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सारांश

आदिप्ररूप दुत प्रजन रिएक्टर (PFBR) े अंत्य - प्ल ा ी वेल्डिं ा D9श्रे ाी ी पू ाित: ऑस्टेनाइटि इस्पात आवर ा नलि ा व 316 M अंत्य - प्ल ा े बीच ी जाती है। प्र ात ईंधन संविरचन सुविधाएँ में आदिप्ररूप दूत प्रजन रिए टर ईंधन े उत्पादन हेतु स्पंद ैास टं ास्टन आ ि वेल्डिं ा त नि ा उपयो ा ि या जा रहा है। ैास टं ास्टन आ ि अंत्य - प्ल ा वेल्डिं ा हेतु ए स्थापित प्रि्या है, इसलिए यह ई देशों े द्वारा अं ाी ृ त ी ाई है। ैास टं ास्टन आ ि वेल्डिं ा ी उच्च ऊष्मा निर्विष्ट, आ ि अंतराल संवेदनशीलता व दाचनि त्रुटियों यथा टं ास्टन सनावेश जैसी ु छ निश्चित सीमाएँ हैं। लेसर ि र ा वेल्डिं ा े लाभों ो दे ाते हुए इसे प्र ात ईंधन संविरचन सुविधाएँ में ैास टं ास्टन आ ि वेल्डिं ा े स्थान पर प्रतिस्थापित रने े प्रयास ि ए ाए हैं। यह रिपोर्ट आदिप्ररूप दूत प्रजन रिएक्टर ईंधन अवयव े संविरचन हेतु वेल्डिं ा प्राचलों े इष्टतमी र ा से संबंधित है। स्पंद लेसर Nd -YAG वेल्डिं ा प्रि्या ो सु ाम रने हेतु शि ार शक्ति, स्पंद अंतराल, स्पंद ऊर्जा, आवृत्ति एवं ार्य ांड पर लेसर ि र ा ा डिफो सन जैसे प्राचलों ो इष्टतमी ृ त ि या ाया है। इन इष्टतमी ृ त प्राचलों े आधार पर स्पंद लेसर वेल्डिं ा मशीन आदिप्ररूप दूत प्रजन रिएक्टर ईंधन अवयवों े अधस्तल अंत्य - प्ल ा वेल्डिं ा हेतु यो य घोषित ी ाई है।

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Abstract

End plug welding of Prototype Fast Breeder Reactor (PFBR) fuel elements involves welding of fully Austenitic Stainless Steel (ASS) of grade D9 clad tube with 316M end plug. Pulsed Gas Tungsten Arc Welding (GTAW) is being used for the production of PFBR fuel elements at Advanced Fuel Fabrication Facility (AFFF). GTAW is an established process for end plug welding and hence adopted by many countries. GTAW has got certain limitations like heat input, arc gap sensitivity and certain sporadic defects like tungsten inclusion. Experiments have been carried out at AFFF to use Laser Beam Welding (LBW) technique as LBW offers a number of advantages over the former process. This report mainly deals with the optimization of laser parameters for welding of PFBR fuel elements. To facilitate pulsed Nd-YAG laser spot welding, parameters like peak power, pulse duration, pulse energy, frequency and defocusing of laser beam on to the work piece have been optimized. On the basis of penetration requirement laser welding parameters have been optimized.

key words: Laser welding, Fuel element, End plug welding and Austenitic stainless steel

1.Introduction

Advanced Fuel Fabrication Facility, B.A.R.C, Tarapur, is currently engaged in the fabrication of Mixed Oxide Fuel (MOX) for PFBR. End plug welding of PFBR element involves welding of Austenitic Stainless Steel of grade D9 tube having a thickness of 450 microns with an end plug of ASS of type 316M. End plug welding is an autogenous welding process because of low wall thickness of the clad tube. Welding of PFBR fuel elements was qualified with GTAW. Even though GTAW was successful so far, it has got few drawbacks like Tungsten inclusion in the weld and difficulty in alignment of the electrode with weld joint.

Laser welding has become an important industrial process because of its advantages over the other widely used welding techniques. Laser welds have parallel-sided fusion zone, narrow weld width and high penetration. These advantages of laser welding come from its high power density and low heat input. Nd-YAG lasers continue to replace other welding techniques like GTAW [1] and resistance spot welding. Principal advantages of laser welding over the other processes are its low heat input, low distortion, low heat affected zone and non-contact nature of the process. Complications associated with laser welding of end plug are narrow weld zone susceptible to solidification cracking, concavity on the weld bead, lack of penetration and weld spatter. Most of these defects can be eliminated by proper selection of laser welding parameters.

Narrow welds lead to solidification cracking [2] because of high stress value. Large depth to width aspect ratio will encourage excessive transverse strains in restrained joints in turn lead to solidification cracking. Overlapping of austenitic steel tube on to an end plug is schematically shown in Figure 1. Austenitic stainless steel of grade 316M has chosen as end plug material and it helps in minimising hot cracking problem to some extent[3]. A depth of penetration around 700 to 800 microns is opted so as to meet the criterion of penetration of 500 microns even if the beam is off focused by some margin. Minimum Leak Path (MLP) of 405 microns is required in case of concavity or root pocket.

Absorption of energy depends on the wavelength of the light, resistivity of the material [4] and inclination of the work piece to the incident ray or vice versa. Absorption of light energy for metal varies with temperature. Metal in liquid phase absorbs more energy than solid because of the fact that absorption is directly related with vapor pressure [5]. So only a part of the actual laser pulse energy is utilized in the melting of metal. Despite the widespread use of laser spot welding the effect of parameter selection on heat input is effectively unknown. Because of the uncertainty involved in absorption, there is no invariable rule to find out the fraction of actual light energy needed. However few studies have reported fraction of absorption for stainless steel is in the range of 0.38 to 0.67[6]. Successful spot welds can be achieved by trial and error technique based on the absorption range.

Generally, pulsed laser beam welding involves many variables like laser peak power, pulse energy, welding speed, defocusing distance and type of shielding gas, any of which may have an important effect on heat flow and fluid flow in the weld pool. This in turn will affect penetration depth, shape and final solidification structure of the fusion zone. Both the shape and microstructure of the fusion zone will considerably influence the properties of the weldment. Optimization of parameters is aimed at lowest possible energy required to get the desired weld without any defects.

This paper presents a brief description about Pulsed Nd-YAG laser welding, various parameters and their effect on penetration and optimisation of the parameters for bottom end plug welding of PFBR fuel element.

2.Pulsed Nd-YAG Laser welding:

Nd-YAG laser is a Solid State Laser. Solid lasers use ions suspended in a crystalline matrix to produce laser light. The ions or dopants provide the electrons for excitation, while the crystalline matrix propagates the energy between ions. Neodymium (Nd^{3+}) used as a dopant for Pulsed Nd-YAG and lasers. Excitation is achieved by Krypton or Xenon flash lamps, and an output wavelength of 1064 nanometers in the near infrared region of the spectrum is obtained. The host material in Nd-YAG lasers is a complex crystal of Yttrium-Aluminum-Garnet (YAG) with the chemical composition $Y_3AI_5O_{12}$. YAG crystal has a relatively high thermal conductivity, which improves thermal dissipation in the laser cavity, Hence continuous wave operation up to a few hundred Watts and pulsed operation in the range of kilowatts is possible. YAG crystal is transparent and colorless. Crystal is doped with approximately 1% Nd, and it takes light blue color. With an efficiency of about 3%, a typical Nd-YAG produces much heat during its transmission as laser output; this heat must be removed in order to ensure proper laser operation. Cooling is usually done by de-ionized water with low conductivity.

3. Effect of Parameters

3.1 Pulse Peak Power

Pulse peak power plays an important role in achieving good weld penetration. At constant duration of pulse, increase in pulse peak power increases the energy input and thus the penetration [7]. At constant energy also, increase in peak power increases the depth of penetration because of its dominance over pulse duration. Peak power of a laser device is considerably higher than that of its average power and it will give an opportunity to opt for higher penetration.

3.2 Pulse Duration

Pulse duration is another parameter that can be varied to adjust weld penetration. At constant pulse power, depth of penetration is directly related to pulse duration [7]. At higher pulse duration, more energy is supplied to cause a phase change i.e. from solid to liquid. Pulse duration for welding is in the range of milliseconds.

3.3 Frequency

Frequency is altered according to the speed requirement of the welding. Frequency of pulses will be having an upper limit based on the average power of the laser devise. Increase in frequency will lead to higher heat input and hence better penetration [7]. Increase in frequency will also reduce the chance of weld spatter. Frequency, degree of overlapping and speed of the welding are interrelated.

3.4 Over lapping

Continuous seam of weld is formed by unification of individual spots. Effective penetration is judged by overlapping percentage. Good mechanical strength may be achieved at 40-60% overlap. However for hermetic welding applications, 70%overlap is typically required. Overlapping increases the effective depth of penetration to a great extent and it is clearly illustrated in Figure 2. Maximum penetration also increases with overlapping, as there would be a steep rise in heat input. At large overlapping, welding speeds are very low. Weld Splashing may take place because of large overlap.

3.5 Defocusing

Defocusing of the beam on to the work piece reduces the power density. At lower power density, the depth of penetration will be trimmed down. As the area of laser interaction increases with defocusing, the width of the bead is boosted up and the chance of weld concavity becomes less. Concavity occurs because of intense heat source at concentrated area. Variation in depth of penetration with the focusing distance is shown in Figure 3.

4. Experimental Procedure

Welding experiments have been carried out on PFBR fuel tubes of thickness 450 microns and outer diameter of the tube is 6.6 mm. Pulsed Nd-YAG laser (wave length 1064 microns) spot welds were produced using laser device with fixed processing optics beam delivery [Figure 4]. Average power of the laser device employed was 500watts. The laser beam was focused by a 200mm focal length convex lens with focal plane located at work piece surface. Initial focusing of the machine was verified by stainless steel metal sheet. Focus has been fixed based on the results obtained and the plot is shown in Figure 5. Average power can be measured from the Optical Engineering power probe. Incident angle of the beam was maintained at 15 degrees to the work piece location so as to avoid any interaction of the reflected beam with the incident beam.

Initially focused beam was used for experimental welding with a nominal frequency of 10Hz. Frequency has chosen based on the average of lowest and highest possible frequencies. Because of average power limitation highest frequency that can be attained is 23Hz for pulse energy of 20 joules. Motor was attached with servo control for the rotation of the work piece.

During the Initial set of experiments, energy was varied to get the desired bead profile. Pulse peak power and pulse duration were varied keeping energy constant. Finally defocusing and frequency were altered in another set of experiments to attain desired weld bead geometry. The samples were sectioned using abrasive wheel cutter. Polished samples were etched using aquaregia with 2 parts of HCl and 1 part of $HNO_{3.}$ Microstructure of the samples was examined using Optical microscopy.

5. Results and Discussion.

Figure 6 shows the variation of penetration with respect to energy. The penetration increases linearly with energy. Penetration of 1050 microns was observed at 18 joules of energy. Below this energy limit penetration was considerably low at focus. Welding at focus was not smooth as a result there is a possibility of concavity at weld bead surface. Even though the actual depth of penetration needed was in the range of 700 to 800 microns, more penetration was chosen keeping defusing at later stages. Considering the above-mentioned data, 18 joules of energy input was chosen as pulse energy parameter.

Keeping energy constant, peak power of the pulse was varied in second stage. Pulse duration and peak power were interrelated with energy. Peak power was chosen as independent variable. The variation of peak power and pulse duration at constant energy is shown in Table 1. Weld penetration variation with peak power is schematically shown in Figure 7. Even though energy was constant, depth of penetration increased continuously from sample number 1 to 4. This plot illustrates that the effect of peak power on penetration was more than pulse duration. There was not significant variation in the penetration by increasing peak power at the expense of pulse duration. Increase in penetration because of peak power was not very large. A trace of weld spatter was noticed at 1200 watts. Beyond this power range, the effect of spatter will be severe. To be on the safe margin, the peak power was adjusted at 1000 watts. Selection of lower peak power allowed more pulse duration. More pulse duration reduces the rate of heating of the material, which minimizes any distortions during heating. Optimization of parameters was done at 18joules of pulse energy, 1000 watts of peak power, 18 m.sec of pulse duration.

Defocusing was done to increase the width at the expense of depth. Penetration is decreased with increase in defocusing [Figure 8]. Increase in defocusing resulted in reduction of power density at the surface in turn causing lesser penetration with good weld surface. Defocusing eliminated problems like spatter and concavity. Weld bead obtained was free of any sharp curvatures. Prior estimation of weld geometry was matching at a defocus of -4mm (focus inside material). Frequency was altered to decide the speed of the welding. Frequency was varied at 5Hz, 8Hz, 12Hz and 15Hz. This variation of frequency was based on welding speed and overlapping. The frequency was chosen based on some integer value of welding speed. Overlapping was maintained constant at 70%. Increase in degree of overlapping i.e. more than 0.7 would give good seam of the weld bead but increase the heat input also. Optimum results have been obtained at 70% of overlapping. Slight increase in penetration was noticed with increase in frequency [Figure 9]. This can be attributed to the heat build up. As laser-cooling rate was very high, this heat build up due to frequency was small. At a frequency of 8 Hz, smooth weld was obtained. High speed welding lead to defective welds as the cooling rate further increases. All the parameters were adjusted to get a good weld with out any sort of defects. Final weld bead depth was slightly on the lower side; in order to compensate, pulse peak power was adjusted at 1035 watts and the pulse duration is adjusted at 20 milliseconds. The final parameters chosen are as follows. Peak power of 1035 watts, 20 milliseconds of pulse duration, 70% overlap, 8Hz frequency, defocusing of –4mm. The final microstructure of the weld along with the base metal is shown in Figure 10.

Various experiments have been done to check the feasibility of the weld with tube – plug gap, tube plug fit up. Fit was varied from 10 to 70 microns. Tube – plug gap was varied from 20 to 150 microns. All the welds were accepted in radiography with the optimized parameters. Laser weld is promising in terms of consistency of results. The depth of penetration was almost same throughout the circumference. Pulsed laser welding results have been compared with the TIG welding process. Uniform penetration on either side of the end plug was obtained using LBW as shown in Figure 11. Variation in depth of penetration of opposite sides of LBW weld was minimum compared to GTAW and this can be observed in Figure 12.

6. Conclusions

Effect of different parameters for laser welding on penetration has been studied. Optimisation of parameters was done to achieve predetermined weld geometry. Optimized parameters for laser welding are, peak power of 1035 watts, Pulse duration 20 millisecond, Defocusing of 4mm and frequency of 8Hz. Consistency of results is observed in LBW compared to TIG welding. Laser welding accommodated tube plug gap of 150 microns and fit up gap up to 70 microns.

7. Acknowledgement

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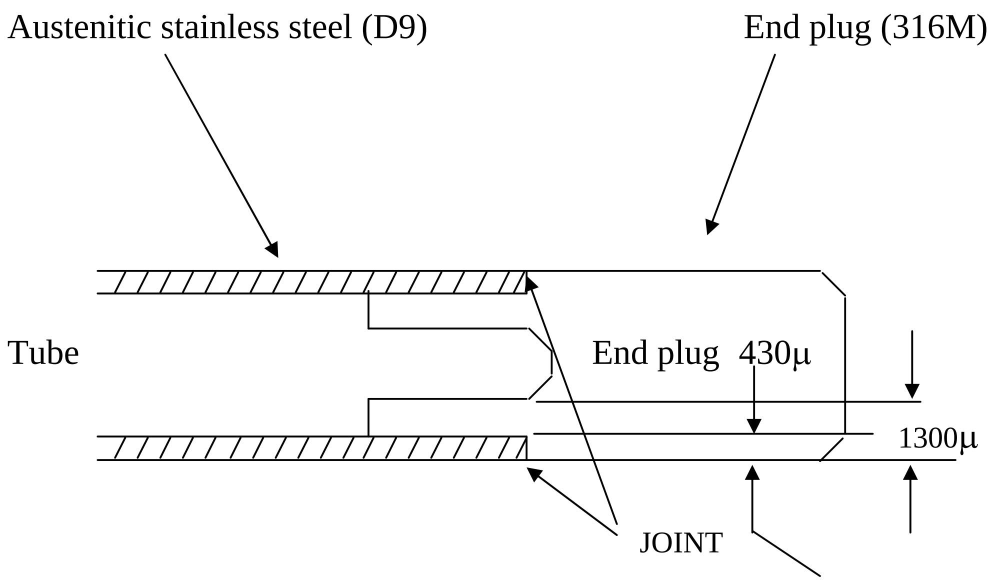
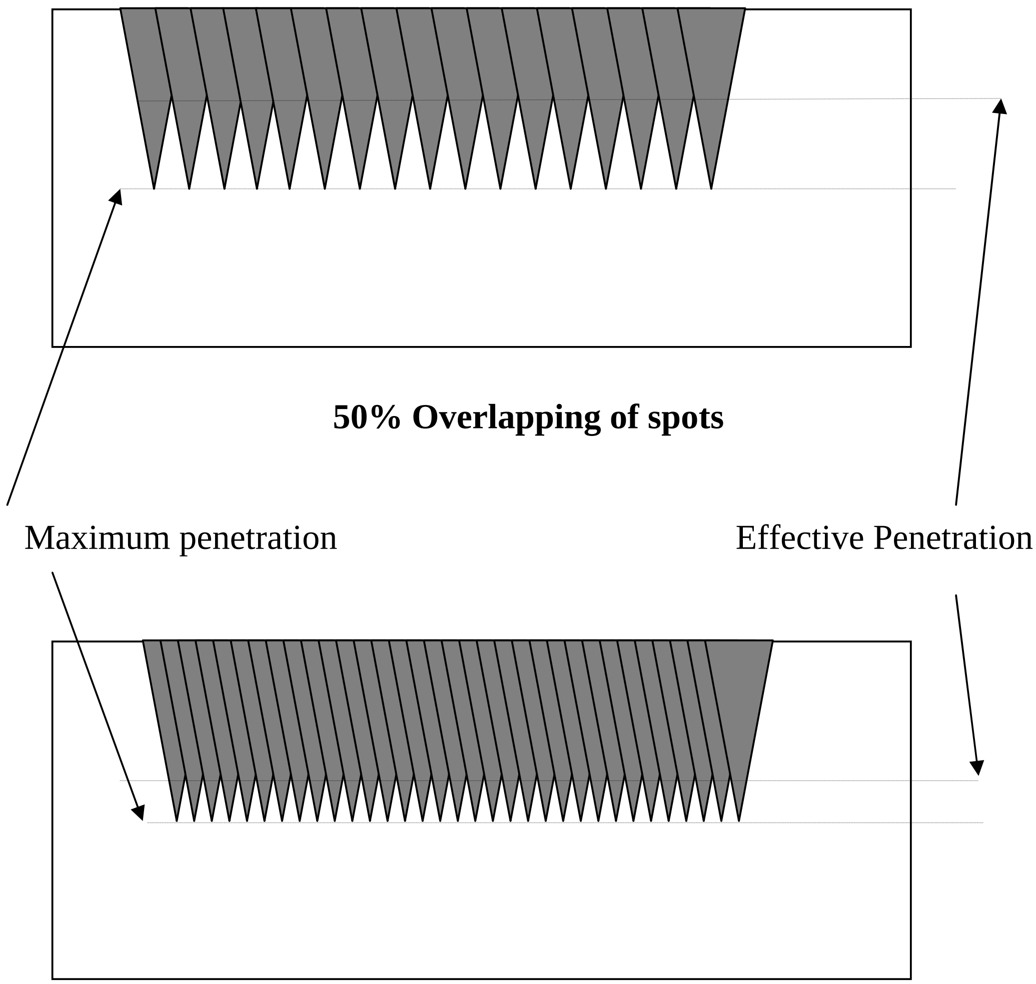


Figure 1 Weld Joint Showing Fuel tube and End plug



75% Overlapping of spots

Figure 2 Overlapping of Spots for continuous seam

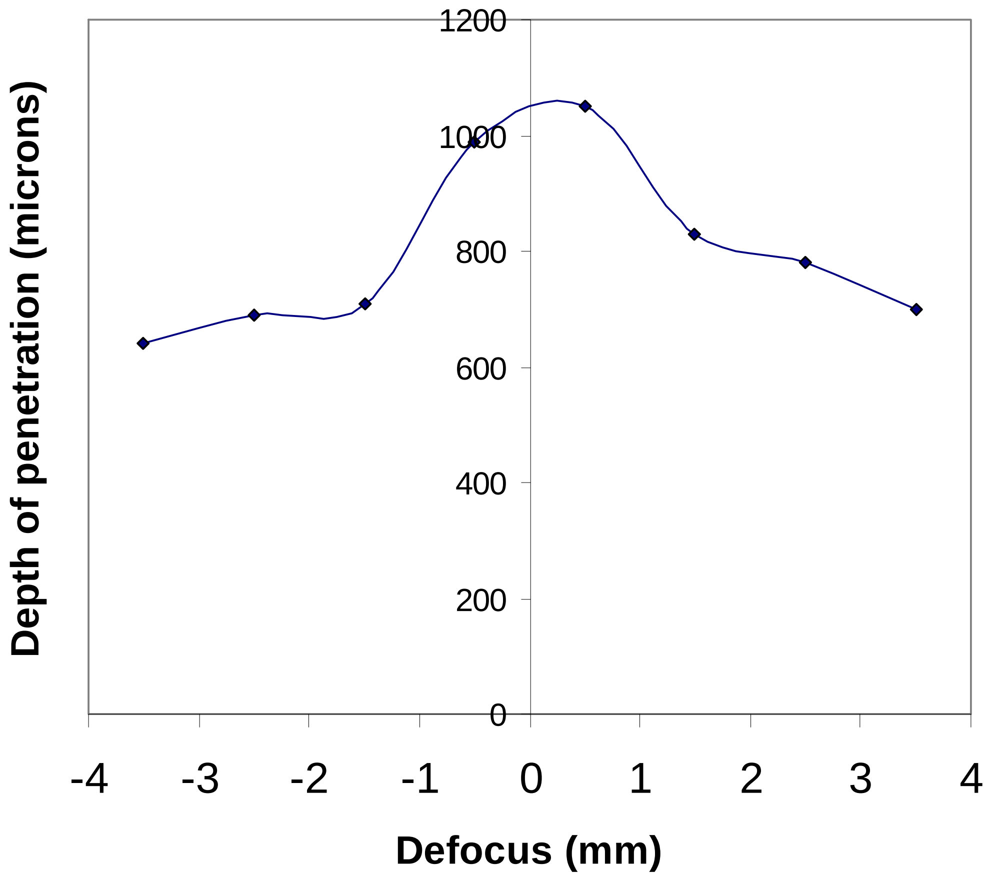


Figure 3 Defocusing Plot

Figure 4 Laser Weld setup showing processing optics and Beam delivery

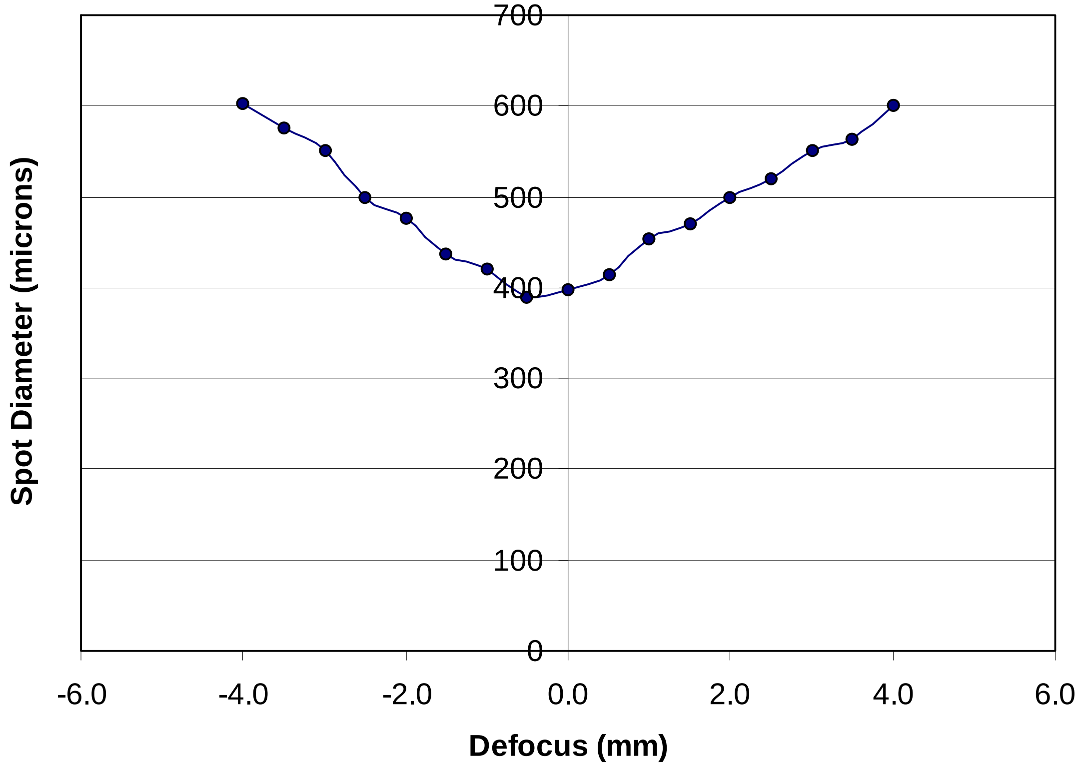


Figure 5 Spot diameter of the pulsed laser with defocusing

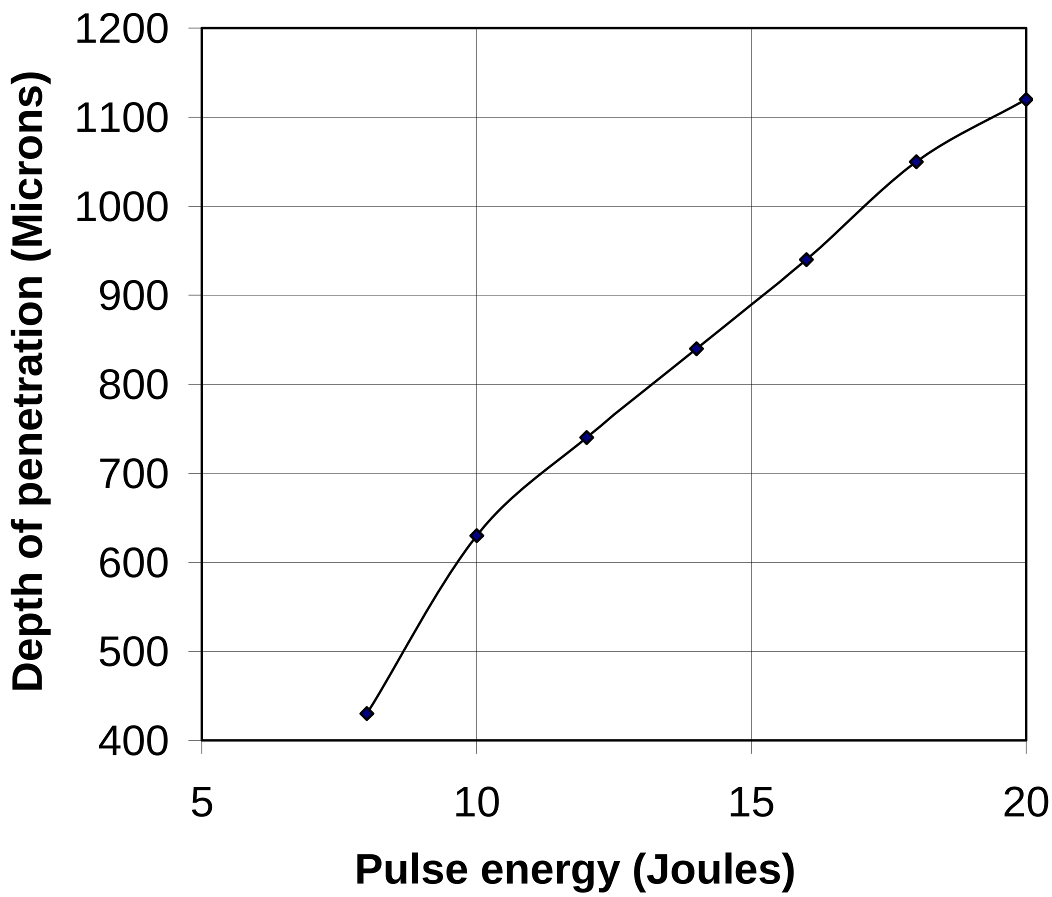


Figure 6 Effect of energy on depth of penetration

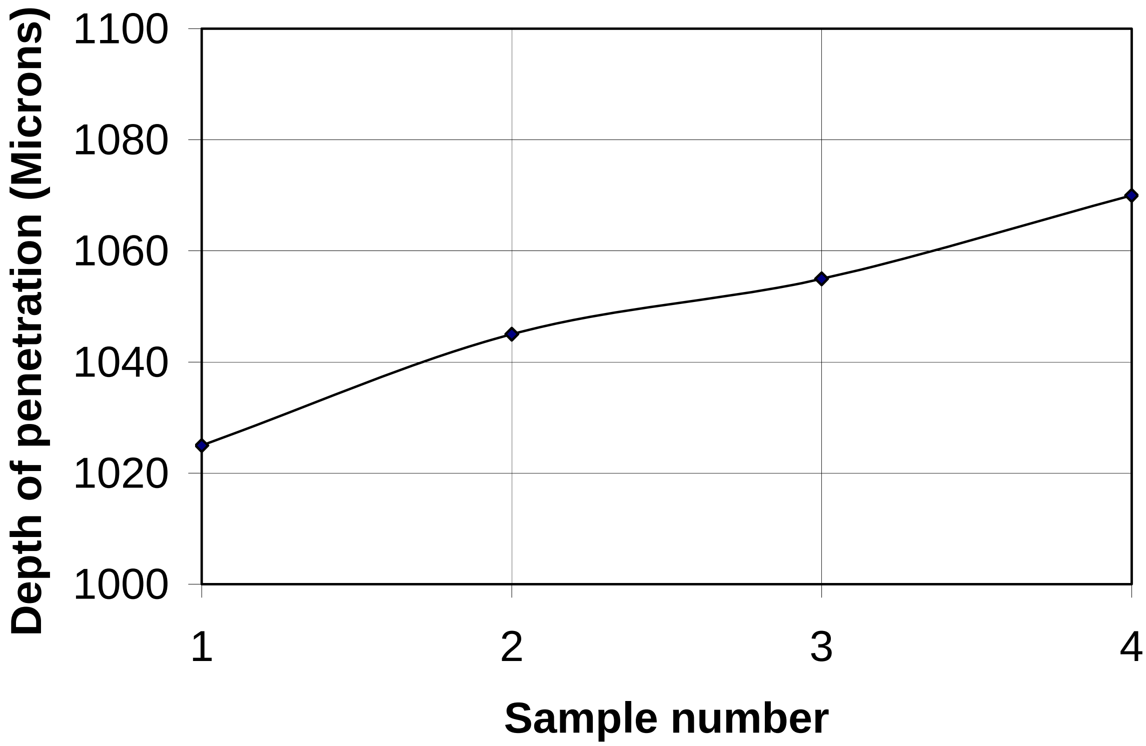


Figure7 Effect of peak power and pulse duration on depth of penetration

Table-1

Sample number	**Pulse peak power (Watts)**	**Pulse duration (m.sec)**
1	900	20
2	1000	18
3	1100	16.4
4	1200	15

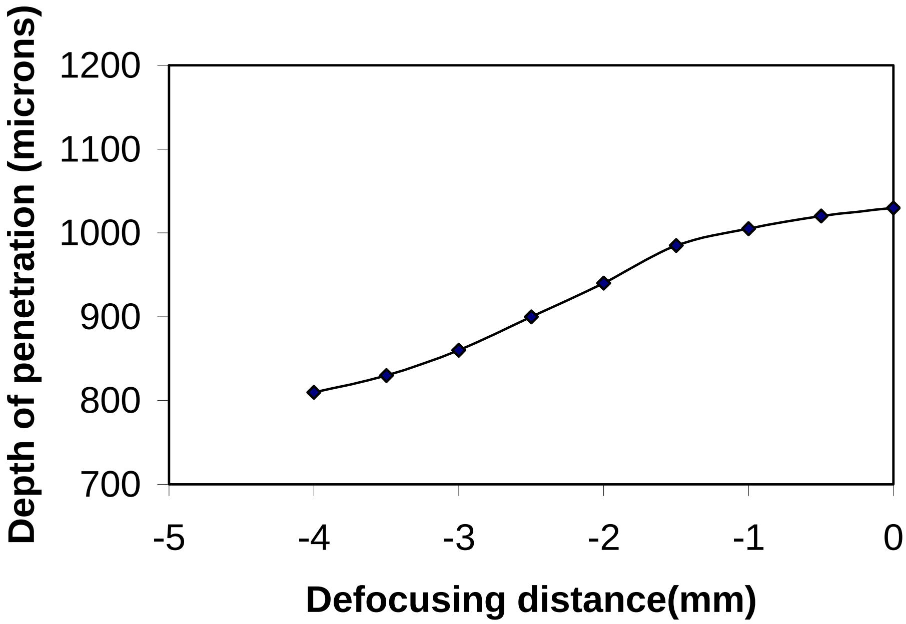


Figure 8 Effect of defocusing on weld penetration

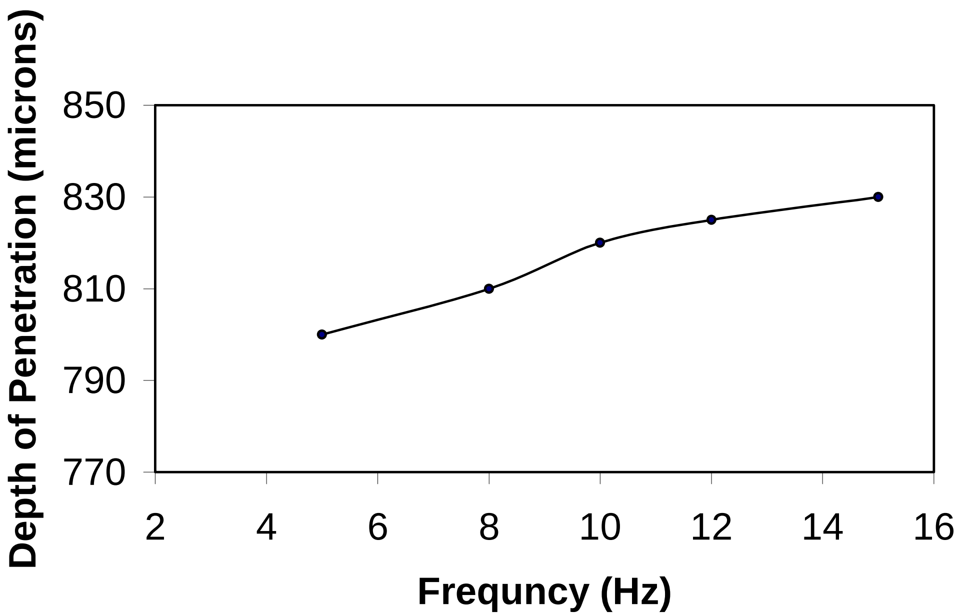


Figure 9 Effect of frequency on depth of Penetration

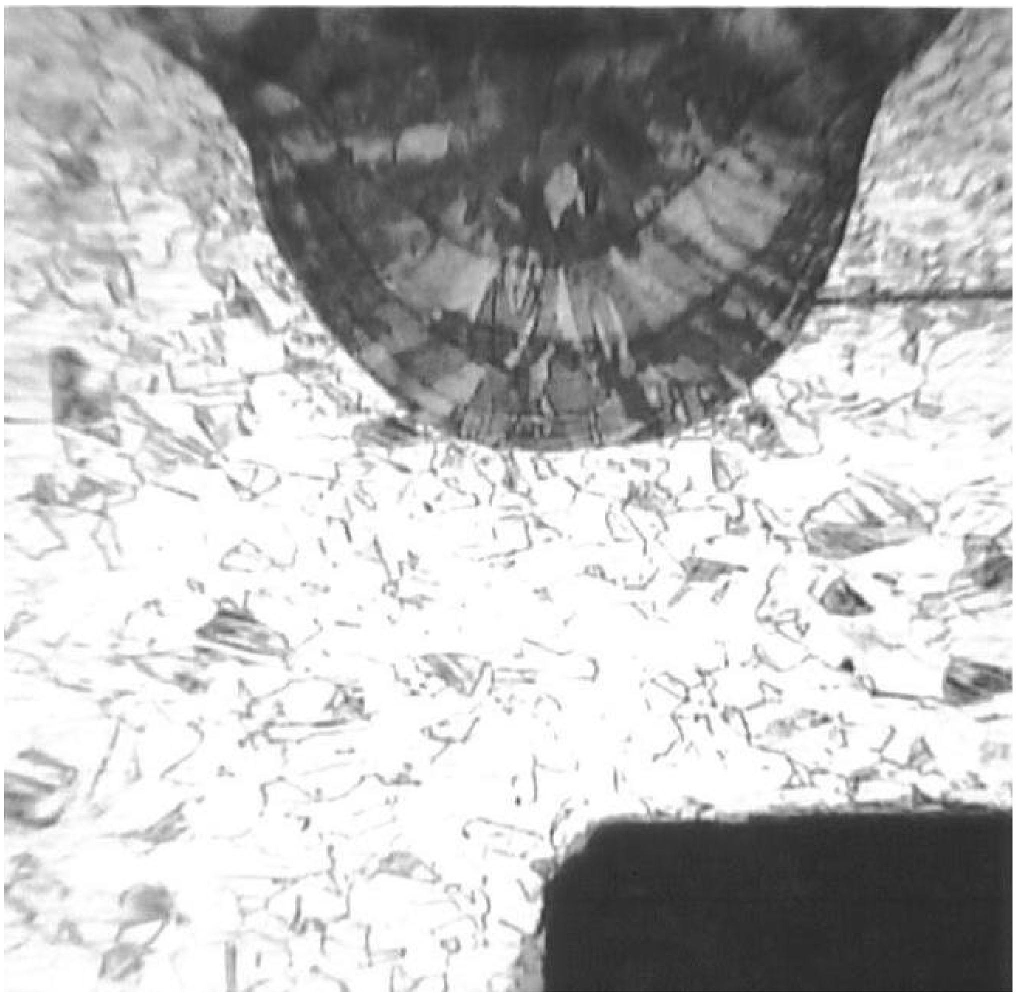


Figure10 Microstructure of the weld

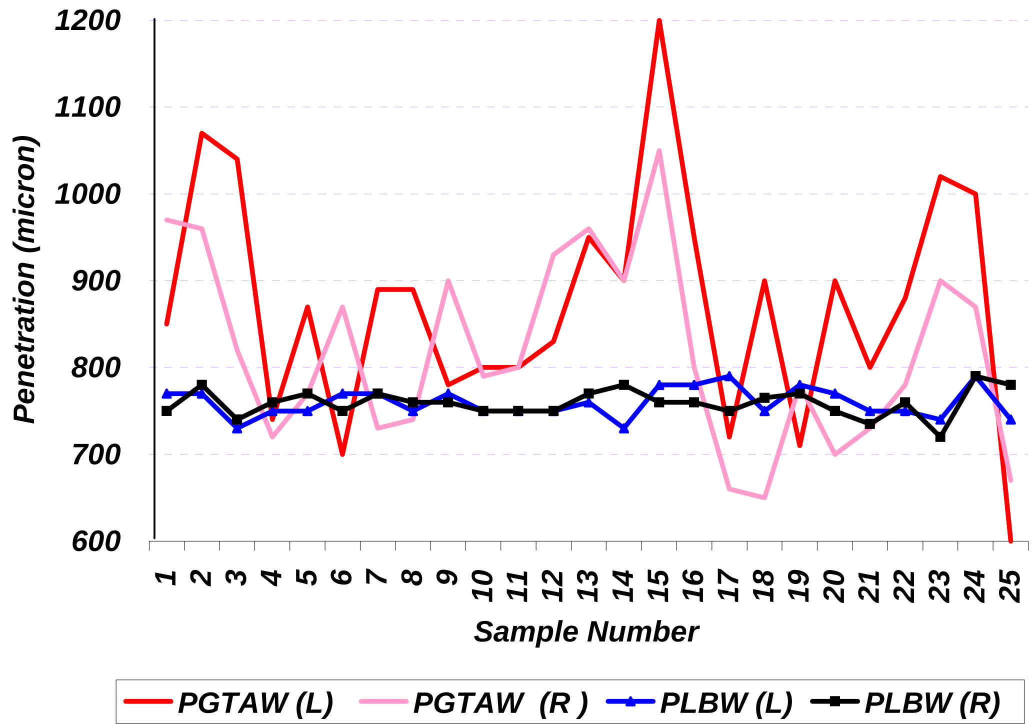


Figure11 Comparison of pulsed TIG and pulsed laser welding

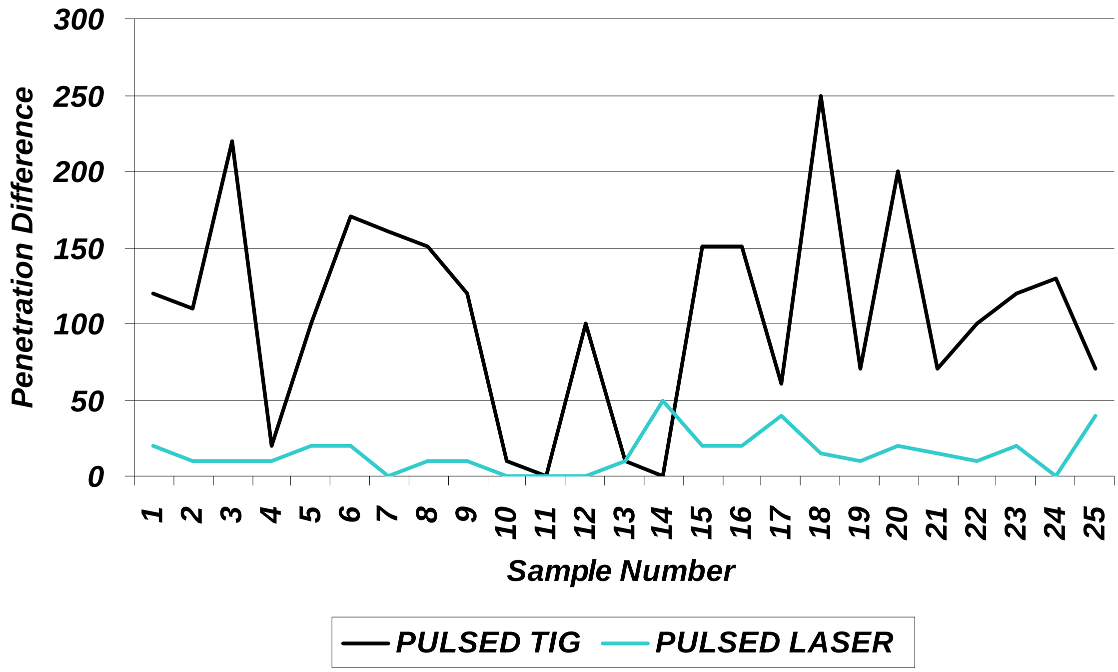


Figure12 Difference in penetration between two sides