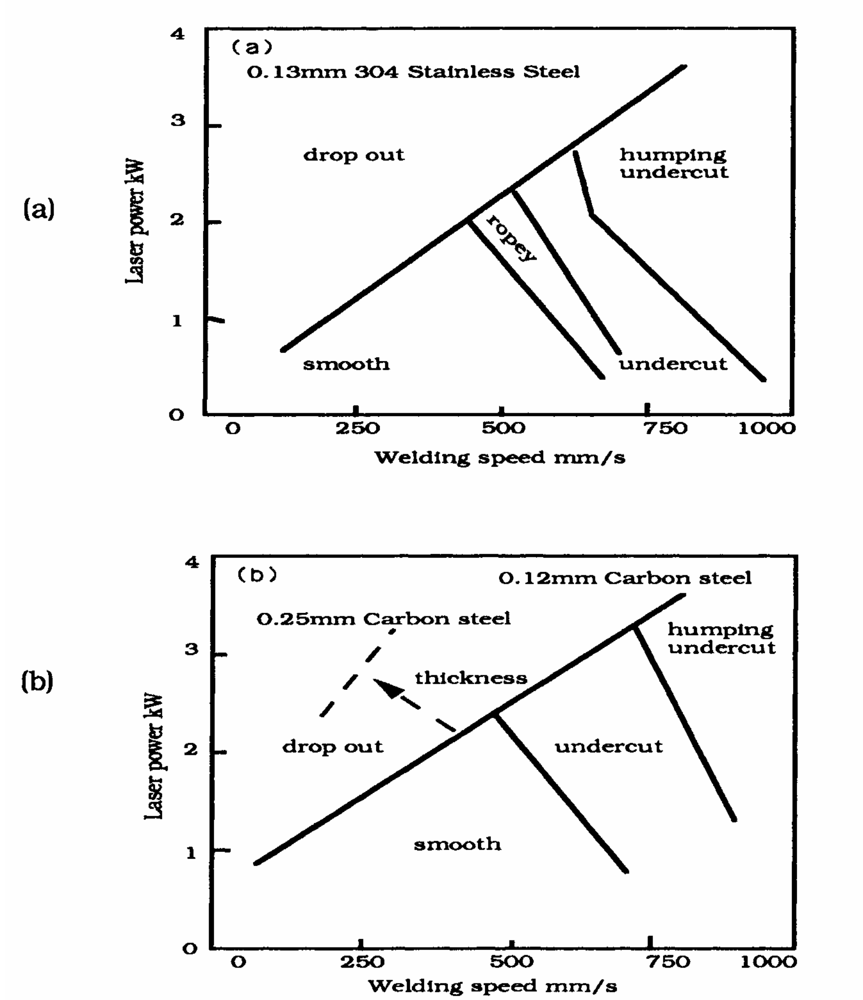


Figure 2.6: Map of weld bead profiles as functions of welding speed and laser power. a) 0.12 mm thick stainless steel, b) 0.12 and 0.25 mm thick mild steel [17].

- *Effect of Speed on Shroud Arrangements*

The faster the welding process the shorter the weld pool. However with increased speed the hot metal extends further beyond the welding point. Thus trailing shrouds are usually needed to avoid atmospheric contamination [17].

ii. Focal Length

The focal length of the optics influences the beam spot diameter at focus. For a given laser beam, the focus spot diameter varies directly with focal length. For a short focal length optic, focus spot size is small and power density is high. This results in a narrow fusion zone at fast weld speed and low laser power for welding thin materials [35]. However, depth of focus is also small for short focal length optics, so the beam diameter increases rapidly with distance from the optimal focus position. Small depth of focus limit the penetration depth or material thickness that can be welded and also requires that the focusing-optic-to-workpiece distance must be accurately maintained during welding. Conversely, long focal length optics have larger depth of focus appropriate for welding thick material, but wider fusion zones results due to the larger spot size. Power density required for deep penetration welding is increased by increasing laser power. Long focal length optics have the advantage of being more tolerant to work distance variations. Today CO_2 lasers with high power up to 6 kW are available with a beam quality which allows the use of focal lengths up to 1500 mm [39]. Also, because the focusing optics are more remote from the interaction point, they are less susceptible to fume or spatter contaminants generated by the welding process. From the previous discussion, it can be seen that selecting appropriate focusing optics is essential for achieving optimal welding performance for each different application [24].

iii. Joint Geometries

Laser beams welds prefer a joint which helps the absorption and hence the formation of the keyhole. High intensity welding processes are not sensitive to different thicknesses of the pieces to be joined. This allows some new types of joint as shown in figure 2.7, [23].

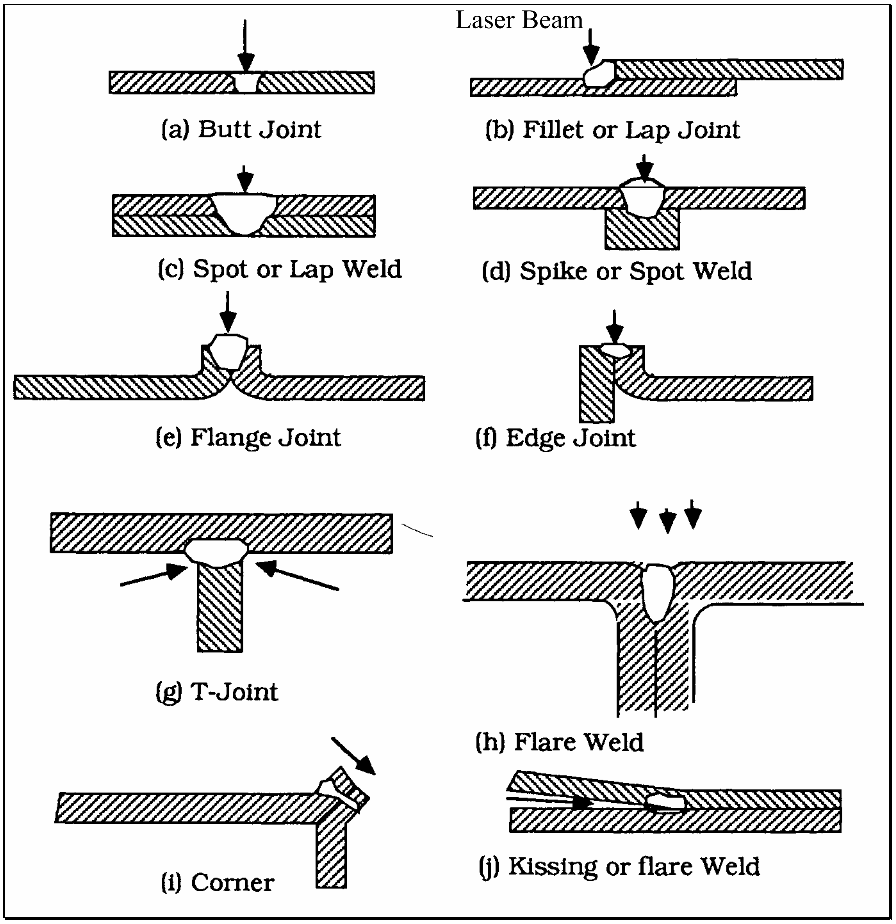


Figure 2.7 : Various welding joints arrangements [23]

iv. Gap Tolerance

For good quality welds to be made, it is essential that the fixturing should ensure the specified fit-up tolerances for weld joints since excessive misalignments and gaps between the parts to be joined have an adverse effect on the absorption of laser energy. The vertical misalignment and the gap between the parts to be butt welded should be no longer than 0.25 and 0.15 of the part thickness, respectively. The gap between the sheets to be lap welded should not exceed 0.25 of the sheet thickness. Adherence to these restrictions will lead to a higher weld efficiency and good reproducibility and quality of welds [3].

2.5.3 Assistant Gas Properties and Method of Delivery

Laser welding occurs in an ambient environment and atmospheric pressure, unlike electron beam welding which occurs in a vacuum or partial vacuum. Consequently, an assist gas is needed for most metals to protect the weld pool from oxidation and to protect the focusing lens from weld splatter [40].

The correct choice of assist gas is based on the size and profile of the weld and the reactivity of a particular gas with the metal or alloy being welded. Argon, helium and nitrogen are typically used in laser welding as assist gases. Argon forms a beam absorbing plasma with CO_2 laser welding that prevents deep penetration. It is good for shallow penetration when a wide weld is desired. Helium has the smallest potential for plasma formation of the gases listed here. It can be used for narrow, deep penetration welds with CO_2 lasers. Nitrogen forms a plasma, though not as readily as argon. It reacts with a number of metals, for example titanium and stainless steel. The result is embitterment of some materials, improved properties in other materials (such as some low ferrite number stainless steels), and no effect in other materials. The assist gas must be delivered so it protects the metal in the weld and HAZ throughout the heating and cooling cycles. It must also protect the lens or cover slide [32, 39].

The gas shroud can affect the formation of plasma which may block or distort the beam and thus the absorption of the beam into the workpiece. The formation of plasma is thought to occur through the reaction of the hot metal vapors from the keyhole with the shroud gas [23].

2.5.4 Effect of Plasma

Many problems in laser welding results from unwanted plasma effects. The desirable condition as shown in figure 2.8.a has a vapor capillary inside the metal to be welded. The laser beam transfers energy to the partially ionized vapor, and radiation from the incandescent plasma heats the metal. Under some conditions, vapor escaping from the capillary forms a cloud over the keyhole as in figure 2.8.b. This usually happens with laser powers over a kilowatt and argon shield gas. The vapor cloud absorbs some of the laser beam before it gets to the keyhole, and radiates this energy to the surrounding area. The result is less power entering the keyhole and consequently reduced weld penetration. Energy reradiated from the incandescent plume widens the top of the weld. In addition, the vapor cloud is often unstable, producing irregular penetration, which adversely affects process consistency. High-power laser welders generally use helium as a shield gas. It is thought that the high thermal conductivity of helium quenches the plasma as it escapes from the keyhole, reducing the density of the cloud. For further plasma reduction, a gas jet is used to blow the plasma away from the keyhole as in figure 2.8.c. The best efficiencies have been obtained with jets that push the plasma back into the keyhole as shown in figure 2.8.d, maximizing the capture of laser power. Such devices are not in general use, probably because the jet must be aimed very accurately at the keyhole and they are hard to control during the beginning and end of a weld [21, 40].

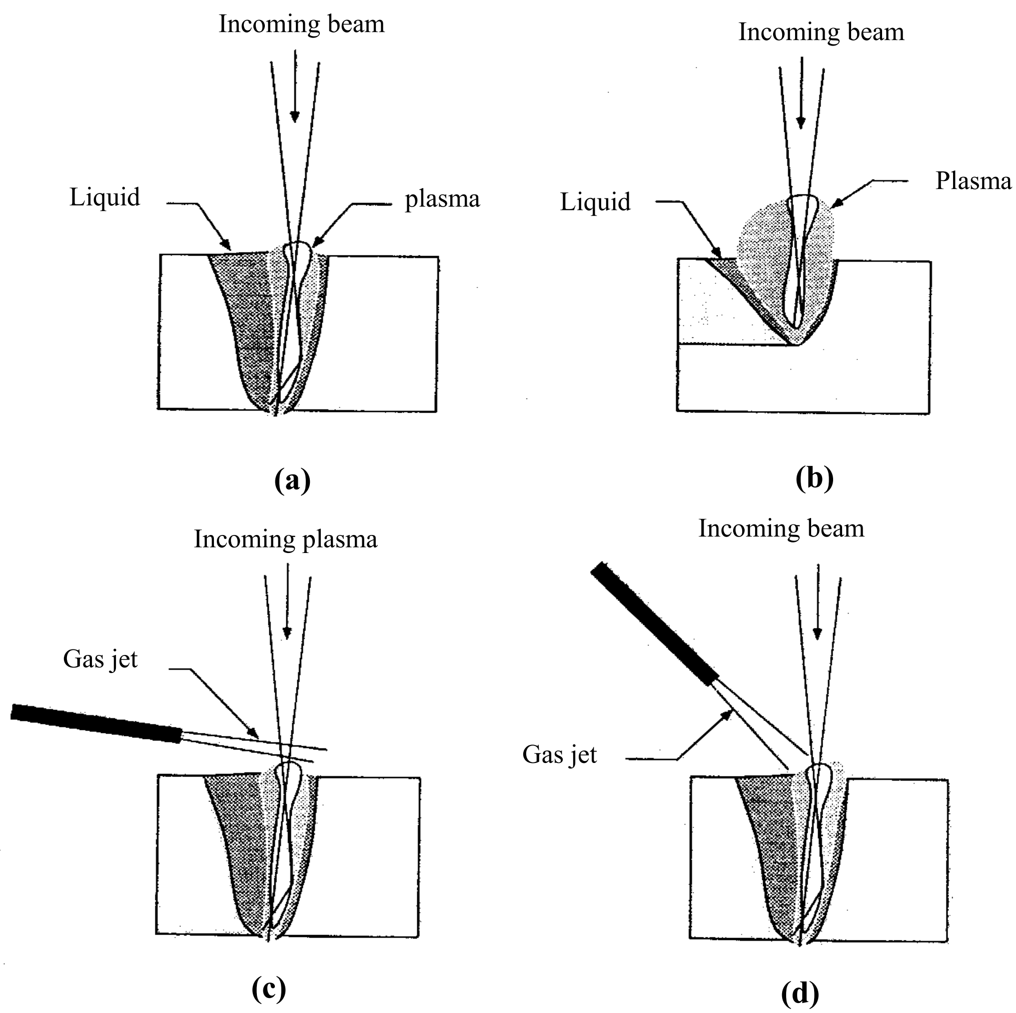


Figure 2.8: (a) Keyhole coupling through plasma, (b) Plasma absorption, (c) Plasma dispersal and (d) Plasma confinement [21].

2.5.5 Effect of Material Parameters

Effective melting and welding with lasers depends on the following material parameters:

i. Effect of thermal properties

Melting of a material by laser radiation depends on heat flow in the material. Heat flow depends on the thermal conductivity K. But thermal conductivity is not the only factor that influences the heat flow. The rate of change of temperature also depends on the specific heat c_p of the material. In fact, the heating rate is inversely proportional to the specific heat per unit volume, which is equal to γc_p, where γ is the material density. The important factor for heat flow is $K/\gamma c_p$. This factor has the dimensions of cm^2/s, characteristic of a diffusion coefficient. Thus, it is known by the descriptive term "thermal diffusivity", to recognize that it represents the diffusion coefficient for heat. The factor $K/\gamma c_p$ is involved in all unsteady-state heat flow processes, such as pulsed laser heating. The significance of this material property is that it determines how fast a material will accept and conduct thermal energy. Thus, for welding, high thermal conductivity allows longer penetration of the fusion front with no thermal shock or cracking. The thermal diffusivity of an alloy is usually lower than that of the pure metal that is the major constituent of the alloy. A low value of thermal diffusivity for a material limits the penetration of heat into the material and may reduce the laser weld ability [41].

The depth of penetration of heat in time t is given approximately by the equation [21]

$$h = (4at)^{1/2} \tag{2.2}$$

Where h is the depth of penetration of the heat and a is the thermal diffusivity. These ideas lead to the concept of a thermal time constant for a metal plate of thickness x. The thermal time constant is equal to $x^2/4a$. The thermal time constant represent the length of time it takes for heat to penetrate to a specified depth. Strictly, is the time required for temperature increase at the back surface of a plate to reach 37 percent of the temperature increase at the front surface when heat is absorbed in a very short pulse at the front surface. The thermal time constant gives a convenient order-of-magnitude of the time required for heat flow through the plate [21].

ii. Reflectivity

Another important parameter that affects laser welding is the laser reflectivity of the workpiece surface. It defines the function of the incident light that is absorbed and contributes to heating effects. The reflectivity is defined as the ratio of the radiant power reflected from the surface to the radiant power incident on the surface. Thus, the reflectivity is a dimensionless number between zero and unity. The reflectivity of several metals as a function of wavelength is shown in figure 2.9. These curves represent typical smooth surfaces. The exact value of the reflectivity is a function of variable conditions, including surface finish and state of oxidation. The reflectivity of all metals becomes high at long infrared wavelengths. At wavelength longer than 5μm, the reflectivity strongly depends on electrical conductivity. Metals with high electrical conductivity have the highest values of infrared reflectivity. Thus, the reflectivity of gold is higher than that of aluminum, which in turn is higher than that of steel [21, 42].

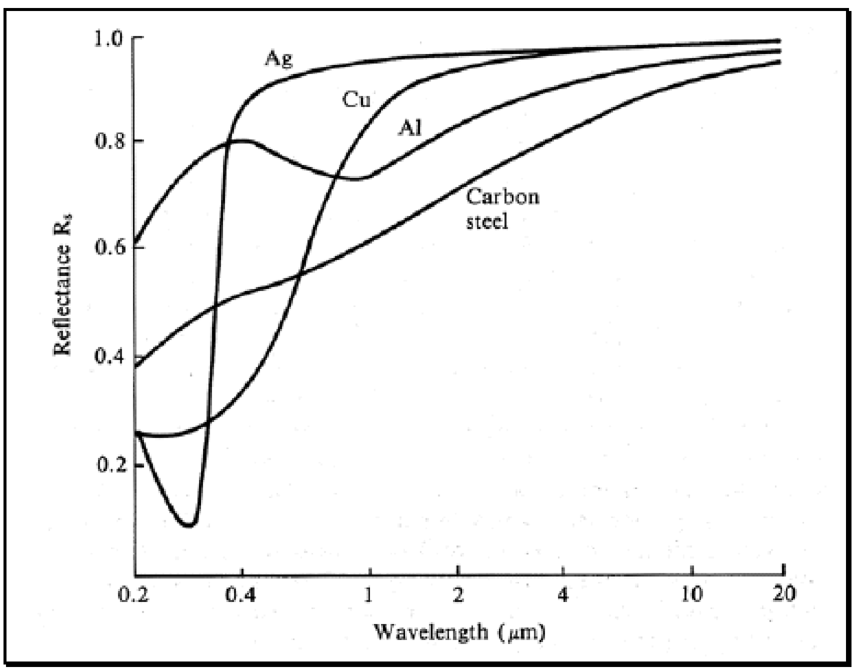


Figure 2.9 : Reflectivity as a function of wavelength for several metals [21].

2.6 Basic Regimes of the Heating of Metal Targets by Laser Irradiation

Convenient analytic formulae are given for calculating the evolution in space and time of the temperature field inside metal targets under various irradiation conditions and target geometries. The variation with temperature of the optical and thermophysical properties of the metal ─including the transition through the melting point─ is given particular emphasis [43].

2.6.1 Heat Transfer Equation

The conduction of heat in a three-dimensional solid is given in general by the solution to the equation [44]:

$$\gamma c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(K\frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(K\frac{\partial T}{\partial y}) + \frac{\partial}{\partial z}(K\frac{\partial T}{\partial z}) + A(x,y,z,t) \tag{2.3}$$

where the thermal conductivity (K),the density (γ),and the specific heat (c_p) are dependent both on temperature and position, and heat is supplied to the solid at the rate A(x,y,z,t) per unit time per unit volume. Any temperature dependence of the thermal parameters makes the equation non-linear, and solutions are very difficult to obtain although numerical solutions are possible in a limited number of cases when the temperature dependence of a (thermal diffusivity), K, γ, c_p is known [44, 45]. However, since the thermal properties of most materials do not vary greatly with temperature they can often be assumed independent of temperature and can be assigned an average value for the temperature range of interest. In this case, solution are possible for a number of cases in which thermal properties vary discontinuously or in those cases where a simple analytic expression is available for the spatial variation of K [23].

If the solid is taken to be homogeneous and isotropic, then equation (2.3) reduces to:

$$\nabla^2 T - \frac{1}{a}\frac{\partial T}{\partial t} = -\frac{A(x,y,z,t)}{K} \tag{2.4}$$

where (a=$K/\gamma.c_p$) is the thermal diffusivity. In the steady state ($\frac{\partial T}{\partial t} = 0$) and this equation becomes:

$$\nabla^2 T = -A(x, y, z) / K \tag{2.5}$$

Equations (2.4) and (2.5) can be solved in a large number of cases. If no heat is applied to the material, then A=0 and equations (2.4) and (2.5) become:

$$\nabla^2 T = \frac{1}{a}\frac{\partial T}{\partial t} \text{ (time-dependent)} \tag{2.6}$$

$$\nabla^2 T = 0 \text{ (steady-state)} \tag{2.7}$$

In practice, cases in which heat sources are present or absent are usually solved by imposing on the solutions of equations (2.6) and (2.7) the appropriate boundary conditions of applied heat flux and heat transfer across the surface of the solid [44, 45].

2.6.2 Analytical models

2.6.2.1 Uniform heating over the surface bounding (A semi-infinite half-space)

The simplest heat transfer problem encountered in laser interaction studies is given by the system of a semi-infinite half-space that is heated uniformly over its bounding surface [44]. In this case heat transfer is only in one direction which is the depth (z) because the transverse of the laser beam considers large comparing with a depth of penetration through the duration of the laser pulse. And thus the heat transfer is depends on the z-axis .Thus equation (2.3) becomes:

$$\frac{\partial}{\partial z}\left(\frac{\partial T}{\partial z}\right) - \frac{1}{a}\cdot\frac{\partial T}{\partial t} = -\frac{A(z,t)}{K} \tag{2.8}$$

And this model have the following cases:

i. Surface source, constant in time

When laser radiation can be considered to be absorbed in a very thin surface layer and the temporal variation of the pulse is given by [44]:

$$F(t) = \begin{cases} F_0, t > 0 \\ 0, t < 0 \end{cases}$$

Then the variation of temperature with depth is given by the equation [44]:

$$T(z,t) = (2\varepsilon F_0 / K)(at)^{1/2}\, ierfc[z/2(a.t)^{1/2}] \quad (2.9)$$

where ierfc is the integral of the erfc,

$$ierfc(x) = \int_x^\infty erfc(S)dS \;\;, \text{ and } \quad erfc(x) = (2/\pi)^{1/2}\int_x^\infty e^{S^2} dS \quad (2.10)$$

To reach a predetermined temperature with given pulse energy, it is more effective to shorten rather than to lengthen the pulse. This shows clearly the importance of the rate of energy input in establishing a final temperature. If the radiation is applied in the form of a pulse [46],

$$F(t) = \begin{cases} F_0 \,, 0 < t < t_p \\ 0 \,, t < 0 \,, t > t_p \end{cases}$$

where t_p is the time of pulse.

Then T(z,t) is given by the equation [44]

$$T(z,t)_{t>t_p} = \frac{2F_0.a^{1/2}}{K}.\left\{ t^{1/2}.ierfc\, \frac{2}{2(a.t)^{1/2}} - (t-t_p).ierfc\, \frac{2}{2[a.(t-t_p)]} \right\} \quad (2.11)$$

ii. Distributed source, constant in time

The laser pulse as given in equation (2.11), except that the absorption can not be considered to localized in a surface layer, and temperature are to be estimated within the region of absorption.

The absorption coefficient for radiation of the material in this case is small specially dielectric sheets and the laser pulse be constant in time and uniform above the surface [46].

iii. Surface source, pulsed

The simplest solution is obtained when the source generates a series of rectangular pulses as shown in figure 2.10. Figure 2.10.a represents laser pulses while figure 2.10.b shows the temperature rise on the surface of a semi-infinite solid which can be considered continuous [44].

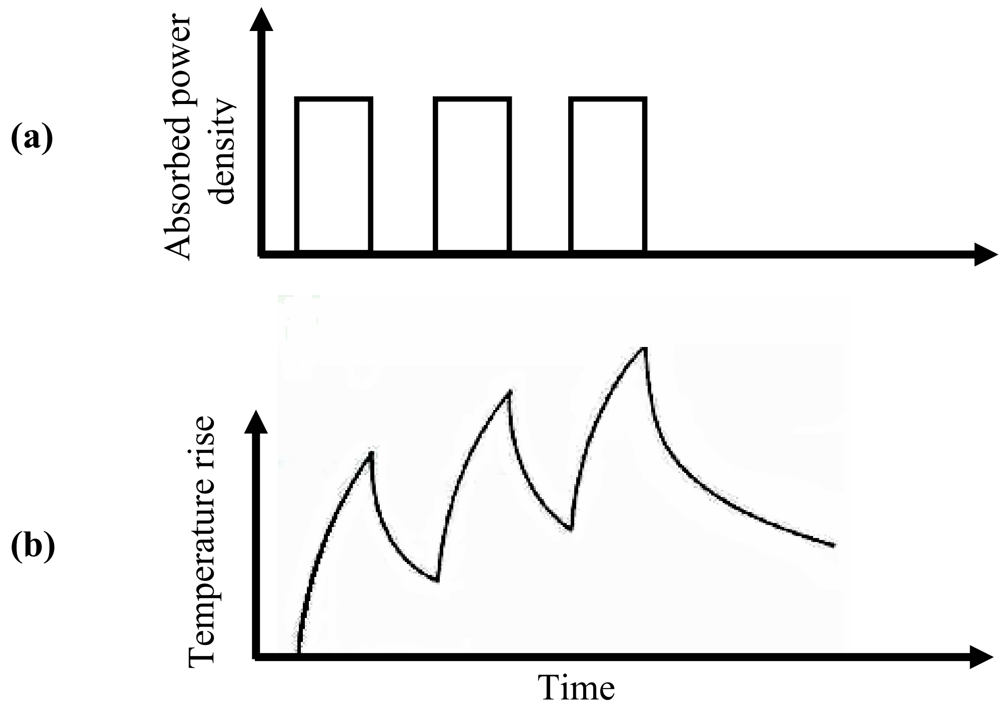


Figure 2.10: Variation of temperature with time for a semi-infinite half-space on irradiation with a series of pulses [44]

2.6.2.2 Gaussian surface source on semi-infinite half-space

In this case consider the intensity distribution in the focal area can best be described by a Gaussian function. This is the situation in the case of a laser operating in the TEM_{00} mode and focused with distortion less optics. The intensity on the surface of the material can be written [44]:

$$F(r) = F_0 \exp(-r^2 / d^2) \tag{2.12}$$

where F_0 is the intensity at the center of the spot and d the Gaussian beam radius [44, 47].

For a Gaussian source [44],

$$Q = 2\pi . r' q_0 \exp(-r'^2 / d^2) dr' \tag{2.13}$$

where q_0 is the energy per unit area at the origin, r' is the radius of the ring source.

Substituting for Q in equation (2.13) and integrating we obtain [44]:

$$T_{inst\ .Gauss}\ (r,z,t) = \frac{q_0}{2\gamma c_p(\pi a^3 t^3)^{1/2}} \exp[-\frac{r^2+z^2}{4at}]$$

$$.\int_0^\infty \exp[-r'^2(\frac{1}{4at}+\frac{1}{d^2})] I_0(\frac{rr'}{4at}) r' dr' \qquad (2.14)$$

2.6.2.3 Circular surface source on semi-infinite half space (Uniform source, constant in time)

Various approximation to the intensity distribution within the focus of a laser beam are possible, while consider the total laser power (P) is incident over a circular area πA^2 and the intensity within this area is constant at the value $(P/\pi A^2)$. In practice, the distribution of intensity within the focus is a complex function of position and time but laser-induced thermal effects do not seen to be overly sensitive to this distribution provided that the temperature (i.e., thermal effect) is sampled away from the immediate are in which the interaction occurs. For this reason, it is often convenient to assume as above that all "fine structure" in the intensity distribution is eliminated and that the thermal effect is the same as that which would be produced by absorption of the equivalent total power over a circular area whose radius may be chosen empirically.

Consider the case of heating a large block of material with laser radiation focused onto the surface as shown in figure 2.11 [44].

The time-independent temperature distribution in the solid is obtained by solving equation (2.4) for the applied power (P) for (t > 0) over the circle $x^2+y^2=A^2$, z=0, of the semi-infinite region:

$-\infty \le x \le +\infty$, $-\infty \le y \le +\infty$, $0 \le z \le +\infty$

The solution at the point whose cylindrical coordinates (r,z) is then [44]:

$$T(r,z,t) = \frac{P\varepsilon}{2\pi AK}\int_0^\infty J_0(m'.r).J_1(m'.A).\{\ e^{(-m'z)}.erfc[\frac{z}{2(a.t)^{1/2}} - m'(at)^{1/2}]$$

$$- e^{(m'.z)}.erfc[\frac{z}{2(a.t)^{1/2}} + m'.(a.t)^{1/2}]\ \}.\frac{dm'}{m'} \qquad (2.15)$$

where ε is the fraction of the energy absorbed from the beam, and J_0 and J_1 are Bessel functions of the first kind. This integral can be evaluated numerically to determine the temperature at any point in the solid at any time. Of greater interest is the temperature variation with time for points directly below the focal spot. The temperature at positions along the z axis is given by:

$$T(0,z,t) = \frac{2P\varepsilon(at)^{1/2}}{\pi A^2 K}\left[ierfc\left(\frac{z}{2(at)^{1/2}}\right) - ierfc\left(\frac{(z^2+A^2)^{1/2}}{2(at)^{1/2}}\right)\right] \tag{2.16}$$

while the temperature at the focusing center and on the surface is:

$$T(0,0,t) = \frac{2P\varepsilon(at)^{1/2}}{\pi A^2 K}\left[\frac{1}{\pi^{1/2}} - ierfc\left(\frac{A}{2(at)^{1/2}}\right)\right] \tag{2.17}$$

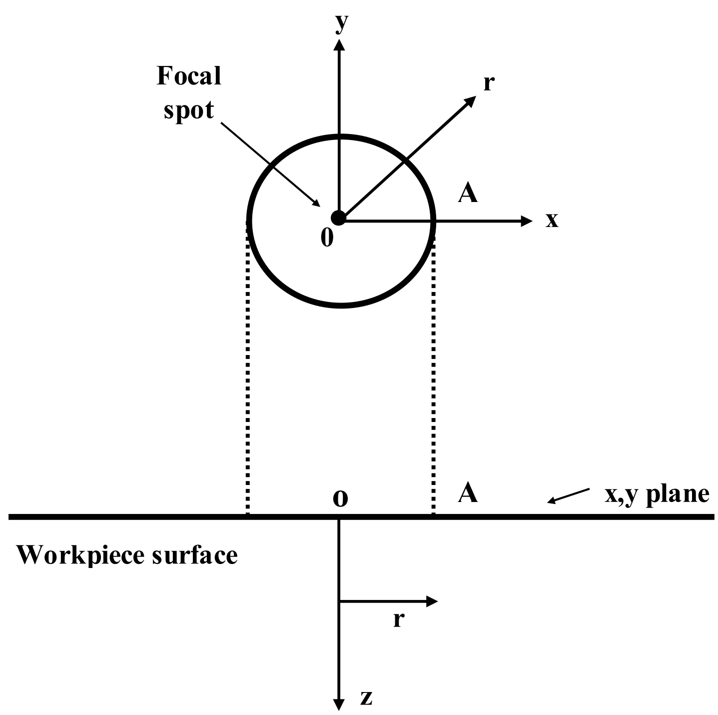


Figure 2.11 : Coordinate system [44].

2.6.2.4 Moving heat sources

In welding metals with high-power CW CO_2 lasers, material is removed completely from a long roughly elliptical cylinder and incident radiation is able to penetrate deeply into the material. This effect, which is known as "keyholing", permits welds to be obtained whose depth is much larger than that expected simply on the basis of heat transfer theory. The geometry of the melt region is shown schematically in figure 2.12. Heat transfer at the surface of the keyhole forms an egg-shaped melt region whose flat end lies ahead of the laser beam. The width and depth of the melted zone depend on laser power and the speed at which the weld is produced. This dependence has been calculated using a moving line source model [44, 48].

The temperature at the point (r,x) is given by the equation [44]:

$$T(r,x) = \frac{\varepsilon P}{2\pi K r} \exp\left[-\frac{\upsilon r}{2a} - \frac{\upsilon x}{2a}\right] \tag{2.18}$$

where υ is the velocity in the positive x direction and $r=(x^2+y^2+z^2)^{1/2}$.

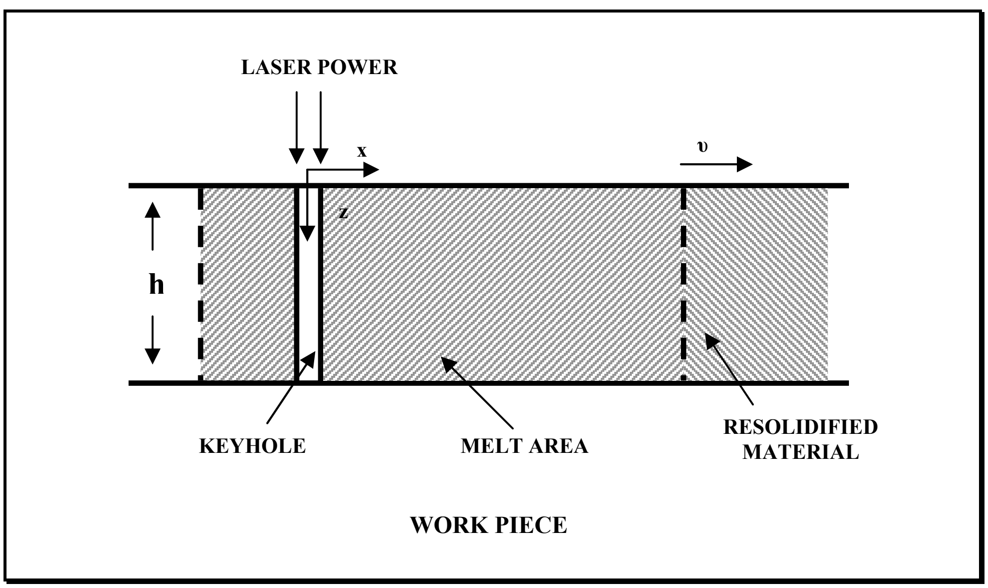


Figure 2.12: Geometry for penetration welding of a semi-infinite sheet [44]

2.7 Laser Welding Applications

The utilization of laser welding in manufacturing industries has increased rapidly during the last few decades and can be regarded as a more or less mature technique. The most common laser for high power welding is the carbon dioxide laser (CO_2 laser).This laser emits light with a wavelength of 10.6µm. The laser gas mixture used in CO_2 lasers consists mainly of helium, to ensure the removal of generated heat, carbon dioxide, the laser-active medium, and nitrogen, in which a gas discharge creates the energy necessary for excitation. The CO_2 laser is especially cost-effective when used for the high-speed welding of comparatively thin-walled structures like car bodies. The disadvantage of this type of laser is that it requires a sophisticated system to distribute the laser beam to the workpiece. This also means that the work stations are not as flexible as they might be. The quality of the beam is also reduced if it is necessary to transfer the laser beam via many mirrors.

The other dominant laser source is the Nd:YAG laser. This type of laser has a wavelength that is ten times shorter (1064nm) than that of the CO_2 laser. The laser-active medium, neodymium (Nd3+-ions), is located in a solid crystal made up of yttrium-aluminum-garnet and is usually rod-shaped. The optical excitation in pulsed lasers (p-lasers) generally occurs by means of krypton flash-lamps, whereas krypton arc lamps are used in continuous-wave high power lasers (CW-lasers). The principal advantage compared with CO_2 lasers is that the light from the Nd:YAG can be transmitted to the workpiece by optical fibers and can therefore be more easily integrated into a large variety of systems.

However, the development of more flexible and efficient lasers is continuing and in recent years can see new products, such as diode-pumped Nd:YAG lasers or direct-acting diode lasers, starting to be used in commercial production [49, 50].

Demands for improved production quality, productivity, and flexibility are constantly enlarging the field of laser welding applications . This process is being used for an extensive variety of applications in the industry [51]. Typical laser welding applications are shown in the table 2.2, [52].

Table 2.2 : Typical applications of laser welding [52].

Industry sector	Application areas	Materials	Thickness [mm]
Aerospace	Weld-joining of airframe components Weld-joining of aero engine components Welding combustion chamber components	Al alloys Ti-, Ni-, stainless steel alloys	< 3,0 < 3,0
Automotive	Weld-joining of pressed sheet body parts Welding of tailored blanks (coated/uncoated) Welding of high strength steel Welding catalytic converters	Mild steel Al alloys HSLA steel Stainless steel	0,7 - 1,0 1,0 - 2,5 < 3,0
Defence	Low-distortion welding of structures	Ti- & stainless steel alloys	> 3,0
Domestic products	Low-distortion welding of domestic appliances Welding of double glazing frames	Mild steel Al (1 000 & 6 000)	0,4 - 0,8 1,0 - 2,0
Electronic	Weld-joining of electronic packages	Al (4 000 & 6 000)	0,5 - 2,0
Maintenance & repair	Weld repair of gas turbine blades & nozzle guide vanes (aero engine / power generation turbines) Sleeving technology (power generation repair) Weld rebuilding or cladding of worn surfaces	Ni alloys (IN738-single crystal) Stainless steel Wear/corrosion resistant metals	0,5 - 3,0 < 5,0 ≤2, 0 per layer
Oil & gas	Welding of thin-wall pipework	Steel & duplex stainless steel	>4,0
Packaging	Welding of thin sheet for can or tube applications	Steel, Al & Cu	0,2 - 1,0
Power generation	Weld-joining of pipework & containers	Stainless & modified steels	> 3,0
Process plant	Weld-joining of tube-to-tube plate	Ti alloys & stainless steels	> 3,0
Shipbuilding	Butt, fillet & stake welds	Steel	6,0 & 14,0
Popular high-volume production applications		**Materials**	**Thickness [mm]**
Low-distortion laser spot welding of colour TV gun		Stainless steel	≤ 0,5
Low-distortion spot welding of razor blade cartridges		Pt-hardened stainl. steel	< 0,5
Joining food mixer whisks by lap-stake welds (3x sheets)		Ferritic stainless steel	1,0
Stake weld-joining of gas hob manifold		Al coated mild steel	0,75
Butt joining of cutting tips to rotary saw blade		Special tool type steels	< 6,0
Hermetic low temperature joining of heart pacemaker package		Titanium	< 0,5
Accurate low-distortion seal joining of opto-electronic transmitter ferrule to casing		Stainless steel	< 1,0
Airtight low distortion joining of tappet housing		Case hardening steel	1,2
Fillet-butt welding of dissimilar thickness tailored blanks		Zinc coated steel	0,8 & 2,0
Joining differential splined part to hub or housing		0,3% Carbon steel	3,0
Tube manufacturing (longitudinal butt weld)		Stainless steels	0,5 - 6,0
T-butt joining of heat exchanger fins to tube		Stainless steel	< 3,0
Weld-joining solenoid valve to cylinder assembly		Steel to stainless steel	< 3,0
Rectangular tube manufacturing		Stainless steel	0,5 - 6,0
Weld-joining of gears to gear carriers		Medium carbon steels	
Weld-joining of clutch discs to drums		Steel	
Weld-joining of exhaust manifolds (filler wire addition)		Steel	
Joining of car roof body to side, front and rear body panels		Mild steel	0,7 - 1,5
Weld-joining of muffler – Ferritic stainless steel		0,7 - 1,5	
Welding of I-beams by means of T-joints		Structural steel	5,0 - 12,0
Weld-joining of fuel filter lid to can body		Al or mild steel	0,5 - 1,0

2.7.1 Aerospace Applications

Welding of airframe structures with low distortion and the laser cutting and welding of complex shapes, typical of the aeroengine industry, become possible with the development of high power Nd:YAG lasers. Laser welding is well established in industry, but it's automated application to the aerospace sector is still relatively new. As solid state lasers increase in power, so their application becomes more relevant. The advantage of the Nd:YAG laser is the ability to transmit the laser beam down a fibre optic, allowing easier manipulation of the beam to remote and complex locations, typically at the end of a robot arm [53]. The laser itself is a versatile tool already established in the aerospace sector for cutting and drilling. With the higher powers becoming available (up to 4kW in a single laser and maybe 10kW with a combination of lasers), cutting and welding of aerospace alloys is now feasible and has been demonstrated on prototype parts. Combining the cutting operation in the one machine with welding, significantly reduces the stripping down and re-jigging necessary with different work stations [54].

2.7.2 Automotive Applications

Some of the keywords in automotive manufacturing today are quality, flexibility, high productivity and cost effectiveness. Laser welding appears to meet all these requirements and the proof can be found in the impressive number of lasers already in operation today at automotive companies [55, 56].

Roof laser welding can be more or less regarded as state of the art among automotive manufacturers and some European car manufacturers will now be mentioned. Laser beam know used in most automotive companies, it is use in Volvo, BMW, Ford, Audi, Volkswagen and Renault. Figure 2.13 explained extensive car body laser welding of the BMW 5 Series model [49].

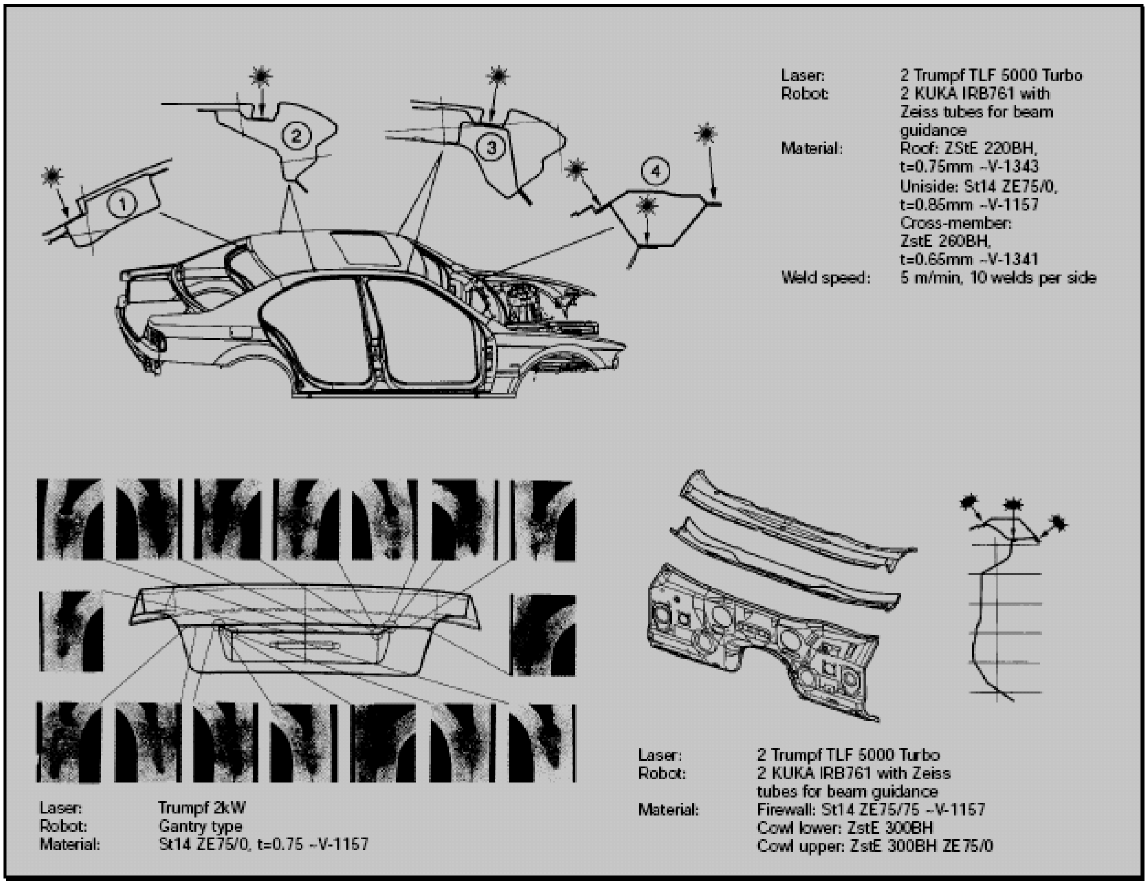


Figure 2.13 : Extensive car body laser welding of the BMW 5 Series model [49].

2.7.3 Micro Technology Applications

Laser micro-processing has grown to become a mature technology for many parts in the electronics industry. It has not only replaced conventional technologies but, as a result of the redesign of product parts dedicated to the new technology, it has also enabled improved product quality and new products. The low cost of ownership, the reliability of the equipment, the high yield of the process, combined with the high accuracy and flexibility, have made the laser a very valuable tool. Laser spot welding is an accepted technology in the electronics industry. Every manufacturer of TV and computer monitor tubes uses this technology for the assembly of the electron gun. Typically, 150 tiny laser welds, applying pulsed Nd:YAG lasers and fiber beam delivery systems, are used to sub-

assemble the cathodes, the electron optic grids and lenses and, finally, to assemble the gun. It would be true to say that the quality of modern TV picture tubes could not be realized
without laser spot welding. Because laser welding involves the introduction of heat into the product, if only to a very limited extent, thermo-mechanical deformation and displacement have to be considered at the design phase, so that they can be utilized in laser adjustment operations. Several thermo-mechanical mechanisms are known to produce both bending and shortening in a part. In this way, it would be possible to manipulate several degrees of freedom in a product that is mounted on the structure. Using this new technology of laser manipulation for the adjustment of parts, elaborate positioning procedures using expensive, complicated tools can be replaced by simple tools and the final accuracy will be produced by laser adjustment. It is clear that laser processing in the electronics industry has become a mature technology and a large number of parts can only be manufactured using this technology. Using solid state lasers with high beam quality, it is possible to create weld sizes in the 100μm range. By adapting the beam geometry and pulse shape for each individual welding application, it is possible to minimize the distortion as well as the contamination of the welded part [49].

2.7.4 Laser Beam Welding of Metals

Laser beam welding can be successfully used to join many metals to themselves as well as to dissimilar metals. Laser welding can be performed on a wide range of ferrous and non-ferrous alloys. Main applications are related to welding steels, titanium, and nickel alloys [17].

- Laser Welding of Steels

Steels are alloys of iron and carbon. Other elements, present as impurities or intentional alloy additions, have strong effects on the properties of steel, and thousands of components are encountered. Variations in steel making clean and dry, the surface of the steel is free of scale or oxide, and by providing adequate shield gas during welding. These practices do not prevent martensite formation: they just reduce its tendency to crack. As a more complex alternative, a filler metal such as nickel wire can be added to the fusion zone to reduce its hardness. Nickel stabilizes the austenite phase at room temperature, preventing martensitic transformation in the fusion zone [19]. Low-carbon steels are readily laser weldable provided that sulfur and phosphorus levels are kept below 0.04%. A higher content can promote solidification cracking. In low-carbon steel the welding zone is martensitic and exhibits increased hardness, the level of which depends upon carbon and alloying elements contents. In the tempering zone, temperature is not high enough for customization, and additional tempering proceeds. Figure 2.14 represent an example of lever-shaft assemblies have been successfully welded using laser beam [57].

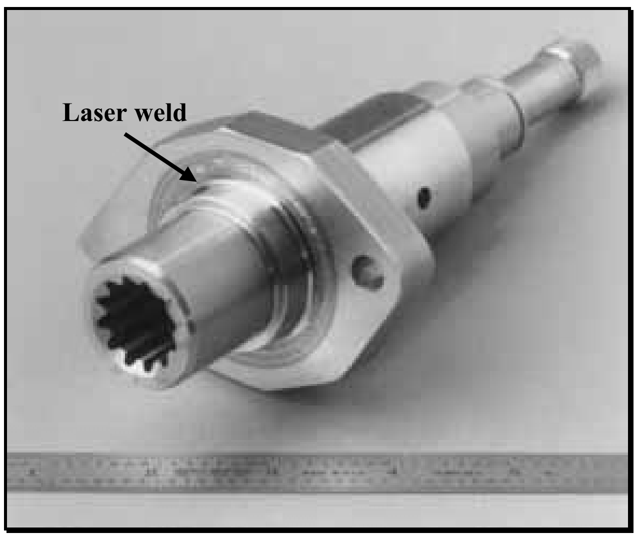


Figure 2.14 : Laser welded lever shaft assembly composed of two steels [57].

- Stainless Steels and Superalloys

The basic metallurgy used in the manufacture of these materials usually results in materials of high quality with insignificant amounts of contamination. The more common austenitic stainless steels, such as AISI 302 or AISI 304, usually have good laser weldability. However, austenitic stainless steel with higher alloy content, such as AISI 316 and AISI 347, may be a bit crack sensitive. Weldability depends on material thickness, and parameter selection. Free machining stainless steel, such as AISI 303, is not usually weldable.

Feritic and martensitic stainless steel are usually weldable by lasers, except those containing moderate amounts of carbon are subject to the same precautions necessary for welding carbon steels with moderate to high carbon content.

Superalloys are classified as heat resisting alloys with nickel, nickel-iron, or cobalt as their base. These alloys exhibit a unique combination of mechanical strength and resistance to surface degradation when exposed to elevated temperatures. Four groups of these materials include; solid-solution-strengthened alloys, precipitation-hardened alloys, dispersion-strengthened-alloys, and cast alloys.

Many of the superalloys respond well to laser welding. Their response to laser welding is similar to conventional welding [58, 59].

- Aluminum Alloys

Aluminum and its alloys are more difficult to weld than iron-base alloys for several reasons. Most obvious are aluminum's high reflectivity and thermal conductivity. Power from a laser is thus reflected away or, once it gets into the metal, it is conducted away from the region to be welded. These properties require a higher power density to form a keyhole in aluminum than for steel. Unfortunately, aluminum vapor ionizes much more readily than iron vapor, so the plasma in the keyhole absorbs more energy once it forms. The overheated plasma exits the keyhole and blocks incoming light. The consequent reduction of power in the keyhole causes it to collapse. This sequence of keyhole formation, plasma blocking, and keyhole collapse makes for unstable welding. In all cases, laser welding for aluminum requires clean joint surfaces that are free of hydrated oxides, complete gas shielding to minimize the formation of oxides during welding, and high power densities to overcome aluminum's high reflectivity and thermal diffusivity [19, 60].

- Dissimilar Metals

When welding dissimilar metals certain considerations with regard to their properties must be taken into account; difference in melting point, heat conductivity, reflectivity, possible formation of brittle phases, and wet ability. To achieve better welding performance the laser beam can be shifted towards the material with higher melting point, heat conductivity, and reflectivity [57, 61].

During welding of dissimilar metals, the micro structural features that emerge as a result of differences in the physical properties of the two metals are potentially very different from the features observed in welding of similar metals/alloys. Solidification must occur from pure base metals into an alloy melt of different composition. A thermodynamic analysis is required to determine the conditions under which such a continuous growth is possible. Hence, from a scientific standpoint, analysis of a dissimilar metal joint offers a number of challenges [62].

2.7.5 Welding Plastics

The application of lasers has created new opportunities in the welding of thermoplastic components, which until now has primarily been performed using ultrasonic or vibration welding. Several different approaches are being developed for laser welding of plastics [63]. The main principle now used to laser-weld plastics is known as "transmission welding". Transmission welding has demonstrated that precise, controllable heating and melting of low melting point thermoplastics can be produced at the interface between a transmissive and absorptive plastic [64, 65]. For this area of application, Nd:YAG and diode lasers, offering radiation near a wavelength of 1μm, are suitable for use because of the absorption characteristics of plastic materials. These absorption characteristics in the materials to be welded are very important when using laser. Only certain materials and combinations of materials are suitable for transmission laser welding. One of the plastics needs to be optically transparent to the laser with the other being absorbing. There are various methods of making the lower plastic absorb the laser energy [66]. The absorption and thereby the penetration depth of the radiation is a function of the laser beam and material composition. Plastic materials absorb the CO_2

radiation in the surface layer and cause the vaporization of the material. The Nd:YAG and diode radiation penetrates into the polymer sample and produces a melting volume which is necessary for the welding process. The absorption properties can be influenced by the content of pigment in the plastic material. So black parts can be welded together, because being black to the eye differs from being black or absorptive for the laser [63, 67]. Pigments have also been developed making it possible to laser weld entirely transparent through to totally opaque assemblies, as shown in figure 2.15 [66].

Virtually all thermoplastic materials can be laser welded. The joining of two different materials is possible if the material combination is weldable, i.e. the temperature ranges in which the materials are liquid must overlap. Fluorinated and temperature resistant materials can be welded with lasers, as well as PMMA and ABS, or plastic to metal. In a combination of increasing interest to the automotive industry, TPEs can easily be joined with thermoplastics using laser radiation [49].

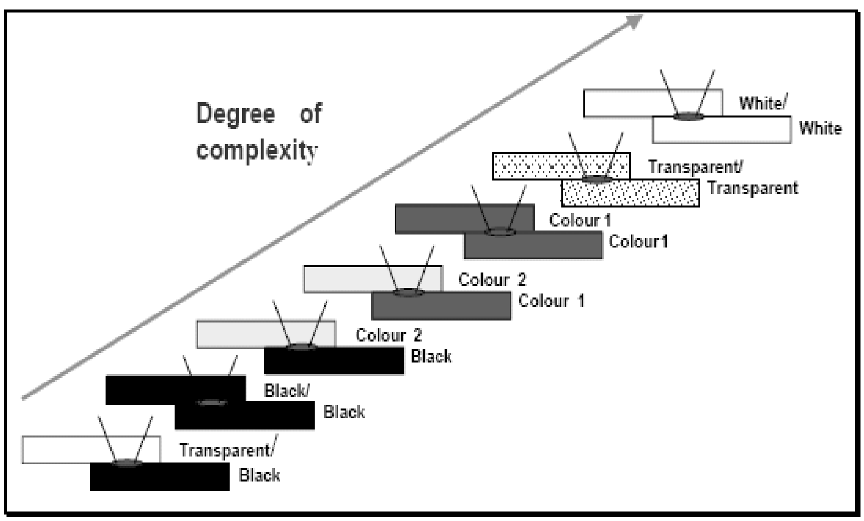


Figure 2.15: Polymer colour combinations for transmission laser welding as a function of degree of difficulty. Black base with transparent upper plastic is deemed to be the most desirable option. Laser joining increases in complexity with different polymer colour combinations [66].

Using the laser also permits excellent quality control of the weld seam during production. Modern electronics and sensor technology provide the means for on-line monitoring and process control of the melt zone temperature during the welding process. The exact temperature needed for the material can be maintained by controlling the laser power with the temperature signal obtained from the measurement. The temperature control unit can be integrated into the optical head and guarantees reproducible and constant quality in the weld seam, independent of material inhomogeneity resulting from previous processing steps [49, 68, 69].

2.8 Dual Beam Laser Welding

In recent years, laser beam welding using two laser beams, or dual beam laser welding, has become an emerging welding technique. A laser beam was split into two equal-power beams and the dual beams were located in tandem (one beam follows another) during welding. Experimental results indicated the dual-beam laser could significantly improve weld quality. For steel, surface quality was improved with fewer surface defects such as undercut, surface roughness, spatter, and under fill. Weld hardness and centerline cracking susceptibility were also reduced. In aluminum, quality improvements were in the form of smooth weld surfaces and fewer weld defects such as porosity, surface holes, and undercut.

Essentially, the dual-beam laser systems could be built by either combining two lasers with an angle between two beams or splitting a laser beam into two parallel beams with an optical splitter. The combined dual-beam laser systems were more flexible in changing inter beam spacing and the power ratio of dual laser beams. However, the split dual laser beams were almost parallel and had the same planes of polarization (coherent) as many lasers produced polarized beams. Based on the arrangements of the two laser beams, the dual-beam process can basically be divided into two types, angled and parallel. Most of the reported dual beam systems were angled and a small inter beam spacing could easily be achieved in these systems. In

the parallel dual beam systems, spacing was usually large and they were often used for reducing cooling rates.

However, the dual-beam laser welds were always smooth and no defects were found for the welds made with the same welding parameters. This implies dual-beam laser welding is a stable process and good welds were achieved over the range of process parameters investigated. Aluminum alloys are well known to be difficult to laser weld because of their high reflectivity, high thermal conductivity, and volatilization of low boiling point constituents. Weld defects such as surface holes, undercut, porosity, and irregular beads are often observed. A complete penetration weld was made using the dual beam CO_2 laser and the weld surface was quite smooth; the single-beam laser weld was irregular with some spatter as shown in figure 2.16, [70].

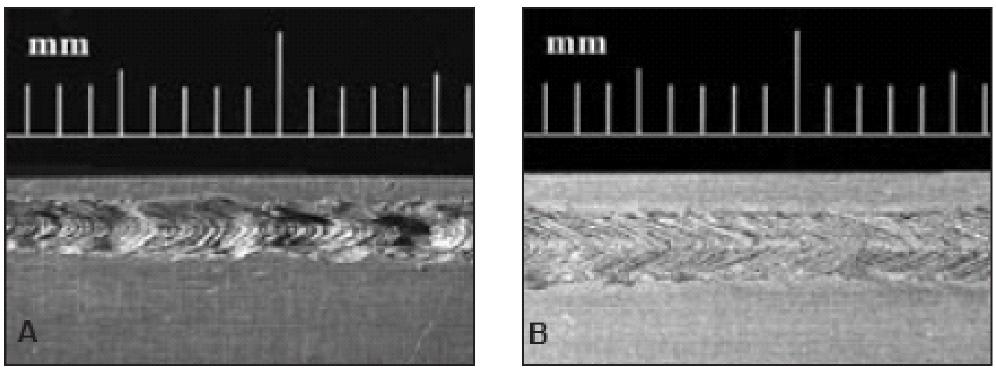


Figure 2.16 : Complete-penetration butt-joint welds of aluminum (5083 aluminum alloy, 3mm, CO_2 laser, 3.81m/min). A- Single-beam laser weld (laser power: 3kW); B- smooth, dual-beam laser weld (laser power: 4.5kW) [70].

Chapter Three

ELECTRON BEAM WELDING

3.1 Introduction

Electron beams offer a unique heat source that may be used for a wide variety of materials processing applications. There are several important physical features that make electron beam based materials processing so attractive, and the ones that will be considered here are: depth energy deposition, very high power levels, and shock generation capabilities [15].

In electron beam welding (EBW) heat is generated by high-velocity narrow-beam electrons. The kinetic energy of electrons is converted into heat as they strike the workpiece [33]. The metal is joined by melting the edges of the workpiece or by penetrating into the material. Usually no filler metal is added [71].This process requires special equipment to focus the beam on the workpiece in a vacuum; the higher the vacuum, the more the beam penetrates and the greater the depth-to-width ratio [33]. Electron beam welding is the first and foremost, with already a long history of successful applications in a large range of different fields, like aerospace, nuclear and electronic components but also for general use for most exacting requirements [16, 71].

In electron beam welding, the power density of the beam of electrons, concentrated and focused, can reach the value of 10^8W/cm^2, which is more than that of any other continuous beam form of energy [16]. Electron beam welding equipment generates x-rays; low voltage machines produce soft x-rays while high voltage machines produce hard and potentially lethal x-ray [15, 71].

Through the development of the electron beam, the use of the electron beam in welding industry is increased. The parameters of the beam and the properties of the workpiece affect strongly to the welding applications [10]. The advantages which electron beam welding offers the designer include [33, 72, 73]:

- Narrow welds can be made on thicker sections with deep penetration and minimal thermal disturbance.
- Because welding is performed in a vacuum there is no atmospheric contamination.
- Accurate control of the welding parameters is possible by controlling the electron beam power and by accurate beam focus.
- Excellent welds can be made even on more reactive metals.
- Lack of thermal disturbance in the process means that there is minimum shrinkage or distortion.
- Almost any metal can be welded by EBW, and workpiece thickness can range from foil to plate.
- The heat-affected zone is much smaller than that of any arc welding process.

While the limitation of electron beam welding are [72, 74]:

- High capital cost. The price of the equipment is very high and it is expensive to operate due to the need for vacuum pumps. In addition, fit up must be precise and locating the parts with respect to the beam must be perfect.
- Extremely high depth/width ratio of these welds can lead to centerline cracking.
- Work chamber size constraints.
- X-rays produced during welding.
- Rapid solidification rates can cause cracking in some materials.
- Time delay when welding in vacuum, waiting for vacuum to build up.

3.2 Electron Beam Welding Mechanisms

Electron beam welding is, like laser welding, a power beam process ideally suited to the welding of close square joints in a single pass. Unlike the laser beam, however, the electron beam process utilizes a vacuum chamber in which is generated a high-energy density beam of electrons of the order of 0.25–2.5mm in diameter [75]. As shown in Figure 3.1a, the cathode of the electron beam gun is a negatively charged filament. When heated up to its thermionic emission temperature, this filament emits electrons. These electrons are accelerated by the electric field between a negatively charged bias electrode (located slightly below the cathode) and the anode. They pass through the hole in the anode and are focused by an electromagnetic coil to a point at the workpiece surface. The beam currents and the accelerating voltages employed for typical EBW vary over the ranges of 50–1000mA and 30–175kV, respectively. An electron beam of very high intensity can vaporize the metal and form a vapor hole during welding, that is, a keyhole, as depicted in Figure 3.1b, [76].

The filament can be heated either by means of an electric current passing through or indirectly by means of an adjacent heater. The higher the electric current the higher the temperature and the greater the electron emission. The electrons require a high potential electric field to accelerate them towards the target and a magnetic field to focus them. Special electron beam guns have been developed that create, accelerate and focus the electron beam [73].

Since electrons can be stopped by all matter, including air, the welding process is almost always conducted in a vacuum chamber. Otherwise, most of the electrons would never reach the parts to be welded. In many industrial electron beam welding devices, the vacuum chamber walls are steel and have a thickness of approximately 2cm [77]. The workpiece is placed inside the chamber and the beam is focused on it by the coil. If the electron beam is focused onto a metal surface the beam can raise the temperature to melting point. The higher the electric potential the greater the electron velocity and the higher the beam energy. The more focused the beam is on the workpiece surface, the higher the resultant energy density [73].

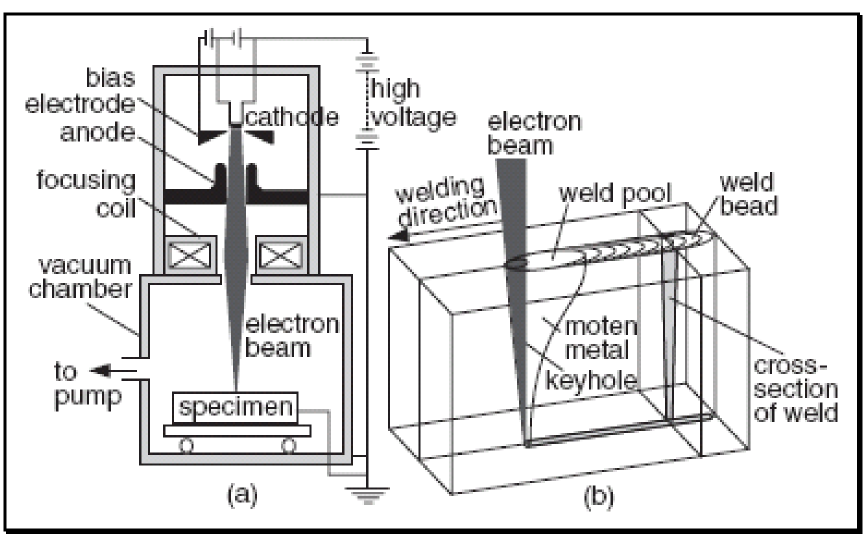


Figure 3.1: Electron beam welding: (a) process; (b) keyhole [76].

Two welding modes are used in the EBW, Conduction and keyhole. Conductance mode: mainly applicable to thin materials, heating of the weld joint to melting temperature is quickly generated at or below the materials surface followed by thermal conductance throughout the joint for complete or partial penetration. The resulting weld is very narrow for two reasons:

a- It is produced by a focused beam spot with energy densities concentrated into a 0.01 to 0.03 cm^2 area [78].

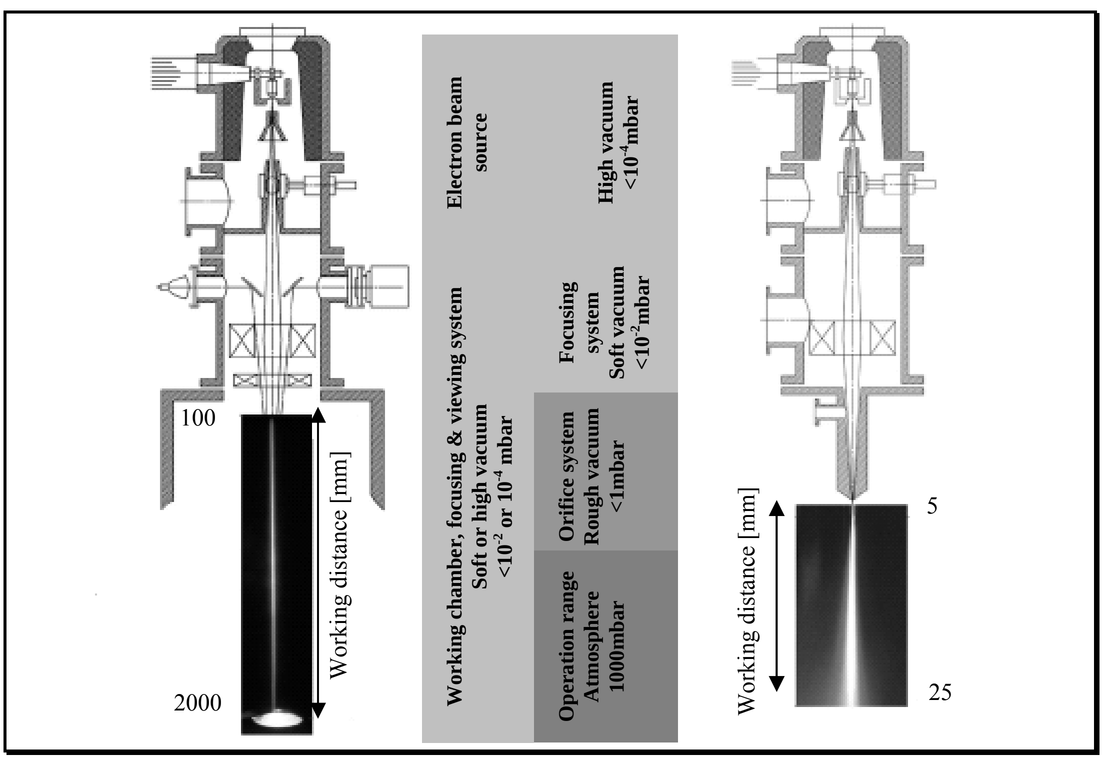
b- The high energy density allows for quick travel speeds allowing the weld to occur so fast that the adjacent base metal does not absorb the excess heat therefore giving the electron beam process it is distinct minimal heat affected zone [79].

Keyhole mode: it is employed when deep penetration is a requirement. This is possible since the concentrated energy and velocity of the electrons of the focused beam are capable of subsurface penetration. The subsurface penetration causes the rapid vaporization of the material thus causing a hole to be drilled through the material. In the hole cavity the rapid vaporization and sputtering causes a pressure to develop thereby suspending the liquids material against the cavity walls. As the hole is advanced along the weld joint by motion of the workpiece the molten layer flows around the beam energy to fill the hole and coalesce to produce a fusion weld. The hole and trailing solidifying metal resemble the shape of an old fashion keyhole.

Both the conductance and keyhole welding modes share physical features such as narrow welds and minimal heat affected zone .The basic difference is that a keyhole weld is a full penetration weld and a conductance weld usually carries a molten puddle and penetrates by virtue of conduction of thermal energy [51, 80].

Welding in non-vacuum conditions requires much greater power and a shielding gas may be required around the weld area. Guns of greater power suitable for non-vacuum chambers have been developed. Difficulties may also be encountered in focusing the beam if there is a variation in the distance between the gun and the workpiece surface due to irregular shape of the component [73]. In contrast to the EBW in vacuum the working chamber is replaced by an orifice system. The evacuation time is eliminated, as the orifice system and the generator column are permanently kept under vacuum. The electron beam is guided to the atmosphere from high vacuum over fine vacuum and rough vacuum. Where as with the vacuum EBW long working distances can be realized by changing lens current, the distance for the non vacuum is fixed. Differences in the working distance are equalized by moving the electron beam generator. Figure 3.2 explains the differences between vacuum and non vacuum electron beam welding system [81, 82].

During the welding process, the beam striking the metal surface generates x-rays [73]. The higher the atomic number of the material struck by the electron beam, the greater the probability of producing x rays. Thus, an electron beam striking metal has a reasonably high probability of producing x rays. The maximum energy of the x rays produced will be determined by the maximum voltage used to accelerate the electrons, which in turn is dependent on the size of the weld, the metals involved, and the depth of penetration. The energy of the x rays is important because it will determine the ability of the x rays to penetrate the vacuum chamber walls [77].



a **b**

Figure 3.2 : Vacuum and non vacuum EBW respectively a, b [81].

3.3 Electron Beam Material Interaction

Material processing with an electron beam involves various thermal processes. The main effects associated with thermal processes are the following [3] :

a) Phase transformation in solids, for example during hardening.
b) Melting in welding, polishing, alloying, cladding, and marking of metals and non metals.
c) Vaporization in drilling, cutting, marking, engraving, scribing, fracturing, trimming of metals and non metals.
d) Sublimation which is vaporization from the solid to the vapor state.

Electron beams that pass through a dense medium lose energy through collisions with electron and nuclei. A fraction of the energy heats electrons in the medium while the remainder is converted to x-ray or γ-ray radiation. Collisions also deflect the light electrons [83, 84].

When electrons hit a metal, a small number will be reflected. More than 90% of them penetrates the metal (between 90^0 and about 30^0 independent of the angle of incidence) and will be decelerated within a distance of approximately 60μm. There the kinetic energy of the electrons is transformed into thermal energy. Because of the power density in the spot, the material melts within microseconds, vaporized to an extent, but to the largest degree is hurled away in the form of small molten droplets. After formation of the first "impact crater" the process is repeated and a capillary which is surrounded by some molten material, develops [2, 79].

In welding processes, metal vaporization begins in less than 100 microseconds, and the rapidly escaping gases produce a reaction pressure which pushes the molten metal aside, drilling a cavity in the base plate. The depth of the hole can be 50 times its width, but for practical welding conditions the depth rarely exceeds ten times the weld width. This deep narrow weld produces less thermal damage to the surrounding metal and reduces distortion as compared with other fusion welding processes. The rapid melting and high travel speeds at these high heat intensities reduce heat loss to the surroundings, with resultant melting efficiencies of 90 percent or more [15].

The process may be used for the welding of material as thin as foil and up to 400mm thick in a single pass. The keyhole penetration mode gives almost uniform shrinkage about the neutral axis of the component, leading to low levels of distortion. This enables finish machined components to be welded and maintained within tolerance. The transverse shrinkage also results in the solidifying weld metal being extruded from the joint to give some excess metal outside the joint as in figure 3.3 , [75] .

Because the maximum energy absorption is beneath the surface, welding of thin foils (less than 0.05mm) is difficult. In such cases lasers are the better tool. The workpiece or at least the welding area is usually placed in a vacuum. Contrary to laser welding, there is no influence of gas particles [2]. Along with thermal losses, the total energy balance involved in electron beam material interactions must take into consideration the losses due to the emission of inelastically and elastically scattered secondary electrons and also losses due to light radiation and x-radiation [3].

Elastic scattering is one of the specific forms of scattering. In this process, the energy of the incident electron is conserved and its propagating direction is changed by the potential of the target [85]. Elastic scattering gives up little energy to the target, but is likely to significantly modify a primary electron's trajectory (an electron which bombards a solid surface, causing secondary emission). The energy of the primary electron, typically thousands of volts, is associated with its velocity (i.e., kinetic energy). During an elastic scattering event the electron's energy loss is likely to be measured in volts. The probability for large deviations in trajectory is directly related to the atomic number of the target, and inversely to the electron's energy [86].

Inelastic scattering is a fundamental scattering process in which the energy of an incident particle is not conserved. In this scattering process, the energy of the incident electron is lost or gained. When an electron is the incident particle, the probability of inelastic scattering, depending on the energy of the incident electron, is usually smaller than that of elastic scattering [85]. Inelastic scattering event exchanges significant amounts of energy with the target. Depending on the amount of energy exchanged, there is a spectrum of energy released during these events. The energy released in such an event is a function of the quantum state of each atom involved, and hence is target dependent.

Inelastic scattering constantly reduces the energy of a primary electron, finally to the point at which it is "captured".

At this point it is instructive to examine the energy loss quantitatively, as a function of distance traveled, and also as a function of target composition. There are an infinite number of target compositions, however they all can be grouped and studied as a function of average atomic number (Z), atomic weight and density (γ) [86].

At the melting point (T_m) and at temperatures above T_m of metals, thermionic emission becomes appreciable. The analysis reveals that the power losses due to the emission of true secondary electrons and thermionic electrons and also due to light emission and x-radiation are negligible in comparison with the beam power. Elastically and inelastically scattered electrons account for the main fraction of losses, for example, up to 50% in tungsten.

There are a few methods for estimating the reflectivity R. The assumption is that R only depends on the beam energy: $E/R=Z^{1/3}E^{1/2}$, where Z is the atomic number of an element. The effective efficiency is $\eta_e=1-nR$, where $n=0.45$ to 0.5 is the proportionality factor defining the energy distribution of backscattered electrons. From the measurements of R it follows that the reflectivity linearly decreases with increasing electron beam power.

R also can be found from expression $R=m/cZ^{1/3}$ with an accuracy sufficient for engineering calculations. In this expression, m is the atomic mass, and c is the constant equal to 106×10^{-23}g and 15.5×10^{-23}g for light elements (Z=6 or 7) and heavy elements (Z=74 to 92) respectively [3].

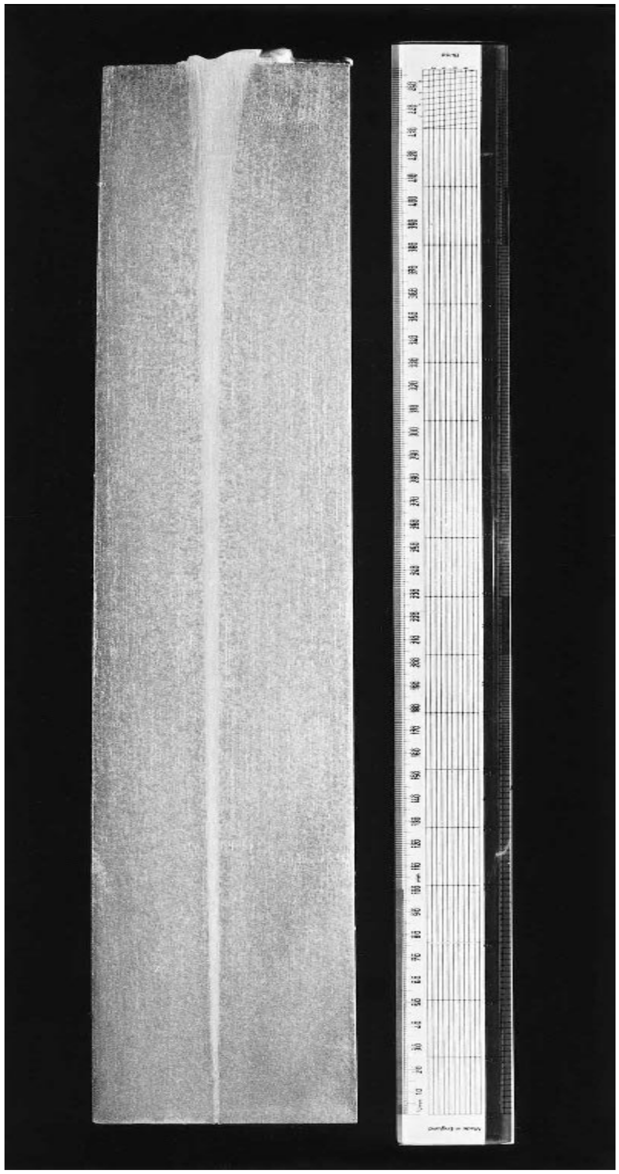


Figure 3.3 : Single pass electron beam weld in 450mm thick A5083 alloy [75].

3.3.1 X-Ray Production

Basically, an electron beam facility may be thought of as a giant x-ray tube with the electron gun acting as the filament and the work piece as the target. Instead of producing x-rays for useful purposes as with the x-ray tube, however, the primary goal of the electron beam facility is the use of the electron beam itself; x-rays become a by-product.

X-ray spectra may be divided into two categories, the characteristic spectrum and the continuous or bremsstrahlung spectrum. The first occurs when a high speed electron strikes a target, losing a large amount of energy by knocking an electron from the inner shell of an atom. An x-ray photon is emitted when the missing electron is replaced by an electron from an outer shell. There is no preferred direction for this x-ray emission and the energy level is dependent on the target element; hence the name "characteristic x-rays".

The second category, continuous or bremsstrahlung x-rays, is usually the more important. Here x-ray production is dependent on deceleration of the high speed electrons in the electric field of the nucleus.

Other factors influencing the intensity of x-radiation produced are the material of the target and the target current. A general rule of thumb for the effect of target material is as follows: for moderate exciting potentials (above 500kV), the continuous spectrum intensity is directly proportional to the atomic number of the target material. For lower potentials, the intensity variation is more closely proportional to the square of the atomic number of the target. If the voltage and target material remain the same, the x-ray intensity is directly proportional to the target current.

It should be pointed out that the continuous x-rays from a given target are not emitted equally in all directions. Equal distribution does occur for the characteristics component of the x-ray spectrum but bremsstrahlung plays the larger part [87].

3.3.2 Neutron Production

Electron bombardment at potentials as low as 1.67MeV may result in neutron production, depending on the target material involved. In this process the electron beam produces x-rays in the target as described, which in turn yield neutrons through electromagnetic interactions with nuclei. With accelerator bombardment these photodisintegration reactions yield neutrons with energies in a broad continuous spectrum, peaked in the 1 to 2MeV region. With adequate x-ray energy, any nuclide may be made to undergo photodisintegration [87].

3.4 Physical Characteristics of Electron Beam

Electrons have dual characteristics just as light does; they have both a wave nature and a corpuscular nature [87]. An electron has mass and thus exhibits kinetic energy when in motion. The amount of kinetic energy in an electron is directly proportional to its velocity; that is, the higher the velocity, the higher the energy level [88]. The charge of the electron is denoted by *e* (coulombs) and mass by *m* (kilograms). Then *e* is 1.602×10^{-19} coulomb and *m* is 9.11×10^{-31}kg. According to the special theory of relativity the mass is a function of the velocity, but this discussion is limited to the nonrelativistic range in which the velocity is only a very small fraction of the velocity of light and the mass is essentially equal to the rest mass [87].

Time-varying fields are also excluded from the discussion. For most industrial uses of electron beams the applied fields are static or varying slowly enough so that they are practically constant during the time any electron is in flight (transit time).

The electric force on a charge e in a field $\boldsymbol{E_f}$ is given by

$$\boldsymbol{f_e} \text{ (newtons)} = e \text{ (coulombs) } \boldsymbol{E_f} \text{ (volts/meter)} \qquad (3.1)$$

which is the defining equation for the electric field. Both $\boldsymbol{f_e}$ and $\boldsymbol{E_f}$ are vectors, and the equation shows that the two differ only by the scalar factor *e*. For electrons, with their negative value of *e*, the force is antiparallel to the electric field.

The magnetic, or Lorentz, force is related to the force on a current element exerted by a magnetic field, which relation defines the magnetic field. The magnetic force on a charge *e* moving with velocity $\boldsymbol{v}$ in a magnetic field (flux density) $\boldsymbol{B}$ if given by the vector relation

$$\boldsymbol{f_m} \text{ (newtons)} = e[\boldsymbol{v} \text{ (meter/s)} \times \boldsymbol{B} \text{ (webers/square meter)}] \qquad (3.2)$$

The vector or cross product in this equation means that the direction of the force is perpendicular to the plane containing the $\boldsymbol{v}$ and $\boldsymbol{B}$ vector, with its sense in the direction a right-hand screw would move if rotated through the smaller angle from $\boldsymbol{v}$ to $\boldsymbol{B}$. the magnitude of the vector product is given by $|\boldsymbol{v}\times\boldsymbol{B}|=|\boldsymbol{v}|\ |\boldsymbol{B}|\ \sin\theta$, where θ is the angle between $\boldsymbol{v}$ and $\boldsymbol{B}$. The vector product is the product of mutually perpendicular components of the two vectors.

Newton's second law of motion in vector form is

$$\boldsymbol{f} = m\,(d^2\mathbf{r}/dt^2) \tag{3.3}$$

where $\boldsymbol{r}$ is a position vector locating the particle with respect to any origin.

Combining Eq. (3.3) with Eqs. (3.1) and (3.2) we obtain the general equation of motion for article in electric and magnetic fields [87].

$$d^2\mathbf{r}/dt^2 = (e/m)\,(\boldsymbol{E_f}\times\boldsymbol{v}\times\boldsymbol{B}) \tag{3.4}$$

A well adjusted electron beam has a rotational symmetric shape. Metallic vapor and droplets, which enter the region of the beam source, can lead to high voltage flash overs. Therefore the beam is often bent by some degrees, to avoid a path for these particles. The bending causes astigmatic distortions of the beam, which need to be compensated by special correcting coils. Beam splitting is not possible. In rare applications, two adjacent parallel joints are welded quasi simultaneously by chopping the beam [2].

There are two modes of operation for accelerators that require different approaches to thermal analyses [83]:

1. Pulsed accelerators with low duty cycle generate intense electron beams with high current density.
2. Continuous or high repetition-rate accelerators create beams with moderate peak current but high average power.

3.5 Factors Affecting Electron Beam Welding Processes

Three parameters were used to characterize the electron beam welding process: the power density incident on the workpiece, the energy density absorbed by the workpiece and the energy absorbed per unit length of the weld [89]. The electron beam parameters essential for material processing are the beam current I (A), accelerating voltage V (V), focusing system current I_f (A), working path length l (m) from the focusing system to the target surface, linear transport speed υ (m/s). The beam diameter d and hence the power density Q which is one of the governing parameters on material processing can be determined:

$$Q = I\,V/(\pi d^2/4) \tag{3.5}$$

The quantity $Q=IV/v$ is not a decisive parameter because in electron beam welding, for example, any shape of the interaction region can be obtained at the same value of energy input per meter of weld seam depending on the power density.

In pulsed operation, the average pulse power is $P=IVF\tau_p$, where F the pulse repletion rate (Hz); and τ_p the pulse length (s). The rate of processing in pulsed operation is $v=d(1-\acute{K})/(\tau_p+\tau_w)$, where d is the diameter of the interaction region (point or spot), $\acute{K}$ the point overlap ratio which is commonly equal to 0.5-0.9, and τ_w the pulse space width (s).

The pitch of points (center-to-center distance) is $S=v(\tau_p+\tau_w)$. The pulse duration-to-pulse period ratio is known as the duty cycle $G= \tau_p/(\tau_p+\tau_w)$ [3].

The beam diameter is the most essential parameter and is most difficult to determine [3]. The minimal spot size depends primarily on the beam current, which ranging between 0.05 mm and 1 mm [2].

Given the density of the emission current from the cathode, cathode temperature, and spherical aberration of the lens system. The minimum diameter of the focused spot of the electron beam of its maximum current can be estimated [2]:

$$d = s(I/V)^{3/8} \quad (3.6)$$

Here $s = [(4^{2/3}k/(\pi e))C^{2/3}f_0T/j]^{3/8}$, s (K) is a constant of the electron optical system; k Boltzmann's constant (J/K); e=1.602×10^{-19} (C) the electron charge; C a dimensionless constant for spherical aberration of the lens or lens system; f_0 the focal length (cm); T the cathode temperature (K); j the cathode emission current density (A/cm^2).

Considering expression (3.6), the power density is given by

$$Q = 1/\pi\ (2/s)^2\ I^{1/4}\ V^{7/4} \quad (3.7)$$

The radial power distribution in the spot can be described as Gaussian [2]. The distribution curves reveal that as distance from the target surface to the focusing system decreases, the diameter of the electron beam decreases too, and the distribution becomes "sharper". For each specific distance from the target surface to the focusing system, the "sharpest" distribution occurs at low current values. With an increase in current, the beam diameter grows and the current density may drops off. The pattern of current density curves is approximately similar to that of curves for normal (Gaussian) distribution [3].

3.5.1 Effect of Beam Voltage on the penetration Depth

The weld penetration increases with accelerating voltage. This is due to a reduced electron scattering by vapor atoms. An increased voltage thus leads to a higher kinetic energy of electron and increases the free path of electrons in metal vapors.

The surface tension linearly decreases with increasing temperature and drops to zero at a critical temperature ($T_c=1.7T_v$), where T_v is the vaporization temperature at atmospheric pressure [3].

3.5.2 Optimal Location of the EB Focus Below the Target Surface

As is known from experiments, other conditions being the same, an electron beam focused at a point slightly below the target surface can melt or vaporize the material to a greater depth. An electron beam focused below the surface can increase the depth of the hole pierced through the material by 30%. The relation between the position of the focal point and EB parameters can be found from simple geometric considerations. If the focus is at the target surface, the beam that penetrates more deeply into the hole diverges more strongly, its power density at the cavity bottom drops off and the process of hole piercing slows down. Experiments show that the beam focused below the surface provides a deeper penetration at the same rate of welding or hole piercing [3].

3.5.3 Effect of Vacuum Pumping System

The predominate part of an electron beam system is that which provides the high vacuum environment, without which the beam cannot be generated. The vacuum portion exerts more influence on the over-all character of the equipment suppliers are primarily vacuum equipment manufacturers than welding equipment or furnace equipment manufacturers. The vacuum system and the vacuum process chamber represent two-thirds of the total equipment cost. As the development of evaporating techniques progresses, the trend appears to be toward ultra-high vacuums, with an additional over-all equipment cost increase of 50%. Three types of ultra-high vacuum pumping units in use are: oil diffusion systems, ion pumping systems; and cryogenic pumping systems.

Welding and melting equipment is often built without baffles or traps since the losses in pumping efficiency they introduce are more serious than the contamination they permit [87].

The three primary methods of EBW are each applied in different welding environments. The method first developed requires that the welding chamber be at a hard vacuum. As a result, the chamber must be small to prevent it from being crushed under atmospheric pressure. Material as thick as 15 cm can be welded, and the distance between the welding gun and workpiece (the stand-off distance) can be as great as 0.7 m. While the most efficient of the three modes, disadvantages include the amount of time required to properly evacuate the chamber and the cost of the entire machine. As electron beam gun technology advanced, it became possible to perform EBW in a soft vacuum, under pressure of 0.1 torrs. This allows for larger welding chambers and reduces the time and equipment required to attain evacuate the chamber, but reduces the maximum stand-off distance by half and decreases the maximum material thickness to 5 cm. The third EBW mode is called nonvacuum or out-of-vacuum EBW, since it is performed at atmospheric pressure. The stand-off distance must be diminished to 4 cm, and the maximum material thickness is about 5 cm. However, it allows for workpieces of any size to be welded, since the size of the welding chamber is no longer a factor [38].

High-vacuum electron beam welding (EBW-HV) has a significant limitation that restricts its usefulness in high production applications: welding must be accomplished in an evacuated chamber, which is pumped down typically to the 10^{-4}torr range. The chamber restricts the size and the number of the workpieces that can be welded, and the vacuum pumping cycle consumes time and energy. Some EBW machines operate and weld at a partial-vacuum chamber pressure range of 3×10^{-3} to 3×10^{-1}torr and are referred to as EBW-MV. This process increases part throughput due to the decreased vacuum evacuation time required prior to welding, but still consumes time and energy. Although the welds are performed in a partial vacuum, they are not as high in quality as with EBW-HV. Weld geometry and penetration at a given power are also affected. The penetration is typically 5–10% less than EBW-HV and the welds are wider and more tapered. A traditional non vacuum electron beam welding machine (EBW-NV) welds at atmospheric pressure and is used for high-production welding. Because there is no vacuum chamber, there is no pump down time required, resulting in higher throughput than that of EBW-HV or EBW-MV with even lower production costs per piece part. Helium is used to reduce beam scattering, increase the beam “stand-off distance,” and to minimize weld contamination. The weld depth-to-width ratio with this process is further decreased along with the distance where the beam exits. The purity of welds produced by this method is generally not as clean as with the other two EBW processes. The EBW- NV process still provides good-to-excellent welds, but not without decreased weld penetration and increased weld width [90].

3.6 Electron Beam Power Capability and Efficiency

Beam power, power stability and efficiency depend primarily on the capacity of the voltage power supply. Production systems up to 100 kW are on the market. Research goes up to 300 kW. However, more than 80% of the present industrial applications can be work with machines between 2 and 25kW beam power. With 25kW one can weld 4cm steel with a weld rate of about 2cm/s. With a 100kW machine a maximum weld thickness of 25cm can be reached. At first approximation double beam power increases the welding depth at the same factor [3].

The power required to operate the cathode, which is the most important element in the guns and the source of electrons, results from three losses: radiation, conduction, and electron cooling. The last loss results from the fact that an electron leaving the cathode must carry away an energy as a result of crossing the work function barrier; in all but the most extreme cases, this effect is negligible. The dominating factor is usually radiation if some care is taken to reduce conduction losses [87].

The power efficiency of electron beam guns is typically 75%. It depends on the vacuum system and percentage is additionally lost by the energy consumption of the pumping system. The power stability depends on the quality of the feedback control loop. The values are between 1% (for welding machines) and 0.1% (for drilling machines) [3].

3.7 Basic Regimes of the Heating of Metal Targets by Electron Beam

3.7.1 Estimation of a source in a two-dimensional heat transfer problem

The finite difference method based on an implicit scheme is used to solve the direct and inverse problems. The equation is the heat conduction equation (3.8). The studied domain is one half of the transversal plane taken perpendicularly to the welding axis (figure 3.4).

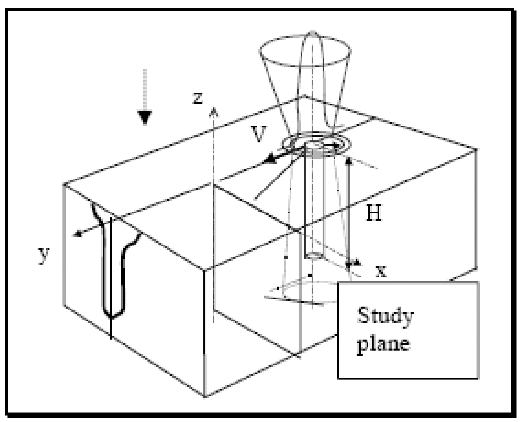


Figure 3.4: Definition of the study plane [91].

$$\gamma c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(K\frac{\partial T}{\partial x}) + \frac{\partial}{\partial z}(K\frac{\partial T}{\partial z}) + A(x,z,t) \qquad (3.8)$$

The boundary and initial conditions are the following: at the lower, upper and lateral surfaces, only the radiative conditions are fixed because the welding process is carried out in a vacuum [91].

A Gaussian source which corresponds to several studies will be presented here [91]:

$$S(x,z,t) = \frac{8\eta V I_b}{\pi d^2}\exp(-\frac{8(x^2+(\upsilon t - y_s)^2}{d^2}) f(z,h) \qquad (3.9)$$

with $f(z,h) = \frac{2}{h}(1-\frac{z}{h})$

where the parameters are : η is the efficiency coefficient, V (kV) is the voltage, current I_b (A), velocity v (mm/s), penetration h (cm), beam diameter d (mm) and y_s spatial coordinates (m).

The Gaussian source is divided in two parts. The first one Sv (most energetic part) (figure 3.5 and figure 3.6) is applied in the domain where it goes inside the material (creation of the keyhole). The second one Ss (a ring shape – figure 3.5) is only a surface heat source corresponding to the "non active" part of the beam [91].

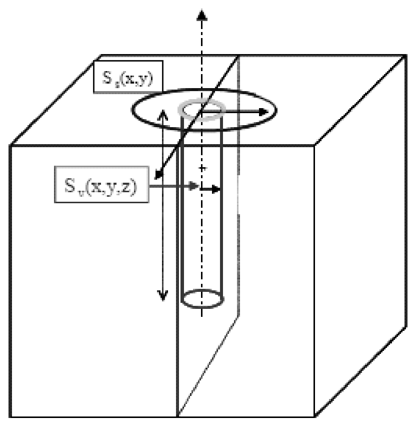


Figure 3.5: Source definition [91].

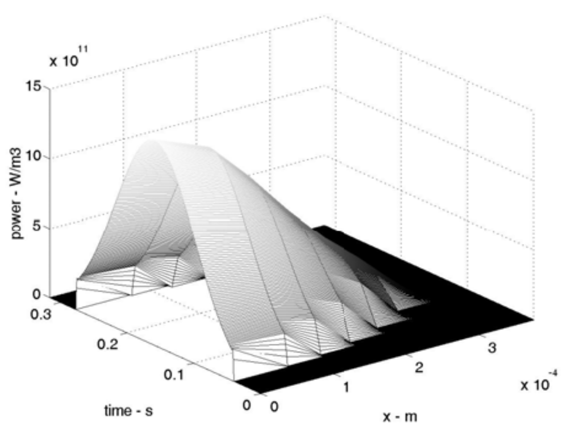


Figure 3.6: Exact Gaussian source at z=0 [91].

3.7.2 Three-Dimensional Models. Stationary Heat Sources

The problems of heating had been considered in terms of the spatial model when $r_f \approx \sqrt{at}$, i.e. the depth of penetration of heat into a body is comparable to the hot spot radius r_f.

A heat source has been assumed of constant power P_0 distributed by the Gauss low acts on the surface of a semi-infinite body starting at the moment t>0. Applying the method of sources, the expression for temperature will be obtained.

$$T(r,z,t) = \frac{2P_0}{c_p\gamma(4\pi a)^{3/2}} \times \int_0^t \frac{d\xi \exp\{-(4a)^{-1}[z^2/\xi + r^2/(t_0+\xi)]\}}{\sqrt{\xi}(t_0+\xi)} \qquad (3.10)$$

where $t_0=(4ak_0)^{-1}$ is a time constant, where k_0 is a concentration coefficient and ξ the integration variable.

Similar relations for the calculation of the temperature field can also be written for the uniform distribution of the heat power density over the hot spot [3, 48].

3.7.3 Moving Heat Sources

If an electron beam produced hot spot of radius r_f travels along the surface at a constant velocity υ, the material absorbs the heat and begins to melt down. After a certain dwell time which depends on the material properties, the heat affected zone (HAZ) reaches a quasistationary state, and the fusion front of constant size propagates in the direction of the moving heat source.

The most popular dynamic model for the calculation of the weld zone temperature is a Gaussian heat source of effective power P_0, which moves at a constant speed υ in the direction of the ox axis along the surface of a plate of thickness δ or of a semi-infinite remain constant during the entire process of heating [92].

The equation for calculating the temperature at point A(x,y) in the moving coordinate system, which defines the position of this point, takes the form

$$T(x,y,t) = \{P_0[\exp(-\upsilon x/2a + bt_0)]/2\pi Kh\}$$
$$\times K_0(\rho_2)[\psi_2(\rho_2,\tau+\tau_0)+\psi_2(\rho_2,\tau_0)] \quad (3.11)$$

Here t is the time counted off from the moment when the center of the Gaussian heat source leaves the given point A(x,y) lying in the plate cross section normal to the ox axis; b=2α/cγh ; t_0=1/4ak; K_0 is the modified Bessel function of an imaginary argument of second kind of order zero; $\rho_2 = r\sqrt{\upsilon^2/4a^2 + b/a}$ is the dimensionless criterion for distance r from the origin of moving coordinates of the point A(x,y); $\psi_2(\rho_2,\tau+\tau_0)$ and $\psi_2(\rho_2,\tau_0)$ are the heat saturation coefficient for a plane heat source propagating along the surface; $\tau=(b+\upsilon^2/4a)t$ is the dimensionless criterion for time constant t; and $\tau_0=(b+\upsilon/4a)t_0$ is the same criterion for t_0 [3].

3.8 Electron Beam Welding Applications

During the stage of early development, EBW was anticipated to have a high degree of versatility due to the uniqueness of the electron beam as a heat source. As the EBW process moved out of the category of a laboratory curiosity in the early 1960's, manufacturers identified critical weldments as the most useful application of the new process. The nuclear power industry was the first reported user of the then unique EBW process. Development of a different type of electron gun as well as the use of EBW at pressures other than that of a hard vacuum influenced the acceleration of EBW applications.

Since the introduction of EBW, the nuclear power industry has continued to utilize the advantages of the welding process. High quality weldments in the less commonly fabricated metals have been a hallmark of the use in this field. Stainless steel components are widely used as well as unusual dissimilar metal couples. Reactive metals and high density metals are also fabricated by EBW. The ability to offset the beam and tailor the heat input to the requirements of the particular metal combination has been one of the clearly distinguishable aspects of EBW. Along with this, the high energy density has permitted the fusion zone to remain small and distortion as well as residual stresses have been minimized. Limited fabrication of heavy structural components have been accomplished by EBW. Other conventional welding processes have generally been used in these applications [1].

Increased emphasis on computer controlled EBW systems, both in the area of beam characteristics and workpiece manipulation, has permitted the trend of EBW expansion. Many major companies have integrated EBW systems in production lines. Additionally, welding operations are performed on other products manufactured by the parent company or it's subsidiaries to promote efficient utilization of the EBW asset. The contract welding companies, or job shops, continue to flourish, receiving a variety of EBW tasks ranging from those that are highly precise to those that do not require the optimum control of welding parameters afforded by EBW [1].

Industries today using EBW in many fields as in table 3.1 [93]:

Table 3.1 : Electron Beam welding applications [Adapted from ref. 93].

Aerospace	• Jet engines and accessories • Missile cases • Space suit backpack components • Rocket motors and controllers • Actuators, hydraulic cylinders, gear trains and controls • Linkages • Various components of electronic modules
Nuclear	• Fuel cells • Assorted cases
Automotive	• Transmission planetary gear carriers • Torque converters • Torque lock-up rings • Catalytic converters • Ball joints • Select frame members • Starter ring gears • Cast intake manifolds
Industrial	• Bi-metal saw blades • Hydraulic components and controls • Thermostatic bimetallic strip • Various linkages and gear assemblies • An array of medical components

3.8.1 Electron Beam Welding in Aerospace Industry

The aerospace industry has traditionally been considered one which demands the maximum performance from materials and fabrication processes. Driven by the need to minimize weight and maximize vehicle performance, welding processes must necessarily yield high joint efficiencies. Frequently, the materials employed in spacecraft and engine applications have proven to be difficult to weld for metallurgical reasons or because of their dissimilarity. Welding in a vacuum has solved some of the problems related to reactive metals. In many cases the narrow fusion zone produced by EBW has enabled maximum joint efficiencies to be attained without fully post weld heat treating the weldment. At the same time distortion has been minimized or judiciously controlled during welding and subsequent operations.

The literature on EBW in the aerospace field is replete with applications which include fittings, seals, precision gearing, pressure vessels, bellows, and rotating and structural components. Quite commonly, high quality components have been produced in an efficient manner due to the precise placement of the beam coupled with the high welding speeds possible with EBW. Repair of damaged components has been demonstrated to be possible with EBW. Cobalt alloy turbine blades and titanium alloy fan blades are routinely repaired with an extension of service life and performance equivalent to new parts [1].

3.8.2 Aneroid Capsules

Manufacturers of absolute pressure aneroid capsules, used to measure barometric pressure in such instruments as aircraft altimeters, weather balloons and ejector seat interlocks, needed to find a fabrication technique which could weld two or more diaphragms at the edges and create an entrapped vacuum within the capsule.

With conventional joining methods such as TIG, microplasma, soft soldering and atmosphere brazing, the capsules were welded first and subsequently evacuated, sealed and leak checked. There was often a high reject rate because all four of these processes put a considerable amount of heat into the component. This tended to upset the heat treated properties of the diaphragm materials, which in turn gave poor reproducibility of the capsule's deflection characteristics.

It was not possible to TIG or laser weld capsules made from beryllium copper, for instance, because of their high thermal conductivity and tenacious oxide layer. Soft soldering and brazing had both the disadvantage of poor reproducibility and entrapment of fluxes. Brazing also suffering from high heat input into the component.

Electron beam welding, performed in a vacuum with very high energy density in the weld zone, not only eliminated all these problems for the open capsules (which have a tube

connector to a variable pressure media) but also enabled a trapped vacuum to be produced for absolute aneroid capsule production.
Electron beam welding can be used to join many types of metals and alloys with the exception of those containing elements with a high vapor pressure such as tin, lead, zinc, etc. Most capsules welded have diaphragms which fall into the thickness range of 0.02mm to 1.0mm. Welding speeds are typically between (760–1500)mm/minute, and total cycle times vary between 5 and 60 seconds depending on the individual capsule. With rapid transfer systems production rates up to 1000 parts per hour can be achieved for the less sophisticated thermostat switch capsule [94].

3.8.3 Automotive Applications

Focus on the high production rate aspect of EBW has been the hallmark of the automotive industry. To achieve this, the partial vacuum or non-vacuum EBW systems have been well suited. By eliminating the time needed for chamber pumpdown, parts flow into and out of the welding machine is significantly increased. The use of autogenous welds has resulted in the significant savings of consumables that would otherwise have been used.
Two widely publicized automotive applications of EBW are catalytic converter and the die cast intake manifold. The catalytic converter is constructed from stainless steel and the intake manifold is fabricated by welding two of rimmed steels have been achieved by the automotive manufacturers. Automotive frame components, steering column jackets, suspension and power train components are among the many parts that utilize EBW for the welding of carbon steels and alloy steels [1].

3.8.4 Electron Beam Welding of Metals

All metallic materials can be melted using a focused electron beam and, in consequence, most pure metals and alloys can be successfully welded. Indeed, the only pre-requisite is that the materials to be welded are electrically conductive and an earth return path for the electrons is provided during welding, otherwise electrostatic charging occurs. In its most simple form, EB welding is carried out by translating the beam, with respect to the parts to be joined, and locally melting the material.

- Electron Beam Welding of Steel

Most steels that are weldable by conventional fusion welding processes can be successfully joined using the electron beam process. Also, because of the narrow thermally strained region that results and the hydrogen free welding atmosphere associated with welding in vacuum, many steels which are otherwise considered difficult or impossible to fusion weld can be joined using EB welding without the need for special consumables or preheating. It is important, however, that steels are specified with low levels of impurities such as sulfur and phosphorus to prevent solidification cracking and that materials are sufficiently well de-oxidized, i.e. degassed or aluminum treated, to minimize the risk of gross weld porosity [95].

- Aluminum Alloys

Welding of the majority of wrought aluminum and magnesium alloys available commercially can be achieved satisfactorily using the EB process. Evaporation of volatile constituents during welding, particularly in the 7000 and 5000 series Al alloys, can cause difficulties due to gun flash-overs, loss of alloy content and subsequent degradation of properties. Cleaning prior to welding is especially important and the majority of weld defects that occur are often a consequence of poor cleaning practice. Many of the cast alloys can also be EB welded although the weld quality achievable depends heavily on the quality of the casting and, in particular, the residual gas content [95].

- Joining Difficult-to-Weld Metals and Dissimilar Metals

EBW has been used for welding advanced materials that are difficult to weld or are thought to be unweldable. One application is high-strength aluminum-lithium alloys.

These alloys have higher strength properties compared with the widely alloys and reduce the welded structure weight by 15 percent to 20 percent.

EBW resolved the problem of welding tubular transition pieces of dissimilar materials, namely, stainless steel to aluminum alloys. Conventional methods that do not melt the edges-explosion welding, metallurgical rolling of the bimetal, or diffusion welding-often are used to make such transition pieces. These traditional processes result in joints that have pure aluminum in contact with steel. Such a joint has the strength properties of pure aluminum, but its performance under thermal cycles is limited due to the intermetallic interlayer in the transition zone.

In EBW of structures with thick edges or with varying cross sections, a technology has been successfully implemented that provides micro alloying of weld metal with modifiers such as scandium or zirconium across the entire depth of the pool. A filler in the form of foil, 100 to 200mm thick, is placed into the joint before welding. The foil is produced by super fast solidification in a vacuum and includes modifiers in amounts that are higher than their mutual solubility in aluminum. This increases the joint tightness and, more important, improves the strength properties of joints of any grades of aluminum alloys and hot cracking resistance.

In manufacturing high-strength stainless steel impellers (figure 3.7) for centrifugal compressors, the cover disk is fastened by a slot electron beam weld to the integral blades of the main disk. Then sections that lack penetration are filled with a high-temperature braze alloy and vacuum brazed. The joint strength is equivalent to base metal at fatigue and in long-term strength testing [96].

Figure 3.7 : EBW is suitable for fabricating high-strength stainless steel impellers for a centrifugal compressor [96].

Chapter Four

COMPARISON RESULTS AND DISCUSSION

4.1 Criteria for the Comparative Study

When comparing lasers with electron beam as tools for welding, one has to consider many technological and economical aspects. When viewing the application of each of these high energy beam systems (electron beam or laser), numerous comparisons have to be made to fully understand and then select the energy source which best affords complete economical and application success.

The following is a listing of welding process comparisons which is made to assist in understanding the practical usefulness of each high energy beam system.

4.2 Technological Comparisons

4.2.1 Power Capability and Efficiency

For the electron beam systems the beam power, power stability and efficiency depend primarily on the capacity of the voltage power supply. The power efficiency of electron beam gun is typically 75%. It depends on the vacuum system and percentage is additionally lost by the energy consumption of the pumping system. The power stability depends on the quality of the feedback control loop. The value is 1% for welding machines.

In the case of the laser beam the power efficiency is rather poor compared with electron beam guns. Typical values are 1% for solid state lasers and 10% for gas lasers. Typical values of the power stability are 1% to 3%, which is enough for most applications [1, 2].

Figures 4.1 and 4.2 describe flowcharts of power distribution process for the laser beam and electron beam welding systems.

In case of laser beam (figure 4.1), 75% from the input power consumed by additional components and 25% from the input power used in beam generation. The total efficiency for the laser beam is between (5-15)%, where 6% from the input power really used in the welding process in addition to the losses caused by the absorption, vaporization and thermal radiation.

Otherwise in case of electron beam (figure 4.2), 25% from the input power consumed by additional components and 75% from the input power used in beam generation. The total efficiency of the electron beam exceed 60%, where the amount of input power which really used in the welding process is approximately 60% in addition of the losses caused by x-ray, vaporization and thermal radiation.

So from these two figures its obvious that the electron beam offers relatively higher output and the greatest ease of generation, and was therefore the first high energy density beam to be commercially applied. The electron beam having power capability and total efficiency higher than the laser beam because the losses of the input power in case of electron beam is lower than the laser beam.

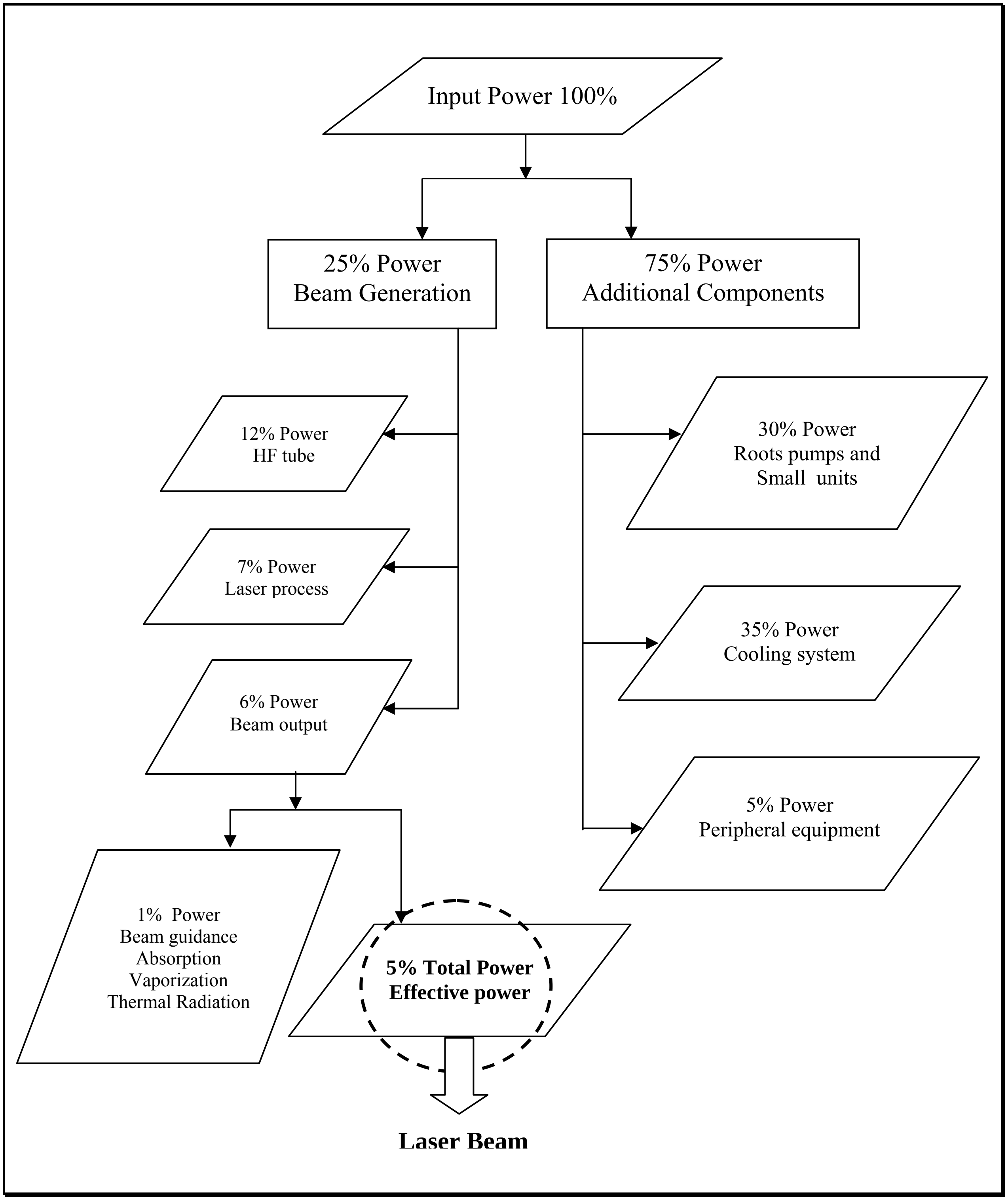


Figure 4.1: A flowchart of laser power distribution in welding process [Adapted from ref. 81].

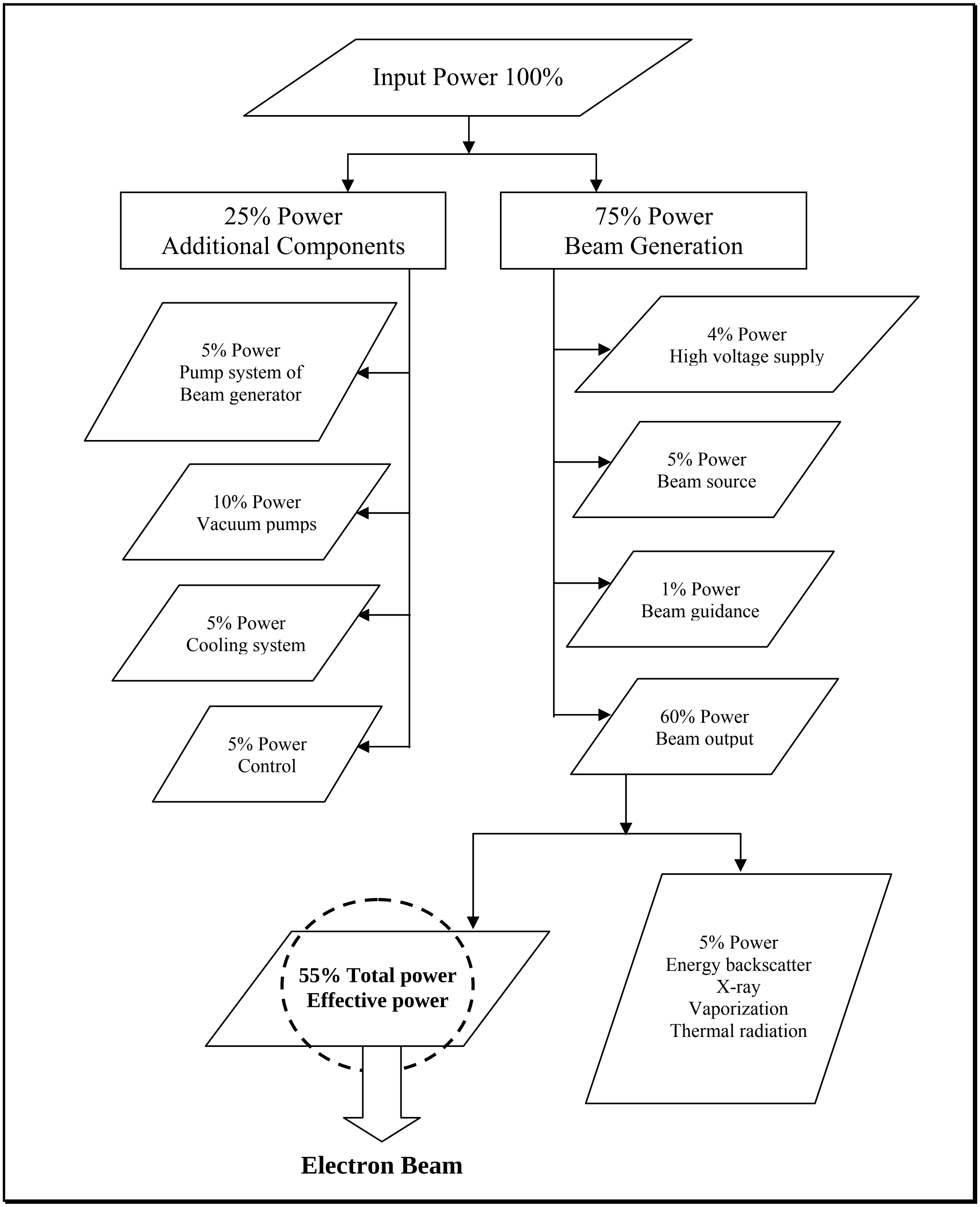


Figure 4.2: A flowchart of electron beam power distribution in welding process [Adapted from ref. 81] .

4.2.2 Generation and Manipulation of Beams

In all high energy density beam welding equipment, one can distinguish the following parts which are discussed below:

- Beam generators,
- Beam transportation to the workpiece,
- Beam concentration on an impact point with high energy density,
- Variation of the focus distance.

Figures 4.3 and 4.4 show the basic elements of laser and electron beam welding machines [5].

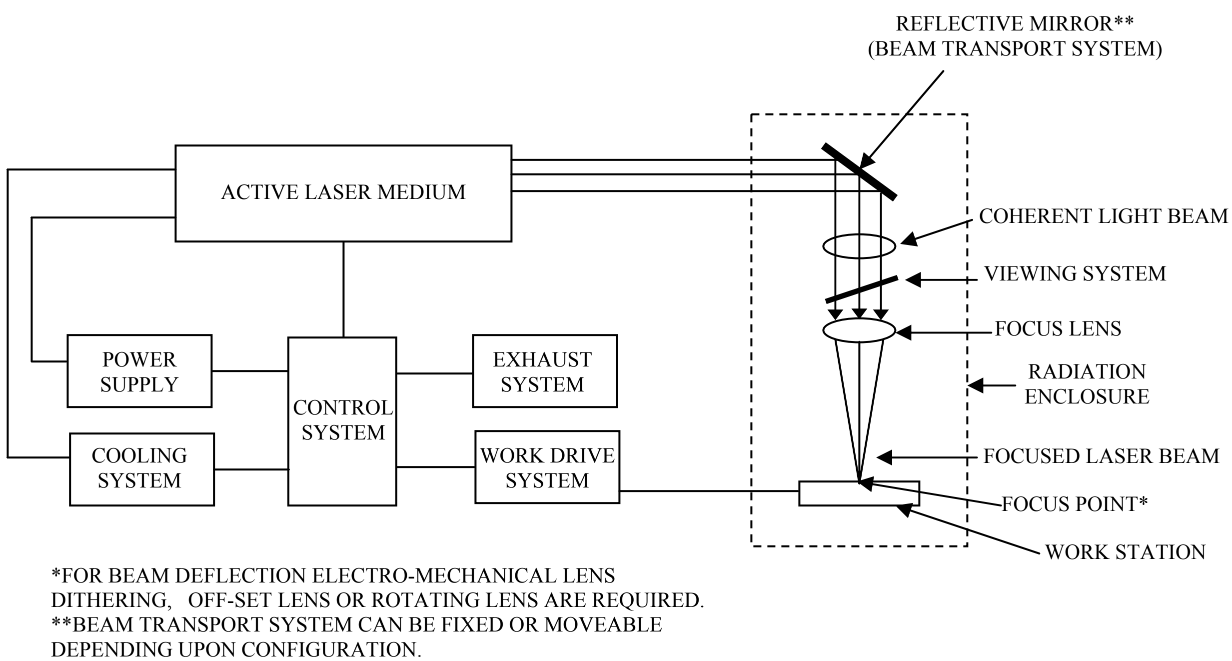
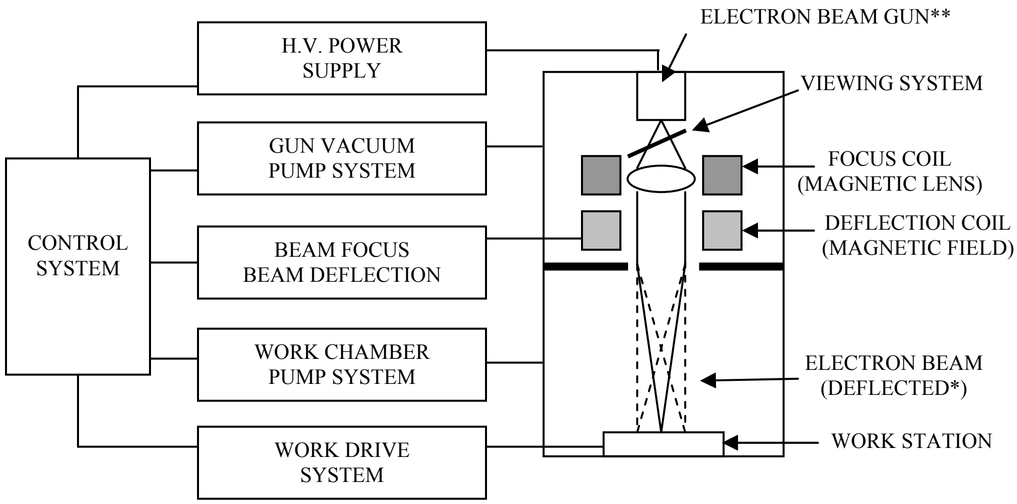


Figure 4.3: Basic elements of a laser beam welding machine [5].



*DEFLECTION CANINCLUD D.C. OFF-SET. LINEAR OSCILLATION CIRCULAR DEFLECTION OR PRECISE PASTER CONTROL THROUGH MAGNETIC FIELD.
**ELECTRON BEAM GUN CAN BE FIXED OR MOVEABLE DEPENDING ON MACHINE CONFIGURATION.

Figure 4.4: Basic elements of an electron beam welding machine [5].

4.2.2.1 Beam Generators

In EB, electrons are produced by an emissive surface (cathode) connected to a negative potential and heated appropriately to a temperature of 1200 to 2400C^0 according to the nature of the cathode. The electrons acquire a kinetic energy when crossing the electric field created between cathode and which is usually connected to ground (electro static part).

An additional electrode called “wehnelt” surrounding the cathode plays the role of a grid in a valve by controlling the electron emission. In addition it affects favorably the formation of the beam and particularly its electrostatic concentration in the cross over, the image of which through one or more electromagnetic lenses constitutes the heat source used in welding.

Because of high voltage breakdown and risks of oxidation of the cathode which is at a high temperature, it is vital that all the electrostatic part is held at less than 10^{-2} Pascal pressure, which is not very difficult to obtain [1].

In LB, photons issue from an optical cavity through which a gas mixture (CO_2, He, N_2) flows at a constant pressure and temperature. The CO_2 gas molecules are excited by an electric discharge, DC or AC, and when they relax they emit photons which, due to stimulation, are in phase and of the same wavelength (coherence). Mirrors located in the optical cavity lengthen the optical path by reflection and thus increase the amplification [30].

The characteristics of the gas mixture in the optical cavity should be maintained constant; pressure should be equally controlled at a fixed value between 30 to 150×10^{-2} Pascal. The flow and temperature of the gas should be maintained constant within a small range of variation in order to ensure good stability in the power.

A window located at one end of the cavity allows a partial transmission of the beam power and its propagation through optical systems (mirrors and lenses) suitably placed in its path before reaching the final point on the workpiece [1].

4.2.2.2 Beam Transportation to the Workpiece

The transport of energy between the centre of beam generation and the workpiece is achieved at a very high speed; speed of light “c” for LB and about 2/3 c for EB. This transport induces widening of the beam due to its natural divergence for LB and to electron space for EB. Modification of beam direction is obtained for LB by reflection (thus with direct contact between the energy and the deflecting element), using mirrors which have been suitably machined and coated to avoid energy absorption; and for EB by circularly symmetric electromagnetic fields of appropriate value and shape, thus without contact between the beam and the deflecting element. The laser beam can be transported over a considerable distance, preferably in a clean and dry atmosphere; indeed dust particles and traces of water vapor absorb the beam and cause considerable perturbation of the operating conditions [1, 73].

The electron beam needs a vacuum better than 1 Pascal for its propagation; if not, collisions between electrons and gas molecules occur, causing dispersion of the beam and loss of its energy density. For both EB and LB particular attention should be paid to positioning and aligning the different element located on the beam path. This is essential to ensure that the beam impact point is actually on the corresponding point of the workpiece [1].

4.2.2.3 Beam Concentration

Beams which can have a diameter of up to 70 to 100mm are concentrated by appropriate means to small spots of 0.1 to 0.5 or 1mm diameter, thus providing heat sources with very high energy densities, up to the order of a million W/mm^2 [24].

Concentration of LB is achieved by transmission optics (lens) which concentrate the beam at the focal point, or by reflective optics (spherical or parabolic mirrors) which concentrate the beam at the focus. In all cases special care is given to the machining of the optics in order to reduce aberrations (astigmatic, chromatic, spherical), and thus obtain the highest energy densities at the focal point [97].

Concentration of EB is achieved by axisymmetric electromagnetic fields which act on the electron trajectories in the beam and concentrate them at the focus. In this case also, alterations should be reduced in order to achieve the maximum energy density; this is done by using stable high voltage sources of low ripple (chromatism) and by optimizing the focus coil geometry as well as the beam envelope (divergence).

It should be pointed out that variation of the focus point in EB is easily obtained by modifying the current in the coil, whereas in LB, it is necessary to change the focusing optics for each focal distance [1, 98].

4.2.2.4 Variation of the Focus Distance

For the electron beam the focal distance is determined by the current of the magnetic lens. It can be varied from some cm to more than 1m within milliseconds, usually controlled by the CNC. This offers the possibility to weld at the bottom of a deep hole within a workpiece or close to high protruding parts of the workpiece. The focal depth depends on the focal distance and has usually values of several millimeters [2].An electron beam focused at a point slightly below the target surface can melt the material to greater depth and increased the depth of penetration through the material by 30% [3].

While in case of laser beam the focal distance is fixed by the lens and can be varied only by changing the lens. Typical values for the focal length are 30mm to 200mm. Focal depth is small, compared to an electron beam [2]. Long focal length optics have larger depth of focus appropriate for welding thick material, but wider fusion zones results due to the larger spot size [24]. The distance between the focusing lens and the workpiece surface has to be adjusted very exactly (sometimes with an accuracy of 0.1mm) [2]. So it can be seen that the selecting appropriate focusing optics is essential for achieving optimal welding performance for each different application [24].

4.2.3 Technical Performances of Laser Beam and Electron Beam

Most comparisons between laser welding and electron beam welding indicate that electron beam welding has no somewhat greater capabilities than laser welding. Figure 4.5 shows a comparison between laser welding and hard-vacuum electron beam welding at the 10kW level for 304 stainless steel. At speed from 1250 to 12500 mm/min, the laser penetration is approximately 70 percent of the electron beam penetration. The electron beam penetration continually increases as speed decreases, where as penetration by the laser beam appears to saturate. This behavior may be associated with the production of a plasma [21].

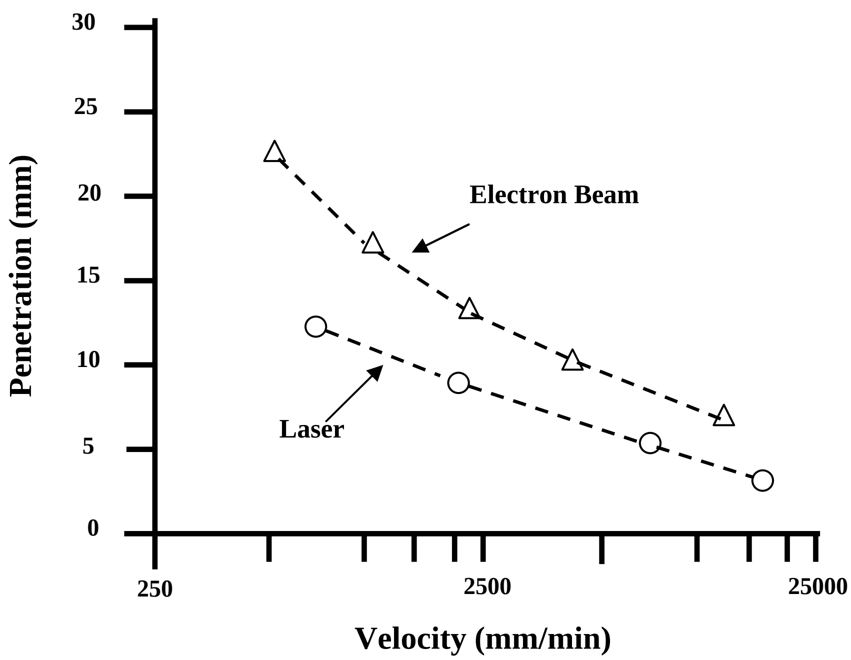
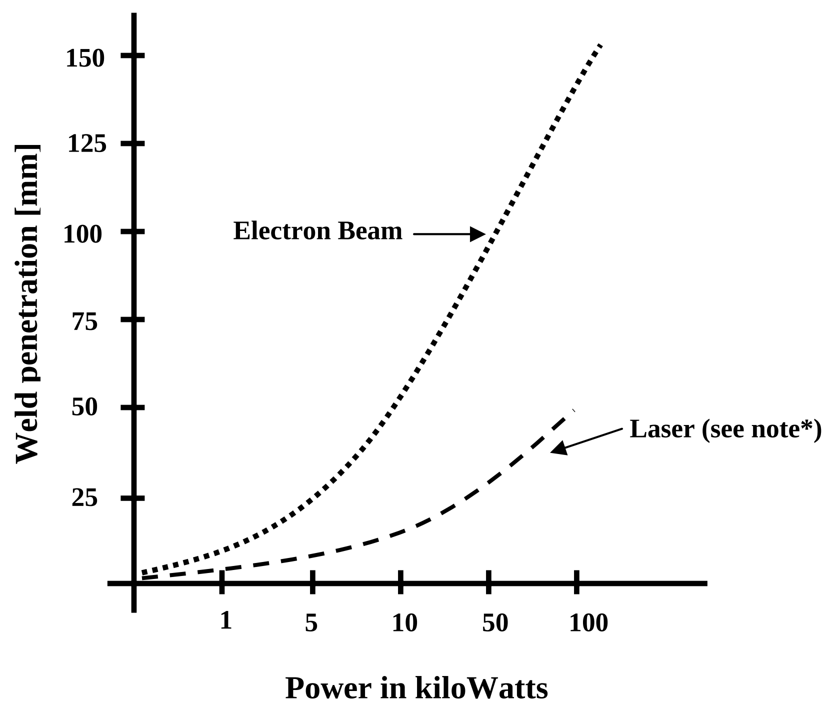


Figure 4.5: Comparison between laser welding and vacuum electron beam welding of 304 stainless steel at the 10kW power [21].

In figure 4.6, weld depth penetration in steel is compared. It can be seen from the graph that the electron beam process can provide substantially deeper penetration with equivalent laser output power. It is felt that the differences in penetration characteristics stem principally from the differences in beam optical characteristics. The electron beam, due to its much sharper equivalent "wavelength", exhibits a much greater depth of focus. Penetration of electrons into the material is therefore more direct and not influenced by reflectivity as in the case of CO_2 laser energy. This has a direct affect on equipment cost and energy consumption cost, particularly for systems above 5kW [5].



* Data points obtained are with a gasdynamic laser which is not available for industrial applications.

Figure 4.6 : Weld penetration comparison, electron beam vs. CO_2 laser, in steel at a speed of 375mm/min [5].

Figure 4.7 shows a quantitative comparison of penetration depth both in electron and laser beam welding. In both processes the penetration depth changes similarly with the ambient pressure. However, in case of electron beam welding the process is mainly governed by collisions with neutral and plasma particles and the total of these particle density in the beam pass directly affects the beam propagation, and the curve shifts to left side as the acceleration voltage is increased. While in laser process, it shifts to right side, if the plasma density is reduced [1].

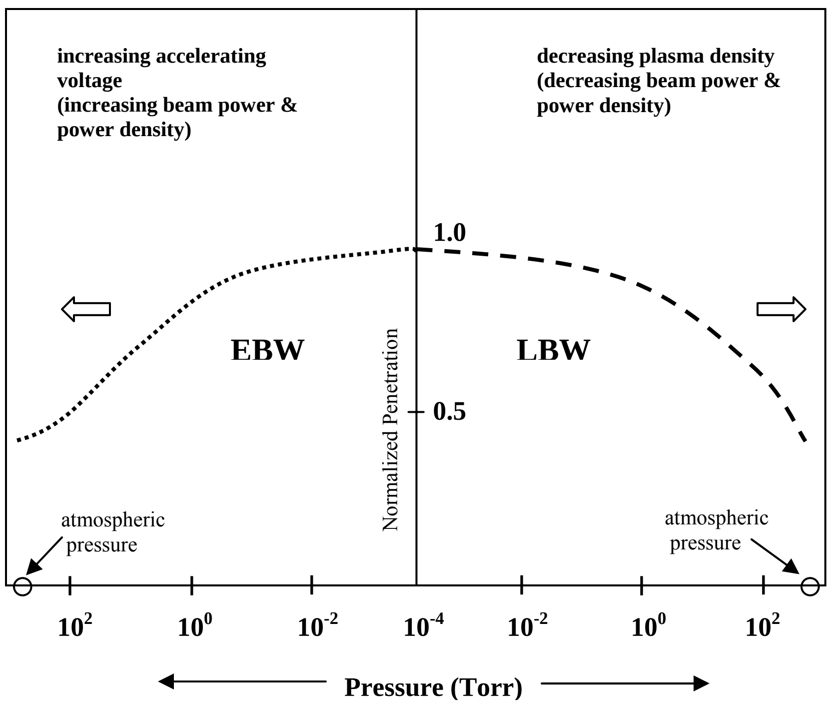


Figure 4.7: Comparison of pressure dependences of penetration depth between electron and laser beam [1].

4.2.4 Comparative Welding Heat Input

Since the laser is able to deliver very high power per unit area to localized regions, the energy input per unit length of the weld seam is fairly low and comparable to that required in electron beam welding. A low amount of heat input results in a very little distortion of the weld zone and a small heat-affected zone because of rapid cooling. The laser beam produces a rather narrow and deep weld similar to an electron beam weld [3]. Table 4.1 presents a comparison of laser welding of 6mm plate with electron beam welding. The table shows that although a greater power is absorbed by the workpiece in laser welding, because of the higher welding speed, there is a lower heat input per unit length, and less total heat into the part. Less distortion of the plate resulted from the EBW and the LBW in which the welds were of relatively uniform cross section through the thickness of the material [58].

Table 4.1: Comparison of LBW and EBW processes for welding 6mm plate [58]

ITEM	LBW	EBW
Power absorbed by workpiece	4 kW	5 kW
Total power used	50 kW	6 kW
Traverse speed	16 mm/s	40 mm/s
Energy per unit length absorbed by the workpiece	250 J/mm	125 J/mm
Alignment accuracy required	± 0.5 mm	± 0.3 mm

4.2.5 Analytical Models

The laser and electron beam sources, whether moving or stationary, can interact with materials in a variety of ways. Systematic studies on the thermal processes that occur in materials exposed to laser radiation or to electron beam allow to select the most efficient treatment procedure, specify the main requirements of the output parameters of LR and EB, and define the optimal interaction conditions [3].

This section presents solutions of two mathematical models, namely the circular source model for the LBW and the Gaussian source model for the EBW. These solution have been made on common bases of power intensity (≈10^6 W/cm^2) and target material which titanium to provide indicators of comparison between the two technologies in terms of theoretical analysis.

4.2.5.1 Laser Beam Analysis

The mathematical model which has been selected to suit laser beam welding is the circular surface source on semi-infinite half-space, and this source is uniform and constant in time. Also it can evaluate temperature distribution in solids in three-dimensions and for invariable material properties. Equation (2.15) represents the mathematical expression for this model [44]. The integration of this equation has been evaluated numerically to determine the temperature at any point in the solid at any time.

The integration of the mathematical function included in equation (2.15) has solved numerically using the Trapezoidal rule as per the following function [99]:

$$\int_0^{m'} f(x)\,dm' = \frac{m'-0}{2n}(y_0 + 2y_1 + 2y_2 + 2y_3 + \ldots\ldots + y_n) \qquad (4.1)$$

where n the number of sub-intervals.

Computer program has been written in MATLAB environment to find the value of the temperature and its distribution along the axes (x,y,z) with the fourth dimension as the time. Figure (4.8) shows the flow-chart of this program.

Figures (4.9) and (4.10) indicate the temperature distribution against the radius at different depths for energy equal to 3J and 5J respectively and 1ms laser pulse.

Figures (4.11) and (4.12) also indicate the temperature distribution but against the depth at different radiuses for energy equal to 3J and 5J respectively and 1ms laser pulse.

The cross-section of the weld pool geometry has been represented in figures (4.13) and (4.14). These figures also explain the melting zone and the heat affected zone.

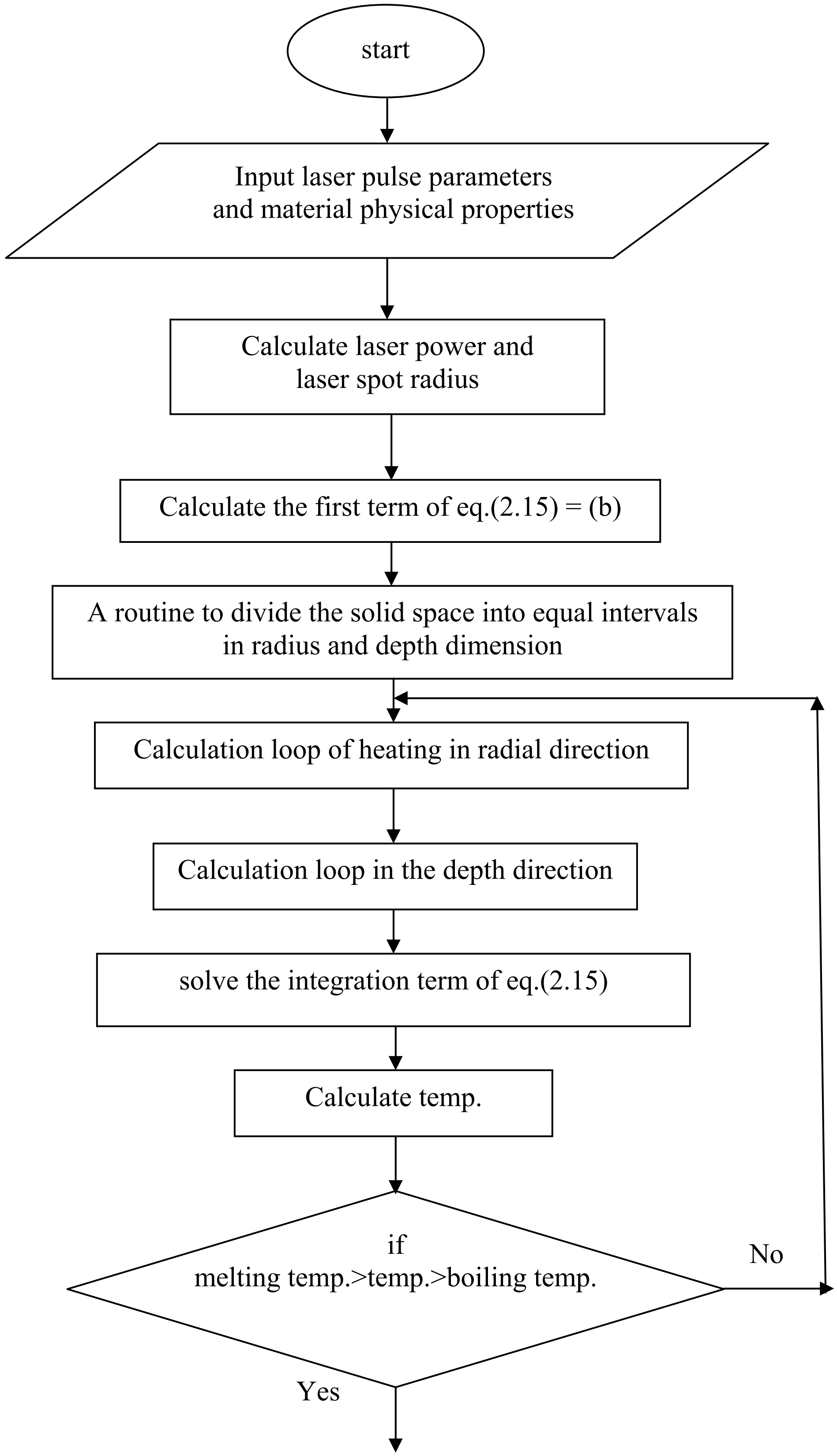


Figure (4.8): Flowchart of the computer program

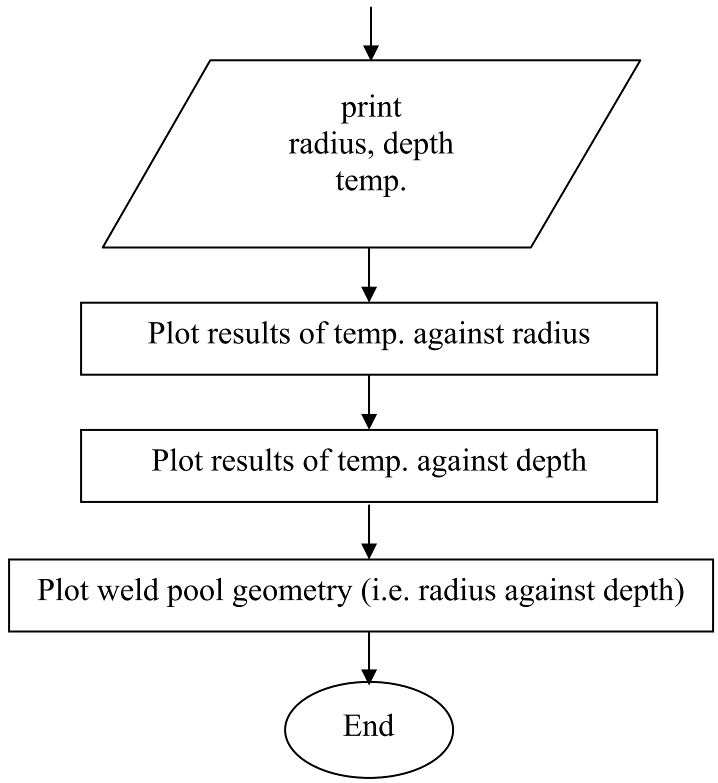


Figure (4.8): Continued

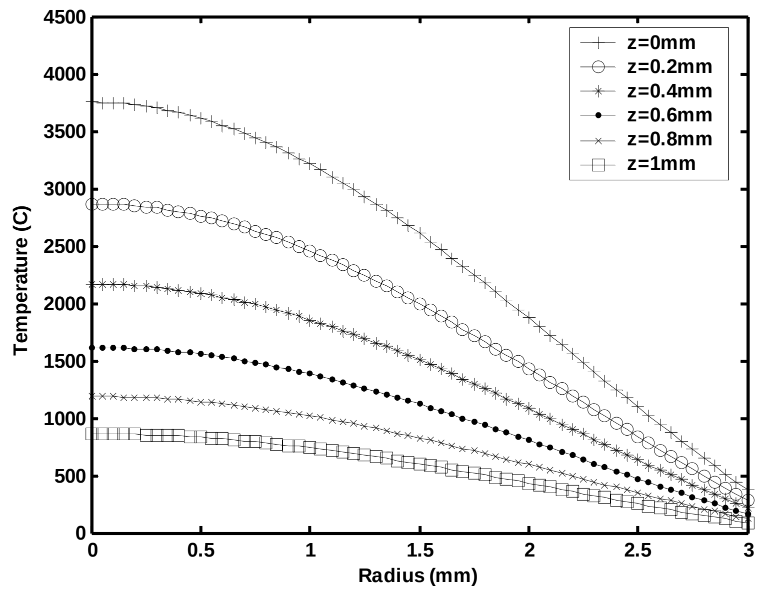


Figure (4.9): Temperature versus radius at different depths for 3J energy, 1ms laser pulse.

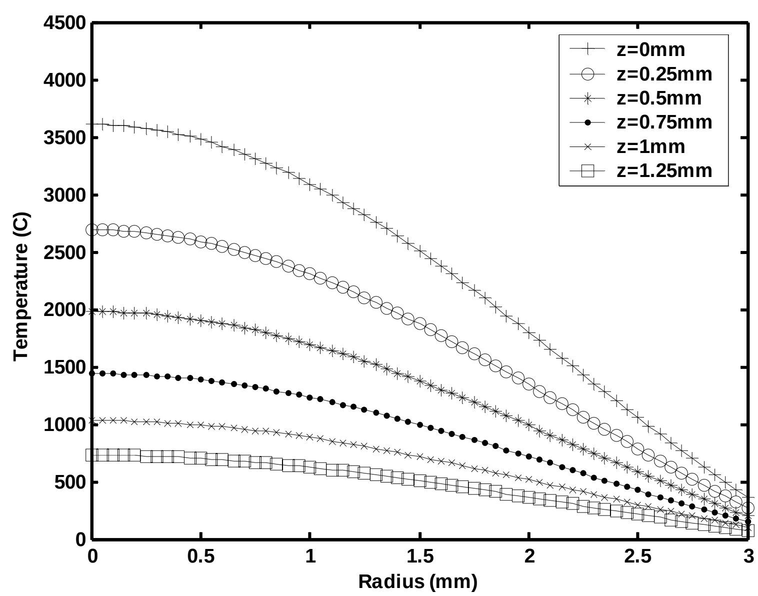


Figure (4.10): Temperature versus radius at different depths for 5J energy, 1ms laser pulse.

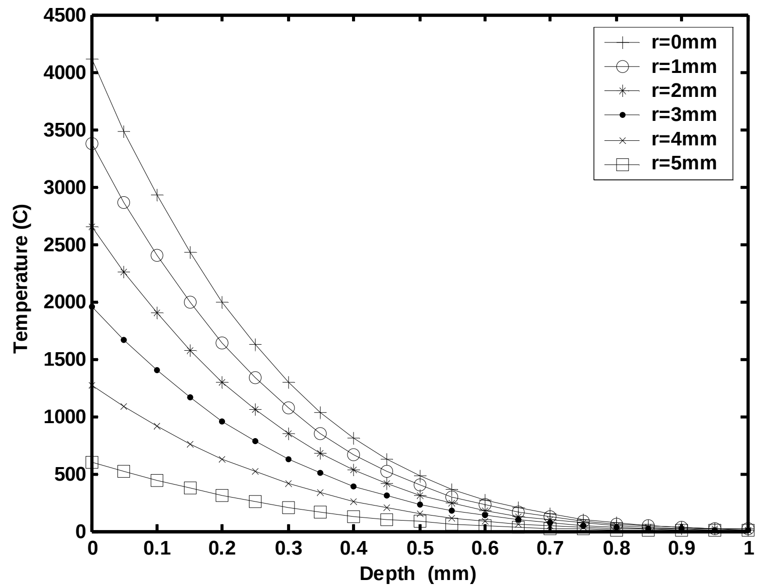


Figure (4.11): Temperature versus depth at different radii for 3J energy, 1ms laser pulse.

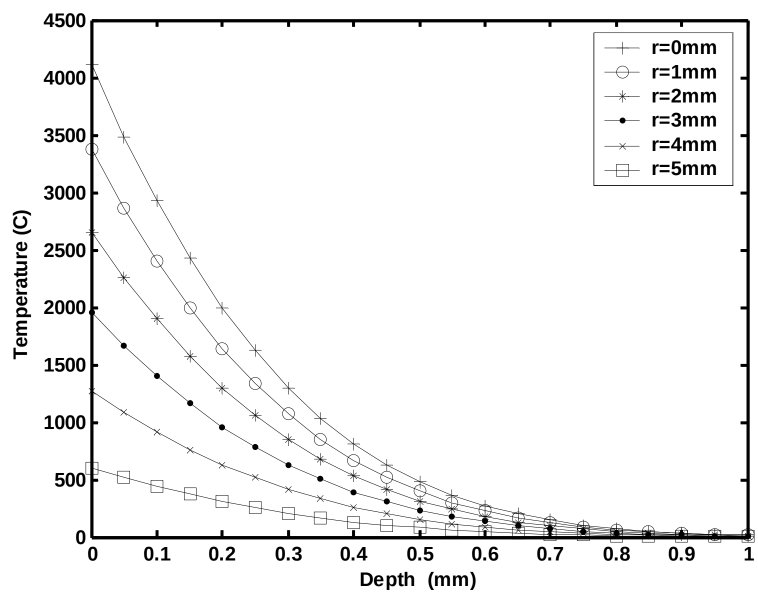


Figure (4.12): Temperature versus depth at different radii for 5J energy, 1ms laser pulse.

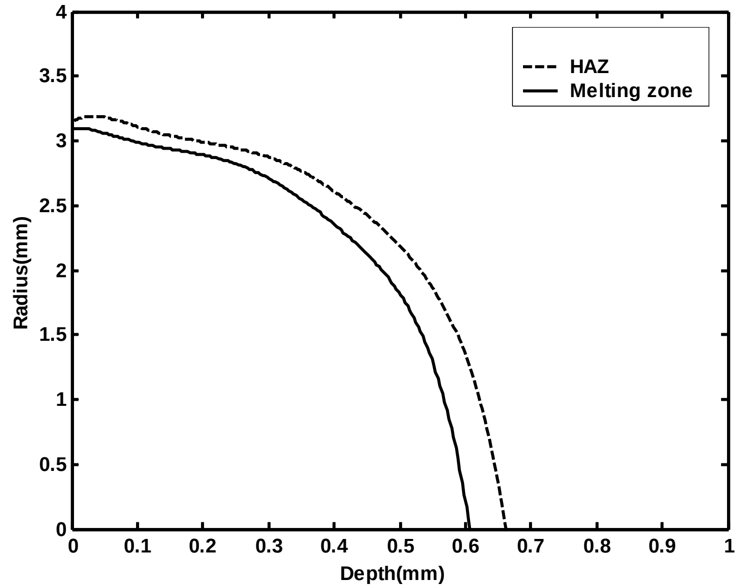


Figure (4.13): Cross-section of weld pool geometry for different zones at 3J energy and 1ms laser pulse.

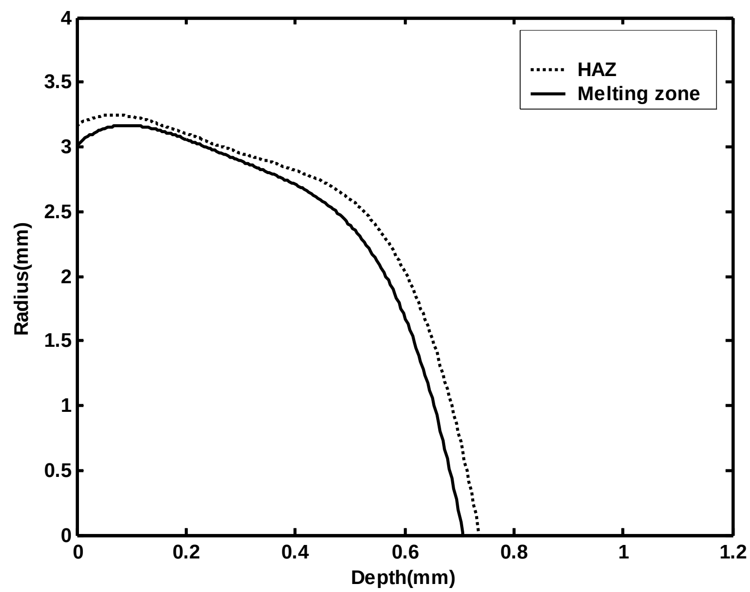


Figure (4.14): Cross-section of weld pool geometry for different zones at 5J energy and 1ms laser pulse.

4.2.5.2 Electron Beam Analysis

For electron beam welding the Gaussian source has been selected. The Gaussian distribution allows uniform high intensity energy application. The mathematical expression for this model has been represented by equation (3.10) [3].

The integration of the mathematical function included in equation (3.10) has solved numerically using the Trapezoidal rule.

Computer program has been written in MATLAB environment to find the value of the temperature and its distribution along the axes (x,y,z) with the fourth dimension as the time. Figure (4.15) shows the flow-chart of this program.

Figures (4.16) and (4.17) indicate the temperature distribution against the radius at different depths for power equal to 50kW and 150kW respectively.

Figures (4.18) and (4.19) also indicate the temperature distribution but against the depth at different radiuses for power equal to 50kW and 150kW respectively.

The cross-section of the weld pool geometry has been represented in figures (4.20) and (4.21), these figures also explain the melting zone and the heat affected zone.

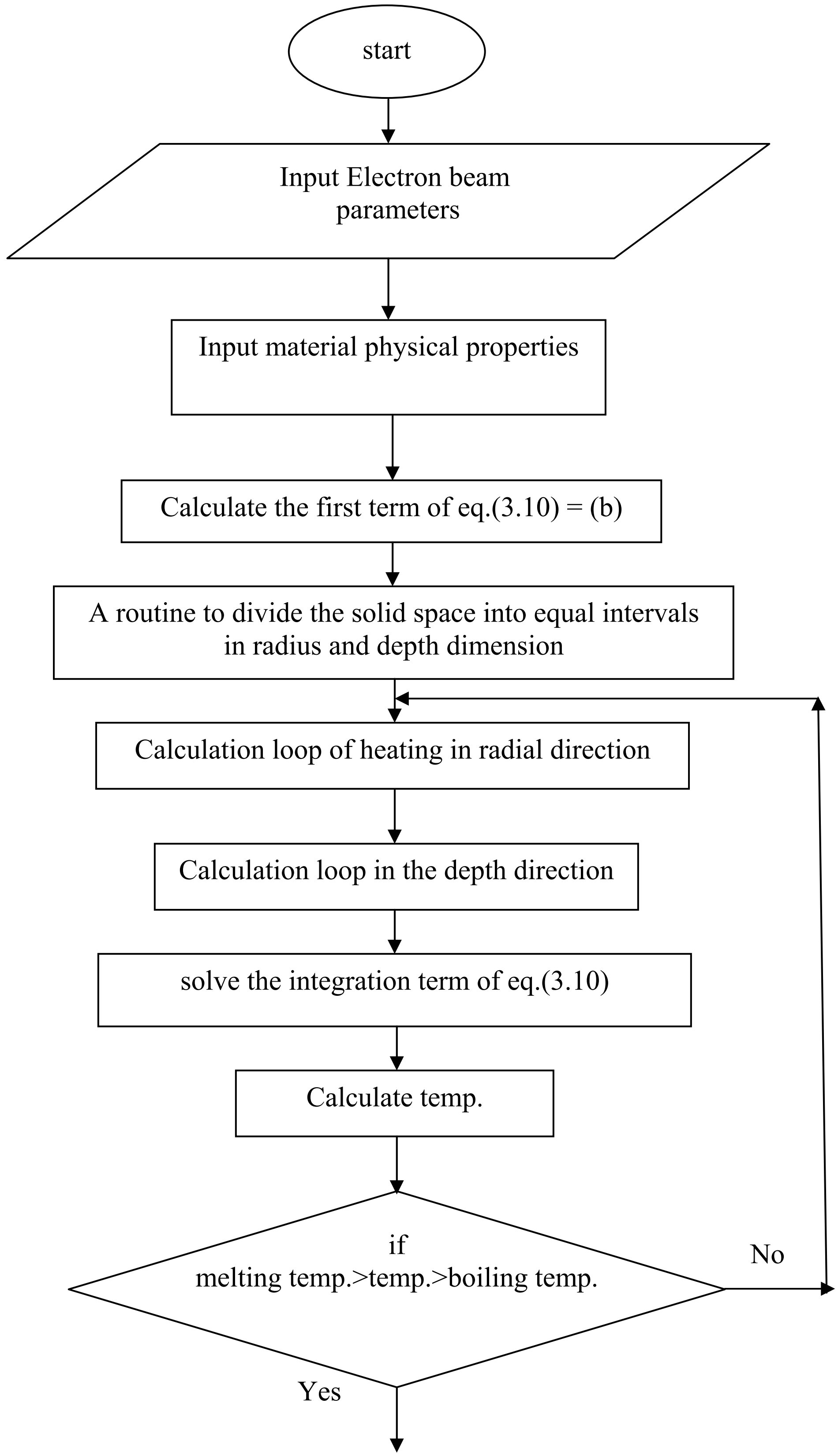


Figure (4.15): Flowchart of the computer program

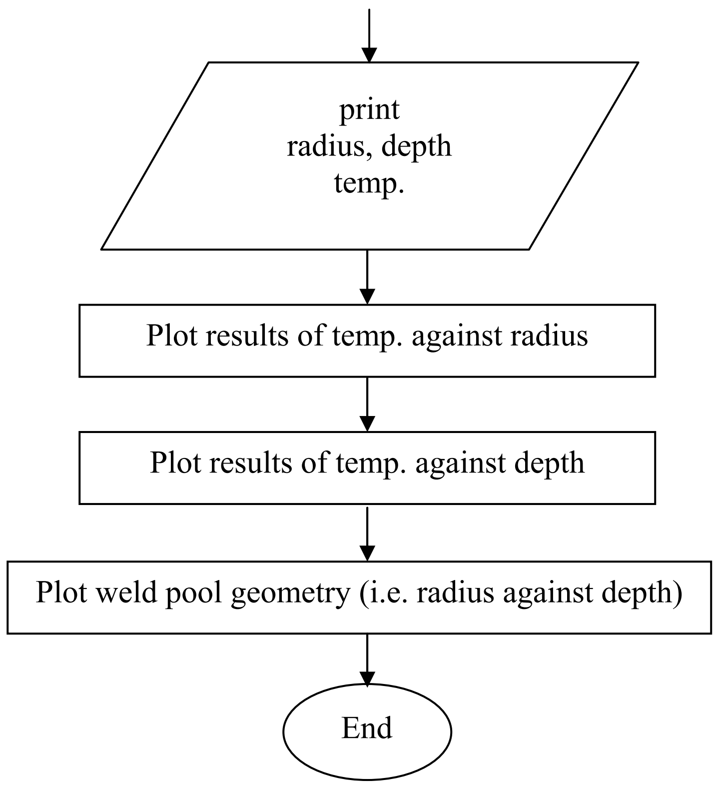


Figure (4.15): Continued

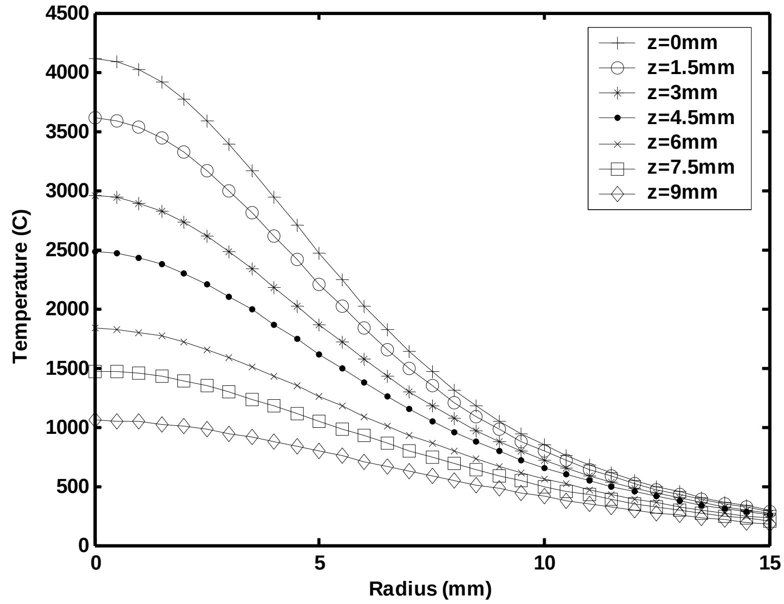


Figure (4.16): Temperature versus radius at different depths for 50kW power electron beam.

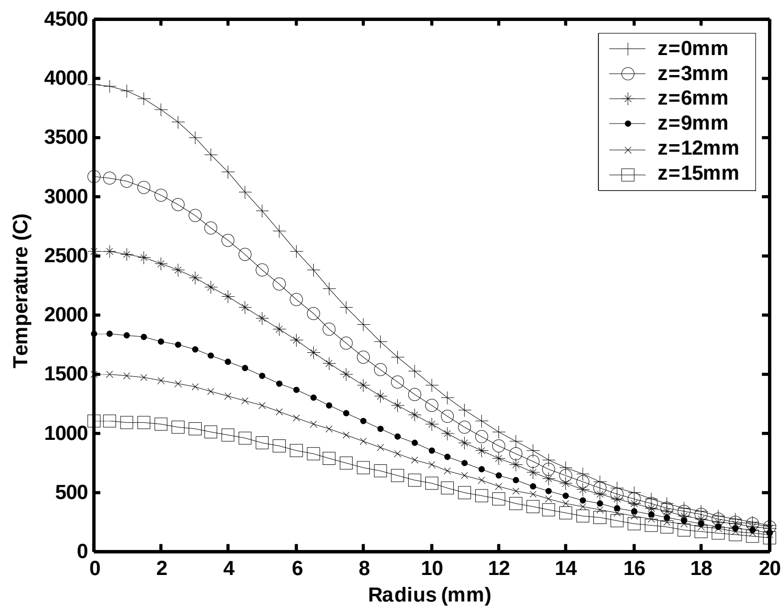


Figure (4.17): Temperature versus radius at different depths for 150kW power electron beam.

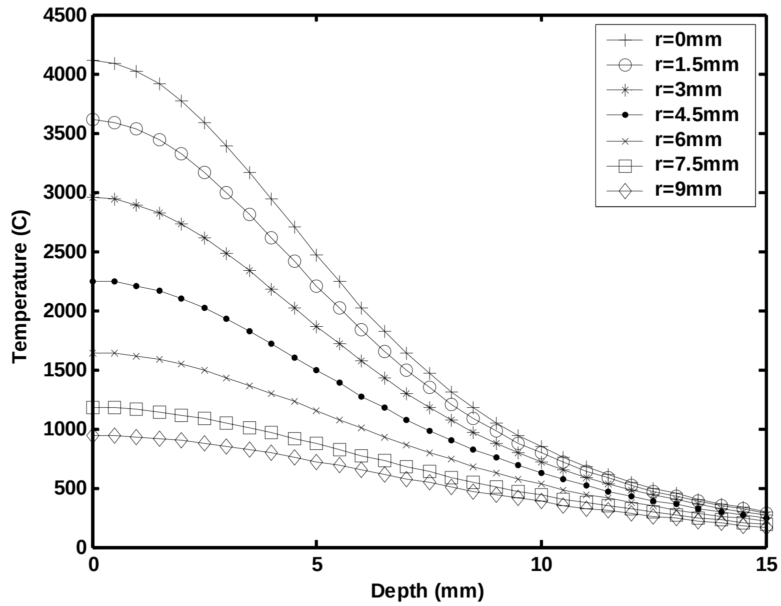


Figure (4.18): Temperature versus depth at different radii for 50kW power electron beam.

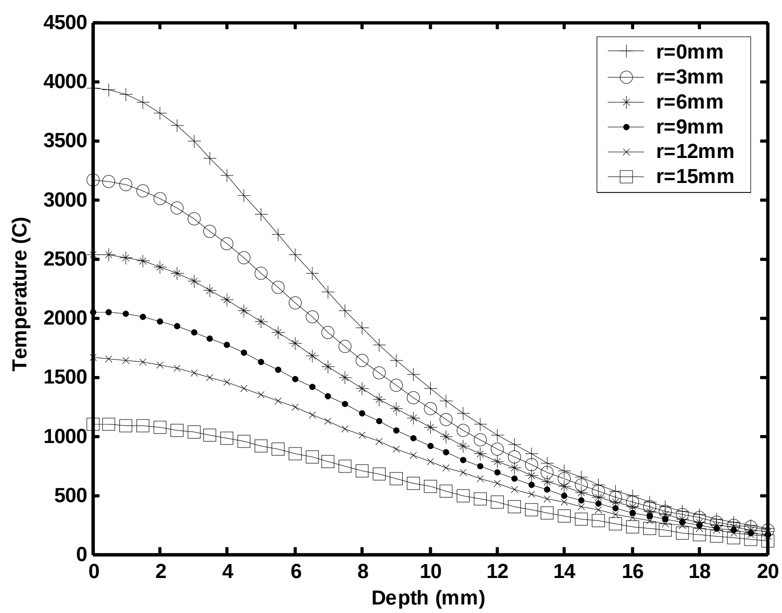


Figure (4.19): Temperature versus depth at different radii for 150kW power electron beam.

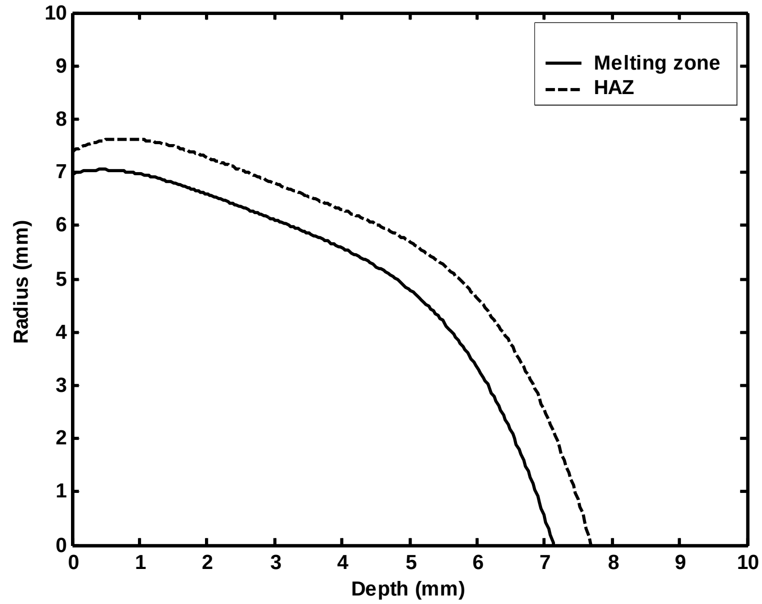


Figure (4.20): Cross-section of weld pool geometry for different zones at 50kW power electron beam.

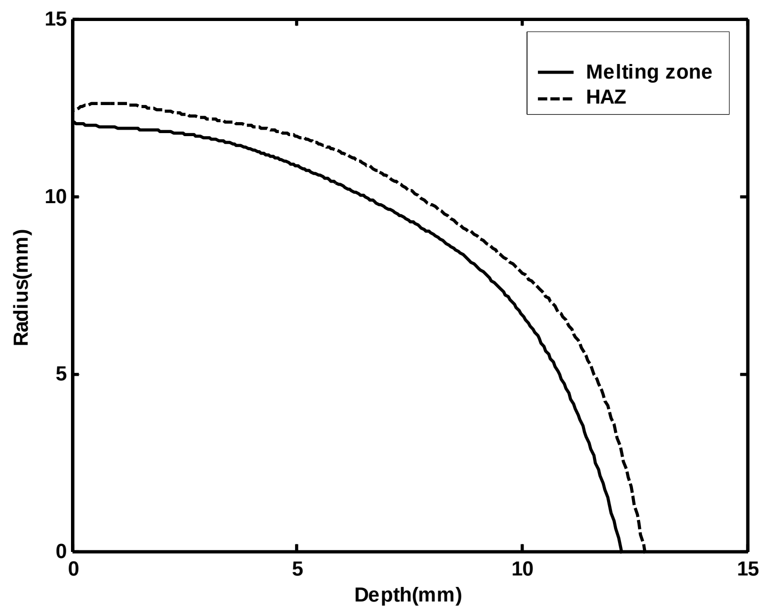


Figure (4.21): Cross-section of weld pool geometry for different zones at 150kW power electron beam.

4.2.5.3 Results and Discussion

The intensity for the welding process of titanium is approximately the same for both laser and electron beam which is in the range of 10^6 W/cm^2.

In the case of laser beam the temperature profile effect on titanium surface is very steep and it became shallow when the depth and the radius increased. The maximum depths which have been estimated were 0.6mm and 0.7mm for 3J, 5J energy. The maximum radii which have been estimated were 3.25mm and 3mm.

In the case of electron beam the temperature profile effect on titanium surface is also very steep and decreased when the depth and the radius increased. The maximum depths which have been estimated were 7.25mm and 12.5mm for 50kW, 150kW power. The maximum radii which have been estimated were 7mm and 12mm.

It is obvious from these results that the mathematical models that have been used for both technologies were not accurate enough. The values of aspect ratio (depth to radius of pool) were less than the expected average.

By comparing the obtained results for both models, the obtained weld penetration for electron beam was much higher than the weld penetration for laser beam.

4.2.6 Application Fields

The main application of electron beam technology is welding. In principle, the characteristics are the same as with laser technology and are as follows: welding with minimal thermal distortion, welding in the vicinity of heat sensitive parts, high welding speed. However the high beam power, the penetration mechanism, the vacuum in the welding region and the controllability of the beam offer additional advantages.

The following examples show areas of applications for electron beam welding [2, 38].

- All welding, where an effective beam power of more than 5kW is required, either because of the welding depth or because of a demanded high welding speed.
- Welding of aluminum, copper, gold, silver, titanium or magnesium alloys.
- Welding, where the ratio of depth to width of the molten zone has to exceed values of up to 10.
- Welding of materials, which tend to porosity. Porosity can be reduced or avoided by specific high frequency beam oscillations.
- Welding of workpieces with inclined parts along the welding path or with varying welding depth.
- Welding, where the workpiece movement is superimposed by an additional beam deflection, either to compensate for a dislocation of the coordinate table and/or to weld protruding parts, e.g. a pipe socket in a base plane.

This cases, where the conditions for an advantageous employment of electron beam welding cannot be met, the laser can be an excellent tool for welding, especially in the range up to 8mm thickness. laser welding is advantageous with “problem free” materials such as steel with low carbon content or alloys which are not subject to crack or porosity. For such welding, laser and electron beams truly compete and the decision concerning the technology to be used depends primarily on economical factors [2].

Applications of laser and electron beam welding cover today a whole range of industries such as: aeronautics, automobile, nuclear, energy, electrical appliance, etc. [1]. The main industrial applications for the laser beam welding and electron beam welding respectively are shown in figure 4.22.

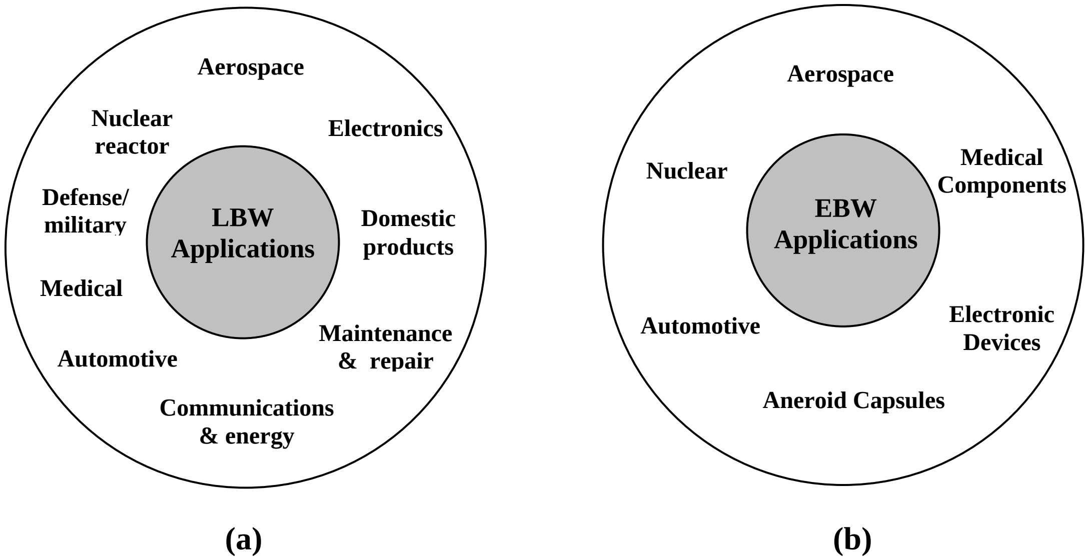


Figure 4.22: High energy density heat sources and their application, (a) for laser beam welding and (b) for electron beam welding.

These welding processes are met [1]:

i. In joining very expensive components (jet engines) as well as in very cheap ones (gears),
ii. In mass production (automobile, electrical applications) as well as in unit production (internal core of nuclear reactor),
iii. In welding small sized parts (pressure transducers) as well as very large components (bodies of aeroplanes),
iv. In welding thin components (saw blades) as well as very heavy sections (pressure vessels),
v. In welding ordinary metals (structural steel) as well as exotic metals (titanium).

Table 4.2 represent a comparison between laser beam and electron beam welding processes and metals [9].

It is not possible to cover all applications in this thesis. So the technology of laser and electron beam welding has been adapted systematically to applications to satisfy better the specific needs of users.

Table 4.2: Comparison between electron beam and laser beam for welding different metals [Adapted from ref. 9].

MATERIAL	THICKNESS*	EBW	LBW
Carbon Steel	S	✓	✓
	I	✓	✓
	M	✓	✓
	T	✓	-
Low-alloy Steel	S	✓	✓
	I	✓	✓
	M	✓	✓
	T	✓	-
Stainless Steel	S	✓	✓
	I	✓	✓
	M	✓	✓
	T	✓	-
Cast Iron	I	-	-
	M	-	-
	T	-	-
Nickel and alloys	S	✓	✓
	I	✓	✓
	M	✓	✓
	T	✓	-
Aluminum and alloys	S	✓	✓
	I	✓	✓
	M	✓	-
	T	✓	-

*****Abbreviations: S, sheet, up to 3mm; I, intermediate, 3–6mm; M, medium, 6–19mm; T, thick, 19mm and up; ✓, recommended.

A few examples had been presented below showing the wide range of applications.

4.2.6.1 Mass Production

This applies mainly to the automobile industry for the welding of machined parts.
In EB welding, the chamber is generally of relatively small volume (a few liters) and is associated with a rotating table with several stations, including those for loading and unloading.
The production rate is around 200 to 300 parts/hour for simple equipment. It is double for equipment with two welding heads and can attain 1000 part/hour for sliding seal equipment where the workpiece is brought in front of the beam via a succession of interlinked chambers, thus eliminating completely the pumping time which is achieved in borrowed time. About 1000 to 1500 EB machines are employed in this field (automobile industry).
The use in the automobile industry of EB welding machines operating in atmosphere should be noted. The beam comes out through successive vacuum chambers and nozzles into the atmosphere onto the workpiece which is located close to the orifice. The number of such equipments is very small compared to those using a vacuum chamber.
LB welding applications in mass production are the most numerous. Parts are presented to the beam on a rotating table or the laser beam supplies different fixed stations (2, 3 or more) successively. It is usual to see two laser sources supplying 4 to 6 work stations on a time sharing basis. This area is undeniably the one where multi-kilowatt laser welding is mostly employed [1, 73, 96].

4.2.6.2 Aeronautics and Space Industry

This field employs a large part of the existing EB equipment whereas LB equipment is present only at a more modest level. The vacuum chamber in EB welding can attain some scores of m^3 or even some hundreds of m^3. The applications cover components of jet engines (compressor guide, vanes, rotors) composed of circular assemblies of welded radial blades; or plane structures (with box for variable geometry wings). Specific advantages of EB include the possibility of fabricating the component from simple preformed parts, instead of machining the whole component, thus making the process economically very attractive. As an example, that machining a nozzle guide van takes about 40 hours on a multi spindle machining centre whereas the assembly by EB of individual blades to form the ring takes about 90 minutes. Another potential application in this domain is the repair of complex and expensive parts of a jet engine which has been locally damaged (wear, cracking, rupture). The economy achieved in repair makes it possible to amortize the investment in the equipment rapidly; this explains why the majority of aeronautic repair centers in the USA, Japan and Europe are equipped with such machines.

It should be said that this field is still dominated by EB, but some LB equipments can already be found in service achieving the same types of application [1,53].

4.2.6.3 Welding of Plastics

Laser welding of plastics has been done for the past twenty years in limited applications. Currently, the application for this technology is becoming more prevalent with the decrease in price of laser systems and a further understanding of the science .

Transmission laser welding involves localized heating at the interface of two pieces of plastic to be joined to produce strong, hermetically sealed welds with minimal thermal and mechanical stress, no particulates and very little flash, making it ideal for medical device applications. Cycle times can be as short as a second, and relatively light clamping pressure is required just enough to keep the parts stationary and ensure there is no gap. Transmission laser welding can be used for rigid or flexible materials and small or large parts [66].

The workpiece in electron beam welding must be an electrical conductor for moderate energy beams, whereas lasers can heat insulators with equal or greater effectiveness as compared with metals [15].

4.2.7 Process Environment

Electrons can travel a longer distance without distortion only in vacuum. Therefore the workpiece or at least the welding region must be surrounded by vacuum of at least 0.01mbar [2]. While laser beam does not need a vacuum, it can be transmitted over a long distance without attenuation or significant diminution [1].

On the one hand the absence of gas molecules gives ideal technological conditions for welding and melting, on the other hand the vacuum system is sometimes the most expensive part of an electron beam machine. The necessity to put the workpiece or parts of it into a vacuum chamber is the essential drawback compared with laser technology. The progress of vacuum technology enables short pumpdown times, for small vacuum chambers even below 1 second. Even $8m^3$ chambers can be evacuated within 15 minutes. Special constructions such as sluices, double or triple chambers with plates or vacuum-tight feed through systems reduce the cycle time sometimes near to almost that of the real welding time [2].

The non vacuum electron beam welding process still providing good-to-excellent welds, but not without decreased weld penetration and increased weld width [90].

Laser welding, though, offers factors that may offset this advantage for the electron beam. Laser welding can be performed without the need for any vacuum system and thus can offer a higher throughput of completed parts per unit time than the electron beam. Even though the electron beam can weld an individual part faster than the laser, the necessity of moving the parts into and out of a vacuum can slow the electron beam processing to a rate below that of the laser processing. The fixturing requirements also are more simple for laser welding. In fact, laser welding has replaced electron beam welding in a number of applications. The higher throughput allows lower unit cost per welded part [21].

4.2.8 Safety Implications

Electrons moderated in the workpiece generate x-rays, which can be especially dangerous in high voltage machines. Therefore the working chamber must be shielded by a 6mm lead layer. Inspection windows are made of lead glass [2]. All doors, ports, and other openings must have proper seals and should be checked periodically to prevent x-ray leakage. Operators should wear film badges to detect accidental radiation exposure. The high voltages required also present an electrical hazard [77, 100].

Laser beam does not produce x-rays, as does electron beam. The major hazard of this powerful beam is to the eyes, which can be partially blinded when hit with the beam. Special eye protection must be used, and care must be taken with any reflective surfaces since both the original and reflected beam are extremely dangerous [1, 100]. The power efficiency of CO_2 lasers is typically 10%. According for 10kW lasers a power dissipation of 100kW must be dealt with. High power lasers require therefore enormous cooling systems. CO_2 lasers require protection in the form of plexiglass panels or enclosures. Solid state lasers can cause permanent eye damage. Therefore windowless enclosures or special widows may be required [2].

4.2.9 Reliability and Reproducibility of the Welding Results

For electron beam welding results can be affected by residual magnetic fields, which lead to irregular beam deflections. High voltage flash overs cause interruptions in the welding process. If the high voltage can be attained within milliseconds, these interruptions do not affect the welding quality. But usually the welding process has to be repeated. The beam parameters are monitored and regulated by along control or by the process computer [101].

Reasons for variations in the welding results in the case of laser beam, can be attributed to unsteady conditions at the impact zone, caused by different reflections and effects of the laser plume. Welding results can be also affected by vapor deposition on the focus lens.

However, with both technologies reject rates of less than 0.1% can be achieved [2].

4.3 Economical Comparisons

4.3.1 Investment Costs for the Welding Machines and Tooling:

Welding machine consists of the beam generating system and the electronic components for controlling all the necessary functions of the system.

For lasers this system is the laser head, the control cabinet and in the case of gas lasers the pumping and cooling systems.

Standard electron beam equipment comprises of the gun, the high voltage supply, the control cabinet and the vacuum system [2].

The size of an electron beam welding machine is determined by the size of its vacuum system. The gun itself has a height of 50-120cm and a diameter of 30-60cm [2]. New applications of electron beam needs huge electron beam plant that have dimensions up to 10m in length and 5m to each of height and width [102].

While the size of high power laser equipment is mainly determined by the gas pumping and cooling systems [2]. Also the dimensions of laser welder not exceeds 1m in height and 0.5m in width and length [103].

The price of electron beam welding welder is essentially determined by the size and the capacity of the vacuum system. This results difficulties making a general economical comparison. Figure 4.23 shows a diagram of the investment cost comparison of electron beam and laser beam welding equipment. The tooling for electron beam machines is usually more expensive than that of lasers. The usage of non-magnetizable material for jigs and workpiece movement in a vacuum increase costs [81].

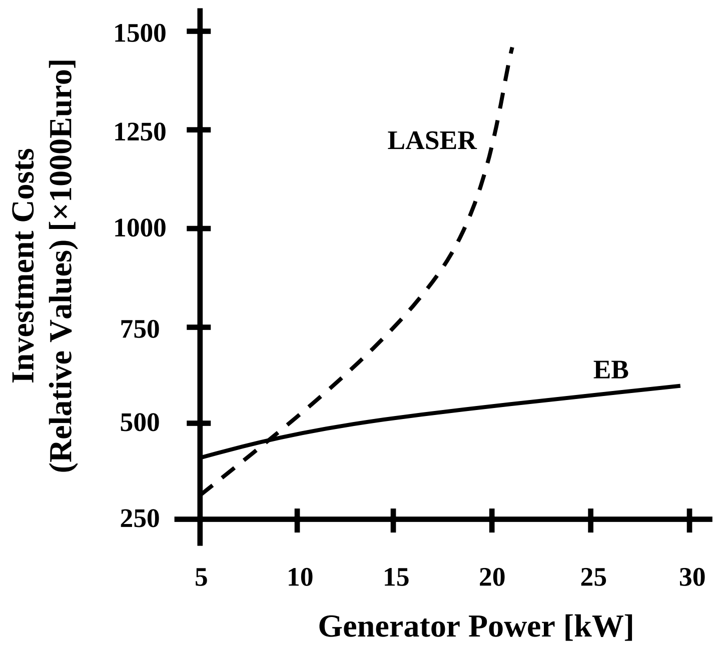


Figure 4.23: Investment cost comparison of standard electron beam and laser beam equipment [81].

4.3.2 Investment Costs for the Infrastructure and Maintenance

The infrastructure cost is usually higher for laser systems. Because of the rather poor power efficiency, the electrical power requirements exceed those of the beam power at least by a factor of ten. Powerful exhaust and cooling systems are not necessary for electron beam machines.

Also the costs for consumables are considerable higher for lasers. Laser gas, shielding gas and the high power dissipation have to be paid.

In electron beam machines the cathode has to be replaced after from 8 to 50 hours working time according of its type. A small amount of cooling is necessary for the vacuum pumps. Several liters of water per minute are sufficient.

Lasers require careful handling of mirrors and lenses. The working chamber of electron beam machines has to be cleaned from time to time [2].

Maintenance costs could be evaluated at 2 to 5% of the equipment price per year according to the nature of the application [1].

4.3.3 Automation and Costs for Preparation of Workpieces

For economical production both technologies require a high degree of automatization. Lasers and electron beam machines also work as integrated parts of flexible manufacturing systems. However, the greater versatility of beam splitting and deflection and working in air gives the laser more possibilities and flexibility.

Sometimes, laser welding require coatings for a better absorption of the beam energy. However the workpieces have to be similarly prepared for both technologies [2].

4.4 Tables of Final Comparison Results

The results which had been obtained and discussed in this chapter, summarized and presented in tables. These tables make the comparison's characteristics between laser and electron beam welding process easier and faster to be noticed.

Table 4.3 shows a general comparisons including two parts, the first one shows the power and efficiency comparisons between laser and electron beam welding and the second shows the generation and manipulation of beams comparisons.

While the tables 4.4 and 4.5 show the technological comparison and economical comparison respectively between laser and electron beam welding.

Table 4.3: Comparison between laser and electron beam in the field of power and generation of beams.

COMPARING PARAMETER	LASER BEAM	ELECTRON BEAM
Power and Efficiency Comparisons		
Maximum power achieved in research devices	up to 25kW	up to 300kW
Maximum beam energy of equipment usually used in industry	6kW	60kW
Power stability	(1-3)%	1%
Power efficiency	(1-10)%	75%
Loss of efficiency due to plasma affect and reflection of the beam	yes	no

Table 4.3: Continued.

COMPARING PARAMETER	LASER BEAM	ELECTRON BEAM
Generation and Manipulation of Beams Comparisons		
Beam generation	photons issue from an optical cavity	electrons produced by an emissive surface (cathode)
Possibility of CW and pulsed mode	available	available
Beam profile	high point density small depth of focus	high point density long depth of focus
Beam concentration	transmission optics (lens)	axisymmetric electromagnetic fields
Variation of focal distance	difficult	easy
Beam splitting	possible	not possible
Beam deflection/ redirection	electro - mechanical metallic mirrors	electro - magnetic (coils, condenser plates)
Distortion	very small	small
Beam mobility	good	difficult
Spot size	100µm-1mm	50µm-1mm
Controllability	very good	good

Table 4.4: Technological comparison between laser and electron beam welding.

COMPARING PARAMETER	LASER BEAM	ELECTRON BEAM
Technological Comparisons		
Speed of energy transport between the center of beam generation and workpieces	speed of light (c)	2/3 of speed of light (2/3 c)
Heat generation	low	moderate
Processes for high energy density beam welding	CO_2, Nd-YAG, direct diode, hybrid processes	high vacuum, partial vacuum, non-vacuum
Process temperature	locally high	locally high
Maximum fused zone thickness	20mm	150mm
Welding speed	moderate	high
Heat affected zone	very small	small
Metallurgical changes	precipitation hardening & cold worked alloys soften in heat affected zone	precipitation hardening & cold worked alloys soften in heat affected zone
Surface preparation	surfaces must be clean	surfaces must be clean
Possibility of welding magnetic materials	yes	no / conditional
Possibility of welding non-ferrous metals	difficult	good
Possibility of welding non-metallic materials (plastics)	yes	no
Weld quality	excellent	more excellent
Joint design	special care to overcome reflectivity	butt or lap

Table 4.4: Continued.

COMPARING PARAMETER	LASER BEAM	ELECTRON BEAM
Weld bead geometry	very good	excellent
Flux required	no	no
Joint strength	high	high
Seam rate	high	high
Welding atmosphere	air/ shielding gas	vacuum
Effect of energy absorption	depending on material and beam intensity	depending on material (Z-number) and fused zone thickness
Effect of focus diameter and focus position on beam energy	low	very high
Multistation operation (time sharing) possibility	yes	no
Approximate joining efficiency mm^2/kJ	15-25	20-30
Fit up tolerance	very close	close

Table 4.5: Economical comparison between laser and electron beam welding.

COMPARING PARAMETER	LASER BEAM	ELECTRON BEAM
Economical Comparisons		
Capital cost (based on 5kW)	high	high
Capital cost (above 5 kW)	high	very high
Equipment costs	very high	very high
Fixturing costs	low	high
Consumables cost	very low	very low
Infrastructure cost	very high	high
Market projection	(20-30)% growth per year in welding application	10% growth per year in welding application
Manual skill	low	low
Automation	semi or fully automatic	semi or fully automatic

Chapter Five

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

5.1 Conclusions

Welding with lasers and electron beams plays a large role in modern manufacturing technology and new areas of applications are constantly being found. The characteristics of the heat source created by these processes give joint qualities which are highly desirable in numerous applications, particularly where the degree of distortion after welding must remain low, where penetration is important or where production is very high.

The laser and electron beam welding processes have many similarities and many differences. They provide unique advantages such as low distortion and extremely rapid processing; however, they can be extremely costly except in high volume applications.

On the scientific and technical side, the physical problems raised in the design of the beam source, its transmission and concentration have been mastered for electron beam, while they are being continuously improved for high power lasers. Associated with a high degree of automation and CNC, laser and electron beam welding processes are becoming reliable, flexible, reproducible and high quality production tools. Thus mass production industries, aeronautics, energy and heavy industries have been continued to give a high priority to these processes.

Investment in these processes remains quite high, but could be compensated by productivity, thus justifying their integration among tools of industrial production. The evolution of the laser and electron beam welding techniques is directed towards the improvement of technical and economic performance. If the two processes are competitive in certain domains, they remain quite complementary in others where they can co-exist harmoniously for the benefit of industry.

The comparison between laser and electron beam welding process leads to the following conclusions:

- Power capability of electron beam is higher than laser beam (up to 100kW), no loss of efficiency due to plasma affect and reflection of the beam.
- The power efficiency of laser beam is low (10%) compared with electron beam (75%).
- Electron beam have true Gaussian distribution which allows uniform high intensity energy application more than laser beam.
- Both processes (laser and electron beam) can produce extremely narrow welds at high speeds.
- The depth of penetration in laser welding is limited. Maximum fused zone thickness is 20mm compared with 150mm for electron beam welding, also narrow welds can be made on thicker sections with deep penetration and minimal thermal disturbance.
- Extremely high depth to width ratio of electron beam welding can lead to centerline cracking.
- In laser welding, careful control of the process is required to avoid surface vaporization.
- Laser beam is not disturbed by stray magnetic fields. Parts must be demagnetized for electron beam.
- Laser beam does not produce x-rays, as does electron beam.
- Laser beam environment allows adaptation to various robotic systems more than electron beam.
- Electron beam vacuum environment provides ultra-clean weld characteristics, there is no atmospheric contamination as in laser welding.
- Laser beam allows more types of joints, there is no limited conditions as in vacuum of electron beam.
- Both processes (laser and electron beam) require good part fit-up and surfaces which are free from scale, rust or grease.
- Laser does not require vacuum chamber as in the case of electron beam. It can be transmitted over a long distance without significant attenuation or diminution.

- Laser beam can be divided into several subsidiary beams of lower power which can be used simultaneously for different functions. Easy beam transmission via mirrors allows beam sharing (multiple work station). In a similar way a high power beam can be composed from subsidiary beams of lower power. Beam splitting not possible with electron beam.
- Electron beam does not require water chiller and compressor for operation as in the case of laser beam welding.
- Time delay for electron beam when welding in vacuum, waiting for vacuum to build up.
- Capital cost based on 5kW is the same for laser and electron beam. Electron beam is dependent upon the total system rather than the kW output, so above 5kW laser price rises rapidly than electron beam.
- Market projection of laser beam is 20% to 30% growth per year in commercial application of welding heavy gauge material, with faster process speeds in light gauge materials. In electron beam market projection is 10% growth per year in specialized areas of aerospace and nuclear applications, as well as heavy sections welding of 2cm thick or more for commercial applications.

As final conclusions, there are prospects which should be envisaged when deciding to use laser or electron beam welding:

i. For applications on material thickness of less than 5mm, LB will continue to take progressively the place occupied until these last years by EB. This place will expand as laser sources become more powerful, reliable and cheaper. On the case of thick material (above 5mm) the electron beam welding must be used.

ii. When the ratio of depth to width of the molten zone has to exceed values of 10, electron beam welding must be used.

iii. For applications of welding insulator materials the laser must be used in welding. The workpiece in electron beam welding must be an electrical conductor for the moderate energy beams.

iv. Laser welding is advantageous with “problem free” materials such as steel with low carbon content or alloys which are not subject to crack or porosity.

v. To get ultra clean welds with no atmospheric contamination, high vacuum electron beam welding must be used.

vi. For aeronautic and space industries, today EB is very well established and will continue to progress during the coming years; the power level needed for these applications is between 5 to 10kW has influenced the preferential position held by EB. Nevertheless, the availability of new laser sources in the future could modify the situation.

5.2 Recommendations for Future Work

1. Theoretical study to discuss economical comparison between laser and electron beam welding in a wide aspects such as cost for consumables, necessity for registration, beam availability for machining, flexibility, possibility of job machining, etc.
2. Theoretical research in welding processes using high energy density beams (laser and electron beam) to focus on the high performance welding in a field of new material production.
3. Studying the place of laser and electron beam in mass production area, and the association of robots with laser and electron beam sources which offers important opportunities for industry.
4. Studying and analyzing of fundamental phenomena and the development of new processes in high energy density beams (laser and electron beam) material processing include: cutting, and surface treatment; as in heat treatment, melting, alloying and cladding, and also discuss their applications to new fields.

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