

Penetration Welding with Lasers

Analytical study indicates that present laser beam welding capabilities may be extended tenfold

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ABSTRACT. A theory has been developed which gives a very good description of penetration welding using both electron beams and lasers. The theoretical results can be expressed as a single normalized curve which correlates all the available data.

Variations in material properties with temperature, specifically in thermal diffusivity $D (= K/\rho c)$, require average values to be used. This leads to uncertainties of order 10% in addition to those due to lack of reliable data for some materials.

Laser beam-to-metal energy transfer efficiencies are in fact quite high for penetration welds (although not for thin plates). They are around 100% at 20 kW, and about 50% at 8 kW. Electron beam-to-metal energy transfer efficiencies are in the region of 85% or more.

The theoretical melting ratio (the amount of heat needed just to melt the volume of metal in the fusion zone compared with the beam power) is no more than 48%. Laser welding can achieve figures close to theoretical, but this is not such an important criterion as power where very narrow fusion zones are involved.

Lasers at present need many times the power of an electron beam to achieve the same penetration (for steel the figures are 1000 kW/m compared with as little as 150 kW/m). However, there is no physical reason why lasers should be any worse (other than lack of experience with them). Better understanding and narrower beams could lead to improved penetration down to a credible

theoretical limit of say, 50 kW/m for steel.

Aluminum needs four times more power than steel and copper, ten times for a given weld size and speed.

Introduction

There is a great deal of interest in the possibilities of deep seam welding (up to 100 mm or more) using lasers. Conventional arc welding techniques for such welds require a great deal of weld preparation (cutting out a large groove to enable the arc torch to reach to the bottom of the seam) and a correspondingly great amount of filling with repeat passes which can take literally days on a single weld. A very effective method is to use a high voltage electron beam, but this requires a very good vacuum and present designs of electron gun give very limited life (8 hours is typical).

The use of a laser eliminates both the need for high vacuum, as with electron beams, and the extensive weld preparation and subsequent filling required for conventional welding. However, laser welding is still in its infancy. Although welds have been demonstrated in materials up to 20 mm thick or more (Ref. 1), the full range of parameters (beam power, power density, speed of travel, material characteristics, etc.) has not been explored. It is very important to know what the physical possibilities and limitations of the process are in order to judge, for example, what laser power would be required for any particular application.

Theoretical Analysis

The Basis of the Theory

The size of the pool and the temperature distribution around it are governed by heat conduction according to the diffusion equation (Ref. 2). For

normal welding with a surface pool, Christiansen et al. (Ref. 3) have studied the situation in great detail. They have compared the moving-point-source theoretical solution (Ref. 4) with a considerable range of practical and experimental data for a wide variety of materials and found very good correlation.

For deep penetration welds a point-source theoretical solution is not appropriate. The beam (electron or laser) must produce some sort of 'key-hole' through the material into which it deposits its energy. The molten pool around this keyhole will be in the form of a cylinder as shown in Fig. 1. For a good weld of uniform width the heat must be deposited more or less evenly through the material and, since surface heat losses are not usually significant, the mathematical description of heat flow in the material will be two dimensional to a good approximation. The appropriate mathematical solution is that for a line source. This solution has been studied (Ref. 5) particularly in relation to very thin plates, but it is interesting to note that the same mathematical solution applies to uniform penetration welding of thick materials.

A great deal of data is available on penetration welding with electron beams and this can be compared with the theory. A little information has been published on laser welding and that too can be compared. Predictions can also be made about the limits beyond which the laser technique could not be developed (due, for example, to fundamental limitations on spot size).

The equation to be solved is the steady state heat diffusion equation in a moving medium (ignoring the transients at the beginning and end of the process).

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$$\nabla K \nabla T = \rho c v \nabla T \quad (1)$$

where T is the temperature rise.

Dealing with Variable Thermal Characteristics

Although the density ρ is substantially constant, both the thermal conductivity K and the specific heat c may vary appreciably with temperature. The thermal conductivity may typically vary by a factor of three between ambient temperature and the melting point. However, it is possible to deal with such variations quite simply. A heat function S is defined which is more or less proportional to temperature rise but which includes the thermal conductivity, thus

$$S = \int_0^T K dT \quad (2)$$

$$= \bar{K} T \quad (3)$$

where

$$\bar{K} = (1/T) \int_0^T K dT \quad (4)$$

is the mean thermal conductivity over temperature rise T. Then

$$dS = K dT$$

and

$$K \nabla T = \nabla S \quad (5)$$

So the equation of heat conduction becomes

$$\nabla^2 S = (\rho c / K) v \nabla S \quad (6)$$

This is the same equation in S as the original one for T, equation (1), if K is constant, so no greater mathematical complexity is involved in dealing with variations of K.

The zero of T as far as heat conduction is concerned should be taken as ambient temperature. The error involved if 0 C is used instead is less than 1%. So temperatures given in deg C can be used directly. Similarly S will be given with respect to 0 C (i.e. the lower limit of integration will be 0 C).

To deal with the actual variations of the other material properties with temperature is more difficult. Variations of specific heat and even the latent heat can be included in the diffusivity

$$D = K / \rho c \quad (7)$$

General solutions are then difficult and numerical solutions must be resorted to if the variation of D is very great. However, solutions can be derived if some average value of diffusivity can be taken to apply everywhere. An appropriate average value to use is the ratio of S to H, the heat content.

The heat content H(T) can be expressed simply as

$$\begin{aligned} H(T) &= \int_0^T \rho c(T) dT \\ &= \int_0^T (\rho c / K) K dT \\ &= (1/D) \int_0^T K dT \text{ if the diffusivity} \end{aligned}$$

given by equation (4) is constant
= S/D

or

$$D = S/H = \bar{K} / \rho c \quad (8)$$

Strictly speaking this amounts to taking the average of the reciprocal diffusivity with respect to S, rather than T, a procedure which is suggested by the form of equation (3). If the variation in thermal characteristics can be taken account of by using the heat function S, together with this suitably averaged value of diffusivity D, the diffusion equation can be written

$$\nabla^2 S = 2U \nabla S \quad (9)$$

where

$$U = \frac{1}{2} v / (K / \rho c) = \frac{1}{2} v / D \quad (10)$$

is a constant.

The Line Source

The solution of (6) corresponding to a line heat source of strength q is of the form (Ref. 2)

$$S = (q/2\pi) \exp(U r \cos \phi) K_0(Ur) \quad (11)$$

K_0 is the modified Bessel function which has a logarithmic singularity at the origin. If the total power is W distributed over depth a ($q = W/a$), and defining a normalized power input per unit depth as

$$X = W/aS, \quad (12)$$

equation (11) becomes

$$X = 2\pi \exp(-Ur \cos \phi) / K_0(Ur) \quad (13)$$

The pool size and heat affected zone can be defined in terms of particular isotherms (e.g. the melting temperature) or constant values of S, and so expression (7) gives their shapes in terms of r and ϕ . For slowly moving pools or at large distances (Ur small) the isotherms are nearly circular (it can be seen that the solution is nearly independent of ϕ). For faster moving pools (or closer to the heat source) they are egg shaped (flat end near the heat source, pointed end trailing behind) and, for very fast movement of the heat source, the pool is long and narrow, see Fig. 1.

It can also be seen from equation (11) that the faster the spot movement, the smaller the pool size and width of molten or heat affected zone (for Ur to stay constant). There is however a limit imposed by the finite size

of the beam and this situation can only hold up to the speed at which the width of the molten zone becomes comparable with the actual beam size. At the other extreme of slow spot movement the pool becomes large (if Ur stays constant).

In the three dimensional case, with a surface pool, the pool reaches a conduction limited size, but, in the two dimensional case we are considering, there is no such limit. This makes the cylindrical solution qualitatively different in character from the spherical one. Any finite amount of power should, in principle, lead to an unlimited increase in static cylindrical pool size provided there are no heat losses top or bottom. Furthermore, for the surface, hemispherical pool, there is a finite amount of power required to achieve any particular penetration, however slowly the pool moves. This is not theoretically so with a penetration weld — in principle, any power level is sufficient to produce penetration melting to any depth provided the keyhole is moved slowly enough (Ur tends to 0). There may of course be practical limitations on how slowly a keyhole can move and still be stably maintained.

The Width of the Molten Zone

From the welding point of view the main interest is in the width of the molten and heat-affected zones, and the maximum penetration, corresponding to any power input. So we need to calculate the maximum width of an egg shaped pool or isotherm given by (7) and this can be done as follows. At any part of the pool the half width is

$$y = r \sin \phi \quad (14)$$

and this is a maximum when
 $O = dy/d\phi$

$$= \frac{\delta y}{\delta \phi} + \frac{\delta y}{\delta r} \cdot \frac{dr}{d\phi} \quad (15)$$

Now, on an isotherm, X is constant and so

$$O = dX/d\phi$$

$$= \frac{\delta X}{\delta \phi} + \frac{\delta X}{\delta r} \cdot \frac{dr}{d\phi} \quad (16)$$

So, eliminating $dr/d\phi$ between (15) and (16) the condition for maximum width is

$$\frac{\delta X}{\delta \phi} / \frac{\delta X}{\delta r} = \frac{\delta y}{\delta \phi} / \frac{\delta y}{\delta r} \quad (17)$$

which, using (13) and (14), reduces to

$$\cos \phi = -K_0(Ur) / K_0'(Ur) \quad (18)$$

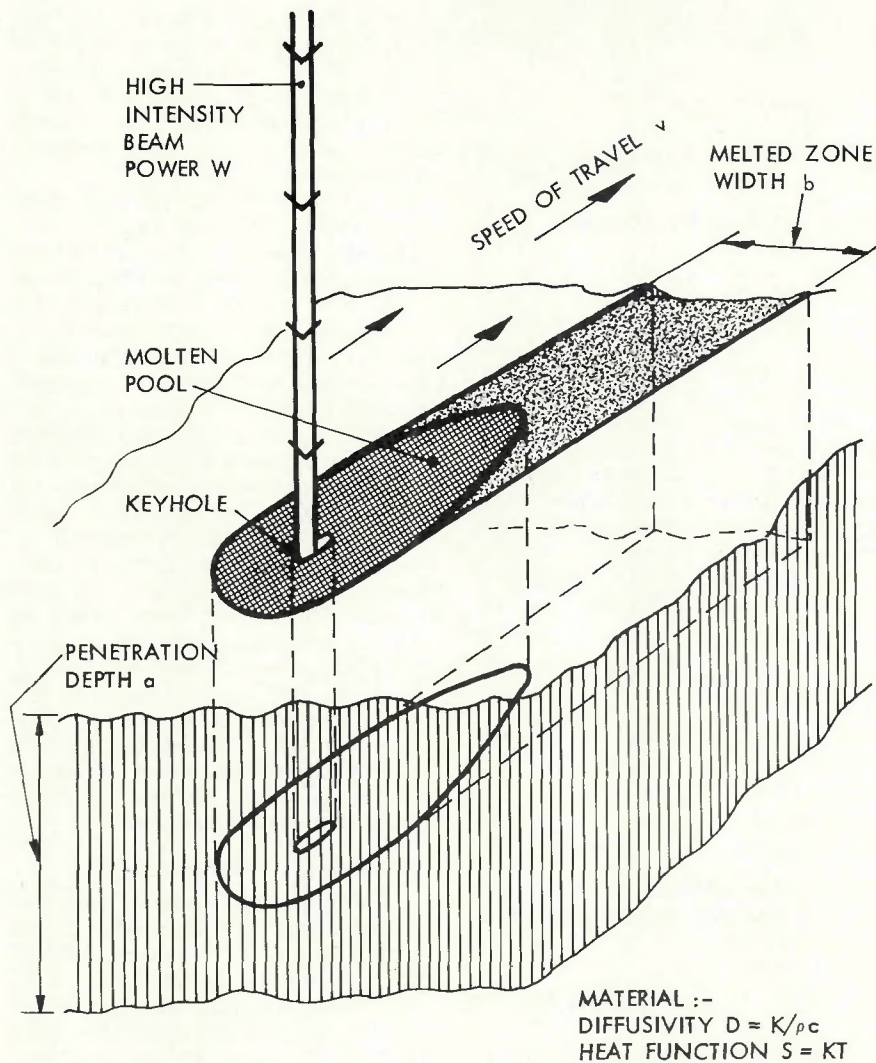


Fig. 1 — Penetration weld geometry

Then, defining a normalized melt-width as

$$Y = vb/D = 2Ub \quad (19)$$

where b is the full width $2y$ of the molten zone, equations (14) and (18) give

$$Y = 4Ur \left\{ 1 - K_0^2(Ur)/K_0'^2(Ur) \right\}^{1/2} \quad (20)$$

Also (13) and (18) give

$$X = 2\pi \exp \left\{ Ur K_0(Ur)/K_0'(Ur) \right\} / K_0(Ur) \quad (21)$$

These two expressions, (20) for normalized weld width (and velocity) and (21) for normalized power input (per unit depth of penetration), are both functions of the variable Ur which can in principle be eliminated between them. In general this will need to be done numerically but it can be done analytically in both the high and the lower power (or speed) limits.

High Speed Limit

At high speeds (large Ur) the asymptotic expansions of the modified Bessel function can be used, thus

$$K_0(Ur) \sim (\pi/2Ur)^{1/2} \exp(-Ur); \quad -K_0'/K_0' \sim 1 - (1/2Ur) \quad (22)$$

So

$$X \sim (8\pi eUr)^{1/2} \\ Y \sim 4(Ur)^{1/2}$$

and

$$Y \sim (2/\pi e)^{1/2} X \sim 0.483X \quad (23)$$

This asymptotic line is plotted in Fig. 2.

Denormalizing and using (8),

$$Habv/W = (2/e\pi)^{1/2} \approx 48\% \quad (24)$$

This represents that proportion of the input power which would be needed just to melt the metal in the molten zone. It should be noted that this limiting value is 48%. For a surface heated

pool of semicircular cross-section the corresponding figure is $1/e$ or 34%.

There is some preheating of the metal ahead of a moving heat source which tends to reduce the heat requirements there but this is more than counterbalanced by the losses from the extended sides of the pool.

Low Speed Limit

At low speeds (small Ur) approximations can be used for the modified Bessel functions, thus

$$K_0(Ur) \approx \ln(2e^{-\gamma}/Ur); \\ -K_0' \approx 1/Ur \quad (25)$$

where $\gamma = 0.577 \dots$ is Euler's constant.

So K_0/K_0' vanishes and

$$Y \approx 4Ur$$

while

$$X \approx 2\pi / \ln(2e^{-\gamma}/Ur)$$

Hence

$$6.3/X \approx \ln(4.5/Y) \quad (26)$$

or

$$Y \approx \exp(\ln 8 - \gamma - 2\pi/X) \quad (27)$$

This approximation is shown in Fig. 2.

The variation of zone width or speed of travel (vb/D) is like $\exp(-A/X)$ and this is characteristic of a physical cutoff. For small values of X , Y falls off very rapidly indeed to unrealistically small values. So, although in principle any amount of power X can be used, there is in practice a cutoff on the minimum power (or maximum penetration) that could be achieved; this corresponds to X somewhat less than unity, say $1/4$.

In principle it is possible to achieve a given penetration and welding speed with less power if a narrower molten zone or beam size is produced, but in this region a power reduction of only 20% would call for a reduction in beam area of more than 6 times, and further reductions are catastrophic.

Intermediate Range

Over the intermediate range of powers and speeds, Ur must be eliminated numerically between (11) and (12). Myers et al (Ref. 5) derived equivalent expressions in a less direct way but did not succeed in carrying out this elimination correctly. The resulting curve is plotted in Fig. 2.

This normalized curve provides a theoretical basis of comparison for uniform penetration melting and welding by electron or laser beams. For such comparisons the thermal properties of the relevant materials are required.

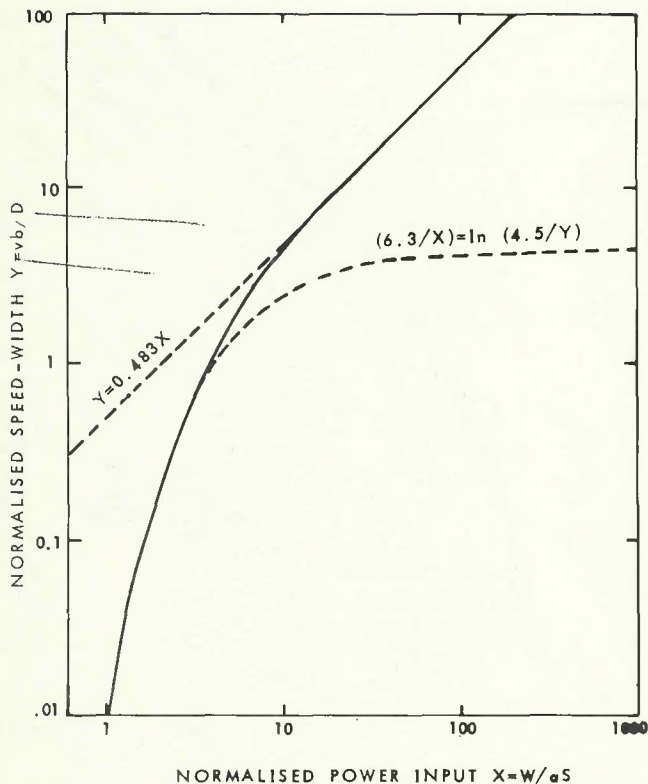


Fig. 2 — Theoretical curve for penetration welds

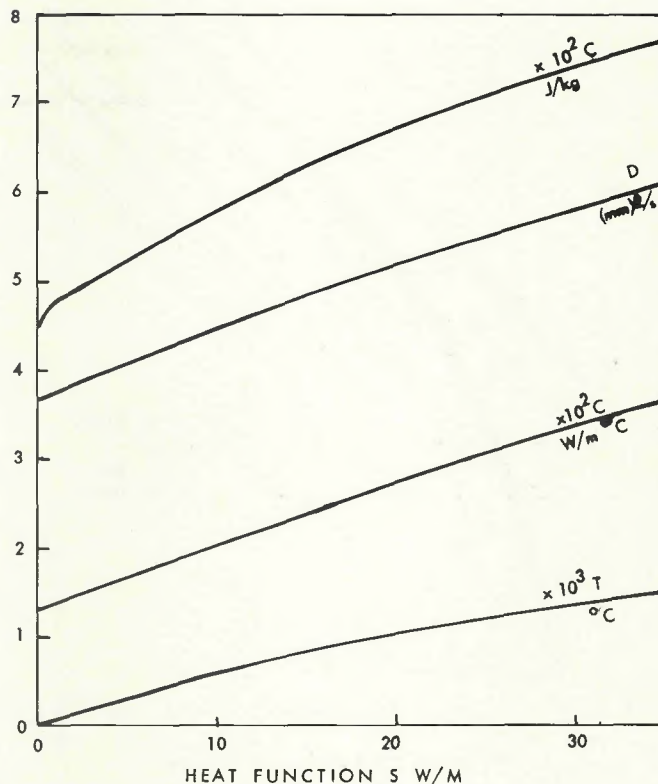


Fig. 3 — Thermal properties of a typical steel as a function of S

Thermal Properties of Materials

A great deal of published data is available on the thermal properties of materials. Significant variations occur in thermal conductivity and specific heat over the temperature range of interest, from ambient temperature to the melting point. Typical variations are shown in Fig. 3 which is derived from Goldsmith et al (Ref. 6). There are of course no significant variations in density. It can be seen that the variations in diffusivity, $K/\rho c$, with temperature are not very great and this provides the real justification for the approximation leading to equation (11).

Average values of the thermal properties of various materials up to fusion are listed in Table 1. Those not derived from Goldsmith et al have been taken from the Metals Handbook (Ref. 7).

Measurement Data

Electron Beam

A wide variety of measurements on electron beam welds is available in the literature and it will be sufficient to give a representative selection of recent results.

For HY-130 steel, Konkol et al (Ref. 8) have given an extensive series of results for bead-on-plate weldments produced with a 150 kV electron beam on a 50 mm thick plate. They covered a 10:1 range of welding speeds and an even wider range of

weld powers as listed in Table 2 and the weld characteristics which they measured (penetration and molten zone width) are also listed. The properties of this steel are similar to those of a 3½% Cr steel as listed in Table 1 and so the measurements can be approximately normalized for comparison with the theory. The results are plotted in Fig. 4.

Gunn & King (Ref. 9) carried out electron beam fusion-zone penetration studies in austenitic stainless steel meeting BSS EN58B. Unfortunately only one suitable data point for a nearly penetrating weld can be obtained from this work. With a 2.5 kW high voltage electron beam (125 kV) moving at a speed of 25 mm/s, 8.4 mm penetration was obtained with a molten-zone width of 0.6 mm. Using the appropriate thermal properties of EN58B as given in Table 1 this result can be normalized and is plotted on Fig. 4.

Using EN58J stainless steel, the Welding Institute (Refs. 10, 11) have studied the effect of electron beam voltage. Table 2 lists their measurements at 30 kV and 130 kV for molten zone in 12.5 mm thick plate. Again the results can be normalized using the data for EN58J from Table 1 and are plotted in Fig. 4.

All the published data available for laser welding relates to the fact that CO₂ lasers produce intense continuous beams of heat in the far infra-

red (at about 10.6 μm).

Little has been published on deep seam welding. Webster (Ref. 12) of Coherent Radiation Limited, California, has reported results using a ¼ kW laser on a variety of metals, but his data as listed in Table 3 are for the thin plate rather than the thick plate situation and his efficiencies are very low. These results are therefore included for comparison purposes since the theory has been previously applied to thin plates but are not otherwise very relevant to penetration melting.

The only data published to date on deep seam welding seem to be those of Locke et al (Ref. 1). They give details of deep welds made by AVCO and United Aircraft using powers up to 20 kW. All their results are for type 304 stainless steel and the various measurements are listed in Table 3. Gas assistance was used to remove the ionized cloud of metal vapor formed at the metal surface. Using the data from Table 1 to normalize, the results are plotted in Fig. 5.

Efficiency etc.

Laser Efficiency

There is some confusion over the definition of efficiency in the welding context and various efficiencies are quoted under different (and sometimes even the same) names. We shall try to standardize our terminology.

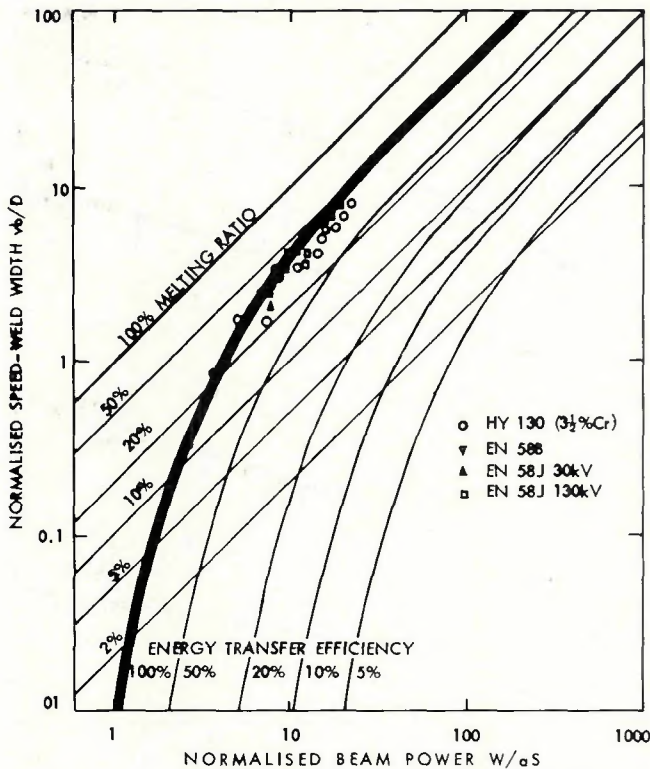


Fig. 4 — Comparison of electron beam welding measurements with theory

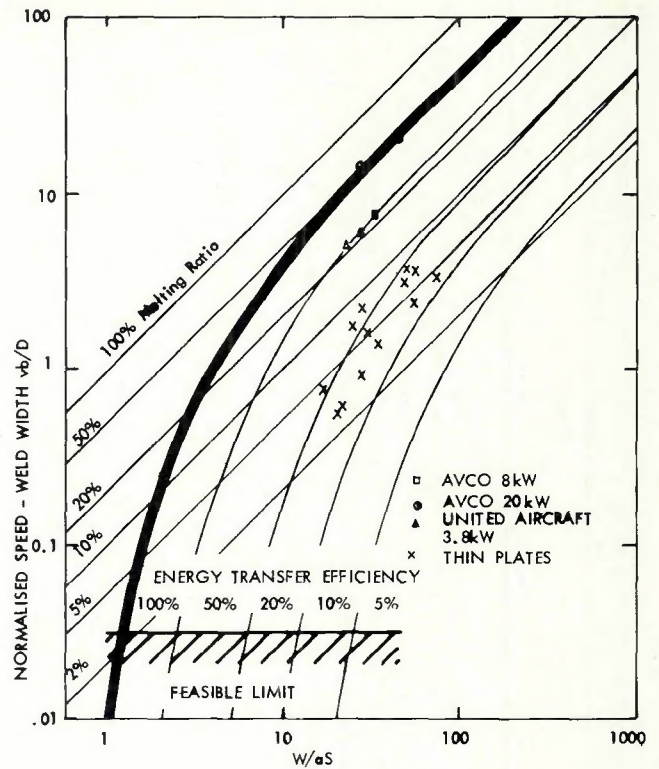


Fig. 5 — Comparison of laser welding measurements with theory

Laser efficiency (or electron beam efficiency) is the ratio of the beam power to the power taken from the supply. Typically this is around 10% for present CO₂ lasers and has a theoretical upper limit of 40%. (Other types of laser have higher theoretical efficiencies). For high voltage electron beams, practical efficiencies are very much closer to 100%.

Energy Transfer Efficiency

Energy transfer efficiency is that proportion of the beam energy which is actually transferred to the material. For electron beam this is usually very high. Although the number of secondary electrons leaving the workpiece can be as many as half of the incident number of primaries, the energies are relatively low. So only a small fraction of the beam power is lost and energy transfer efficiencies can be as high as 90% or more.

With CO₂ lasers one is concerned with absorption of infra-red photons (10.6 μm wavelength) and this is only about 5% for normal reflection at a single surface. However, in a long, narrow 'keyhole,' multiple reflections can occur which give much higher absorption *in toto* as well as spreading it along the whole length of the keyhole. Furthermore if metal is vaporized and ionized inside the keyhole, the absorption could be significantly changed. Thus energy transfer efficiencies very much in excess of 5% can be achieved with CO₂ lasers. Energy transfer efficiencies can be incorporated into Fig. 2 simply by

Table 1 — Averaged Thermal Properties of Materials

Metal	T, Melting point, C	K, Thermal conductivity W/m-C deg	S, Heat function, kW/m	ρ, Density, kg/m ³	c, Specific heat, J/kg	D, Diffusivity K/ρc (mm) ² /S
302 Steel	1530	24	36	7850	620	4.9
304 Steel	1530	24	36	7900	620	4.9
321 Steel	1530	24	36	7890	620	4.9
17-7 P.H.	1530	27	41	7430	620	5.9
EN 58B	1530	24	36	7900	550	5.5
EN 58J	1530	24	36	7950	570	5.3
BS 1501	1530	35	54	7850	590	7.3
Mild Steel	1530	24	36	7800	620	5.0
Nickel	1450	67	97	8900	600	12.5
Titanium	1680	24	40	4600	730	7.2
Monel	1340	35	47	8400	600	7.0
Inconel	1410	24	34	8250	590	5.0
3 1/2% Cr Steel	1530	35	54	7800	590	7.3

dividing them into the power. On a logarithmic scale this merely involves a shift of the whole curve in the direction of the power or X-axis and interpreting the power as that in the beam rather than that deposited in the metal.

The Melting Ratio

A quantity that can be of interest to the practical welder is the amount of heat needed just to melt the volume of metal in the fusion zone compared with the beam power. This quantity

includes the energy transfer losses, but even if the energy transfer were 100% efficient it would still involve the conduction losses and so it can never approach 100%. Using the previous notation this quantity is

$$\begin{aligned} \epsilon &= H_{vb}/W \\ &= (vb/D)/(W/Sa) \text{ by (8)} \\ &= Y/X \end{aligned} \quad (28)$$

The numerator and the denominator are just the normalized quantities which are plotted in Figs. 2, 4 and 5.

Table 2 — Electron Beam Welding Measurements

Author (Ref.)	Metal	W, Power, kW	a, Penetration mm	b, Width, mm	v, Speed, mm/s	W/a, Penetration power, kW/m	W/aS, X	vb/D, Y	ϵ Melting ratio, %	η Energy transfer, %
(8)Konkol	HY-130 (similar to 3½% Cr)	1.5	10.0	0.6	4.16	150	2.8	0.34	12	88
		7.5	40.0	1.1	4.16	190	3.5	0.63	16	80
		1.5	7.5	0.6	10.4	200	3.7	0.85	23	97
		7.5	25.0	1.1	10.4	300	5.5	1.57	29	91
		15.0	37.0	1.2	10.4	400	7.4	1.71	23	72
		1.5	5.0	0.6	20.8	300	5.5	1.71	31	97
		7.5	16.0	1.1	20.8	470	8.7	3.1	36	89
		15.0	25.5	1.2	20.8	600	11.1	3.4	31	75
		22.5	29.0	1.4	20.8	780	14.4	4.0	28	65
		1.5	4.5	0.6	31.2	330	6.6	2.6	43	103
		7.5	12.0	1.1	31.2	630	11.6	4.7	41	92
		15.0	18.0	1.2	31.2	830	15.4	5.1	33	74
		22.5	23.0	1.4	31.2	980	18.2	6.0	33	74
		1.5	3.3	0.6	41.6	450	8.3	3.4	41	100
		7.5	8.5	1.1	41.6	880	16.3	6.3	39	86
		15.0	14.0	1.2	41.6	1070	19.8	6.9	35	76
22.5	19.0	1.4	41.6	1180	21.8	8.0	37	79		
(9)Gunn	EN 58B	2.5	8.4	0.6	25.0	300	8.3	2.7	33	84
(10)Adams	EN 58J 30kV	3.6	12.5	1.92	5.7	290	8.1	2.1	26	74
		3.6	12.5	1.34	9.5	290	8.1	2.4	30	80
		3.6	12.5	1.28	10.2	290	8.1	2.5	30	83
		3.6	10.2	1.15	15.2	350	9.7	3.3	34	84
		3.6	9.8	1.06	18.8	350	9.7	3.8	39	93
		3.6	8.8	0.96	25.9	410	11.4	4.7	45	94
(11)Adams	EN 58J 130kV	5.2	12.0	0.90	21.1	430	11.9	3.6	33	73
		5.2	11.2	0.80	27.4	460	12.8	4.1	32	75
		5.2	9.9	0.84	33.7	570	15.8	5.3	34	75
		5.2	8.8	0.84	40.1	590	16.4	6.4	39	85
		5.2	7.4	0.80	46.5	700	19.4	7.0	36	75
		5.2	7.8	0.76	50.8	670	18.6	7.3	39	86

Constant ϵ curves can therefore be plotted easily; they are just straight lines of unity slope.

The quantity ϵ can conveniently be called 'the melting ratio.' Locke et al (Ref. 1) have called it 'the welding efficiency' but this has led to confusion on a number of counts. Firstly there are several different efficiencies of interest in welding (two have already been described) so their 'the' is misleading and their term too general. Furthermore 'efficiency' has been taken as implying some sort of challenge or the possibility of approaching 100%. The maximum value theoretically possible is only 48% and values very close to this have been achieved in practice. Effort spent looking for ways to achieve higher 'efficiencies' has therefore been wasted. In order to avoid further unnecessary misunderstandings the term 'melting ratio' is to be preferred.

Penetration Power

Conventional arc welding processes need to melt large volumes of metal in order to produce very thick Vee-shaped welds. The melting ratio is then an important indication of the total amount of energy required and the maximum possible melting ratio

(actually 48% or for surface welds 37%) is usually sought.

With a narrow electron or laser beam, or indeed with any other process which produces a very narrow weld with a small volume in a single pass, the total energy required for melting is small and it is much less important to achieve a high melting ratio. (When little total heat is required anyway, one can afford to waste a fair proportion of it). It is much more important to reduce the power requirement (or to achieve the greatest possible penetration for any given amount of power). An appropriate measure of this is the power per unit depth of penetration in kW/m. This (normalized with respect to S) is just what is plotted along the X-axis of Figs. 2, 4 and 5, and low values are sought.

It is clear from the curves of Figs. 4 and 5 that low values of power (for a given penetration) correspond to poor melting ratios, but nevertheless laser and electron beam designers should probably aim for minimum power requirements. The practical limitations due to beam area have already been mentioned.

Heat-Affected Zone

If the boundary of the heat-affected

zone is specified in terms of some temperature below the fusion temperature, the value of S compared with melting is changed by a fixed ratio (roughly the ratio of the two temperatures) and so all values of X are increased in the same proportion (about 75%). The normalized curve for the heat-affected zone is therefore the same shape as for the melted zone, but moved to the right. It will correspond roughly to the 50% energy-transfer-efficiency curve.

Discussion

Electron Beams

It can be seen from Fig. 4 that the theory is in good agreement with experiments. For welding conditions covering a very wide range (speed, beam power, etc., varying by orders of magnitude), all the results lie within a $\pm 20\%$ band which is, incidentally, on the right hand side (i.e. the correct side) of the theoretical curve. Much of the spread can probably be accounted for by uncertainties in the varying material properties and how they should be averaged. Several of the parameters measured will be subject to appreciable error — in particular the uniformity of the melted zone and the accuracy with which it can be specified are probably

Table 3 — Laser Welding Measurements

Author (Ref.)	Metal	W, Power, kW	a, Penetration, mm	b, Width, mm	v, Speed, mm/s	W/a, Penetration Power, kW/m	W/aS, X	vb/D, Y	ϵ Melting ratio, %	η Energy transfer, %	
(12) Webster	321	0.25	0.125	0.45	38.0	2000	56	3.5	6.2	15	
		0.25	0.250	0.70	14.8	1000	28	2.1	7.5	21	
		0.25	0.417	0.75	4.7	600	17	0.72	4.2	20	
	302	0.25	0.125	0.50	21.1	2000	56	2.2	3.9	11	
		0.25	0.203	0.50	12.7	1230	34	1.3	3.8	13	
		0.25	0.250	1.00	4.2	1000	28	0.86	3.0	13	
	17-7 PH	0.25	0.125	0.45	47.0	2000	49	3.6	7.3	19	
		Inconel	0.25	0.100	0.25	63.5	2500	74	3.2	4.3	11
	Nickel	0.25	0.250	0.45	16.9	1000	29	1.52	5.2	17	
		Monel	0.25	0.125	0.45	14.8	2000	20.6	0.53	2.6	14
	Titanium	0.25	0.250	0.62	6.4	1000	21.3	0.57	2.7	14	
		0.25	0.125	0.37	59.0	2000	50	3.0	6.0	15	
			0.25	0.250	0.55	21.1	1000	25	1.61	6.4	20
		(1) Locke	304	8	8.9	2.3	12.5	1000	28	5.9	21.0
	8			6.4	2.1	16.7	1250	35	7.2	21	44
20	20.2			3.3	21.2	990	27	14.3	53	110	
20	12.7			2.3	42.4	1570	44	19.9	45	95	

limited to, say, 10%.

Energy transfer efficiencies (beam-to-metal) appear to be around 85% and to approach 100% in many cases. Correspondingly, melting ratios approach the theoretical level of 48%.

The best utilization of electron beam power for penetration actually achieved was 150 kW/m (10 mm penetration with 1.5 kW or less than 4 kW per inch). At this level the melting ratio is falling off but it would be possible to weld 10 mm material with a relatively cheap, low power (1½ kW) electron beam equipment.

It is interesting to note from the results of Adams (Ref. 10, 11) that, for the same range of penetrations, less power is used at lower voltages (although the melted zone is wider), while higher melting ratios are achieved at higher voltages and speeds.

Lasers

The corresponding results for lasers are plotted in Fig. 5. It can be seen that all the penetration welds have high energy transfer efficiencies (laser beam-to-metal) despite the low level of absorption on a single reflection. It appears that if the beam penetrates deeply, the cavity so formed traps the radiation, as is to be expected on physical grounds. This would not of course be true for a thin plate and, indeed, it can be seen from Fig. 5 that the energy transfer efficiencies to thin plates are between 10% and 20% in practice.

The United Aircraft results at 3.8 kW had energy transfer efficiencies of about 50% but the AVCO results at 20 kW are around the 100% mark corresponding to melting ratios of

around 48% (around the maximum theoretically possible).

Although these efficiencies are comparable with electron beam ones the penetration power achieved with the laser appears to be less. More power is needed for a given depth of penetration. AVCO and United Aircraft have both achieved the same figure of 1 MV/m (about 25 kW per inch). This is about an order of magnitude worse than the best electron beam results. There appears to be no inherent reason for this (other than lack of experience). Laser beams are just as intense as electron beams and so it appears that at least a ten-to-one improvement may be quite possible with lasers enabling more modest laser powers to be used and deeper penetrations to be achieved.

This would only require the laser beam to match the performance of existing electron beams. In principle, it may be possible to produce very well focused, i.e. very high intensity beams, down to a few wavelengths diameter so that the fusion zone could be only a fraction of a millimetre wide, say 0.2 mm. The minimum credible welding speed may be taken as, say, 1 mm/s. Then with a typical diffusivity for steel of around 6(mm)²/s, the minimum value of Y is around 0.03. From Fig. 2 the corresponding minimum X is 1.2. From Fig. 3 and Table 1 a typical value of S at melting point is around 40 kW/m and so the minimum credible power for penetration is

$$W/a > 50 \text{ kW/m for steel} \quad (29)$$

or 1.3 kW per inch. The corresponding theoretical limit for copper is 580

kW/m (ten times worse) and for aluminum 210 kW/m. The figure for steel is to be compared with the 1000 kW/m actually achieved to date by AVCO and United Aircraft, and with the 150 kW/m achieved with an electron beam. Evidently there is considerable margin for improvement in technique, although the results already achieved are sufficiently interesting in themselves.

Any improvements in this direction will be brought about by improved understanding of how the laser beam can be made to penetrate the metal. The theory presented here only describes what the general characteristics of good welding will be if and when a given penetration has been achieved — it does not explain how to achieve a good weld or a given penetration. Still less does it cover any metallurgical aspects. The theory does, however, predict what laser power will be needed for any depth of penetration.

Conclusion

A relationship has been derived between the various parameters involved in penetration welding with high intensity heat sources. Comparison of this relationship with the available electron beam welding data shows excellent agreement, while comparison with laser welding data indicates that present capabilities may be extended by at least an order of magnitude. It has been pointed out that it is not necessarily desirable to achieve high energy transfer efficiencies or melting ratios, but that in most circumstances with a narrow molten zone a high penetration depth per unit power should be sought after.

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