Coupling for laser welds in aluminium alloys

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Abstract

Coupling is the energy transfer from a laser beam to the metal of a laser weld. This value was measured when making full penetration keyhole welds in five aluminium alloys using four laser systems. Alloys used were 2219, 5083, 6061, 7475 and 8090. Lasers used were pulsed and continuous Nd:YAG solid state lasers and continuous CO and CO_2 gas lasers, allowing for a range of wavelengths from 1 to 10 μm. Embedded thermocouples were used to record multiple temperature profiles for each melt run. These were compared against modelled temperatures to calculate the coupling for each weld in a particular laser/alloy combination. The coupling was found to depend strongly upon the laser wavelength. Pulsing the laser reduced the coupling. No variations could be detected between alloys.

1 Introduction

1.1 Coupling

The heat input is one of the main process parameters in welding and has been shown to affect the resulting weld microstructure, heat affected zone widths, joint properties and distortion [1-3]. It may also play a role in hot cracking [4]. Coupling is the dimensionless term used to describe the efficiency of energy transfer from a heat source to a weld. When laser welding, this parameter adjusts the source laser power to specify the heat input to the weld. Thus the coupling, η, is defined as:

$$\eta = \frac{energy\,absorbed\,by\,weld}{energy\,output\,by\,laser\,source} \qquad (1)$$

This study investigated the values of coupling obtained when making full penetration welds of optimum quality in a variety of aluminium alloys using several different laser processes.

1.2 Determination of coupling

As described above, coupling is the ratio of the heat absorption of the workpiece to the power output of a laser source. The power output from the laser is typically given by the laser apparatus and can be checked by calorimetry. The energy absorbed by the weld can be measured by three differing approaches. Some researchers have directly measured the heat input to the material by calorimetry [5, 6], others have determined the heat input using embedded thermocouples to measure thermal profiles near welds [7, 8]. Further researchers have used the weld areas as a measure of the heat absorbed [9, 10].

Previous work has shown that coupling can be constant over a range of irradiances and penetration depths. Direct measurement of heat absorption was carried out by Fuerschbach [5] who investigated coupling in the partial penetration CO_2 laser welding of thick steel, stainless steel and highly reflective tin. The study focused on the effect of process parameters upon coupling and the development of dimensionless parameters to relate weld volume to absorbed energy. A clear dependence was found between the coupling and the irradiance, with the coupling rapidly increasing to a stable value that remained constant over a range of irradiances from $3x10^4$ W mm^{-2} to $9x10^4$ W mm^{-2}.

However, over this range, penetration depth was found to vary by a factor of two. Thus penetration depth was not a good guide to coupling.

Using a different method, temperatures measured experimentally using thermocouples have been compared with temperature predictions based on an analysis of the heat flow from the weld. This approach has been used to measuring coupling in laser beam, electron beam and arc welding [8]. These analyses are based on Rosenthal's analytical solution of the temperature distribution around a moving heat source [7]. As this method allows a determination of the heat input to the weld region in thin sheets where both heat input and welding time are low, this method was chosen for this series of experiments.

The range of values of coupling found in the welding of steel have been measured, as stated above, but measurements of coupling in the keyhole laser welding of aluminium are rare [6]. The work by Mallory [11] used simple calorimetric methods to investigate the energy transfer during the CO_2 laser welding of commercially pure aluminium at power levels up to those required to form keyholes. Anodised surfaces were found to be beneficial in increasing the coupling of both conduction and keyhole welds. Values were presented for the coupling in partial penetration keyhole welds ranging from 30 to 80% for anodised surfaces and from 10 to 50% for as-rolled surfaces. Coupling was claimed to be 'a good indicator of whether a keyhole formed'.

1.3 Aims of the current study

Previous experimentally determined values of coupling ranged from 20 to 90% when laser welding steels [6] and from 10-80% when laser welding aluminium [11]. Hence this study set out to determine coupling values for keyhole laser welding of five different aluminium alloys. Four different lasers were used to study the effect on coupling of altering laser wavelength and characteristics. Since only a narrow range of welding parameters resulted in optimum welds, changes in process parameters were not investigated. In addition, Fuerschbach [5] has shown that the dependence of coupling upon process parameters is likely to be small once the optimum welding conditions have been reached.

2. Experimental procedure and results

2.1 Determining coupling

Rosenthal proposed a numerical solution for the thermal field around a moving heat source and his solution has been used since then [7, 12]. For the full penetration welds in this study, the heat source is modelled as a line through the thickness of the material. The thermal flow is considered to be entirely two-dimensional. For a given point in the workpiece at a given time, the temperature rise predicted using the Rosenthal thin plate model is:

$$T - T_0 = \frac{P/d}{2\pi\lambda} \exp\left(\frac{-\upsilon x}{2a}\right) K_o\left(\frac{\upsilon r}{2a}\right) \quad (2)$$

where:

P	=	absorbed energy (J)
d	=	sheet thickness (m)
λ	=	thermal conductivity (W m^{-1} K^{-1})
v	=	welding speed (m s^{-1})

x = distance travelled along weld (m)

a = thermal diffusivity (m s^{-2})

K_0 = modified Bessel function of the second kind and zero order

r = radial distance from weld (m)

This analytical approach ignores temperature dependent material properties or other heat losses. However, Metzbower's study of the effects of modifications to the Rosenthal approach concluded that these effects do not cause significant differences and that the simple Rosenthal equation is suitable for prediction of thermal cycles near welds [8].

The Rosenthal equation can be used to create dimensionless thermal maps around moving welds. For this study, the equation can be considered in the simple form:

$$\Delta T = (\eta P).f(x,t) \tag{3}$$

where ηP represents the energy input and $f(x,t)$ represents the remainder of the Rosenthal equation.

As the heat change at a given point near the weld is a linear function of the energy input (as shown by the Rosenthal equation), equation (1) can be described in terms of heat change:

$$\eta = \frac{real\ \Delta \mathrm{T}\ due\ to\ power\ input\ to\ weld}{Expected\ \Delta \mathrm{T}\ from\ \ power\ output\ from\ laser} \tag{4}$$

The numerator of this equation can be measured directly from the metal whereas the denominator cannot be measured directly. The latter change can be predicted or modelled for a given energy output of the laser. Thus, by comparison of a measured thermal cycle and a modelled thermal cycle, values for coupling can be determined.

Thermal profiles were predicted for the thermocouple locations in each weld for the laser/alloy combinations described in the following section. Equation (2) was modelled using Mathematica software on a UNIX workstation. In the model, the value for the absorbed power was set at the delivered laser power, values for material thickness and properties are presented in Table 1 and values for welding speed are presented in Table 2.

A moving average treatment was applied to the recorded data to reduce the effect of noise in the signal. The treatment used was a linear average of 100 data points, representing a 0.4 second period.

2.2 Measurement of thermal cycles

Thermal profiles of laser melt runs were measured using thermocouples placed in aluminium sheets. Melt runs were made on rectangular sheets (~100 x 250 mm) of five different aluminium alloys with thicknesses between 1.2 and 3.2 mm. The alloy properties are described in Table 1. Sheets were cleaned and degreased before welding. Although the thicknesses of the thin sheets varied for different alloys, full penetration welds were used throughout the study and so the heat flow could be assumed to be entirely two dimensional. Further experimental details are presented in [13].

The CO_2 laser and the continuous Nd:YAG laser had equal power outputs of 5 kW, although 6 kW power was used to weld the 2219 alloy with the CO_2 laser. For the pulsed Nd:YAG laser, square pulses were used with a frequency of 100 Hz and a duty cycle of 40%. This gave a peak power of 5 kW from an average power of 2 kW. The CO laser was run in the continuous mode.

The laser powers were measured using in-built calorimetry; delivered powers were checked against Joule stick and beam analyser measurements. Variations in power during the course of each welding session were typically no more than ±0.05 kW for the Nd:YAG and CO_2 lasers; for the CO laser, the variation was up to ±0.1 kW.

Melt runs were made close to the thermocouples and temperature profiles were recorded using up to eight chromel-alumel (K-type) thermocouples of 0.35 mm diameter wire. These were mechanically attached into holes drilled in the workpieces. Data were collected at 250 Hz using an 8-channel data logger. These data were averaged using a 100 reading moving average to give plots of the form shown in Fig. 1(a), a sample thermal profile from a weld in 6061 using a pulsed Nd:YAG laser. The high noise in the raw data is thought to be due to the proximity of the thermocouple wires to the rapidly moving plasma around the weld pool. With the exception of the pulsed Nd:YAG laser welding, the thermocouple wires were used in a twisted pair configuration to reduce noise.

2.3 Data treatment

Two methods were considered for extracting coupling values from the comparison of recorded temperature profiles with predicted temperature profiles. In the first, complete recorded temperature profiles were compared with their predicted counterparts; in the second, only the peak temperatures were compared.

Data on the positions of the eight thermocouples and on the process parameters were used in the Rosenthal equation-based analysis described above, in order to produce predicted curves for each of the eight thermocouples on each sheet of aluminium. An example is shown in Fig. 1(b) for a weld in 6061 using a pulsed Nd:YAG laser. These curves were then compared with the experimentally derived curves. At each time step, the recorded temperature was divided by the predicted temperature to give a series of coupling values.

The second method of determining a value for the coupling compared just the peak temperatures from each curve rather than complete curves. The difference in results between the two methods was not significant [13]; the peak fitting method was used to obtain the remaining coupling results presented in this study.

2.4 Values for coupling

The coupling values for welds made using four different lasers in five aluminium alloys are shown in Table 3 and the number of thermal profiles used to calculate each coupling value is presented in Table 4. The data are shown graphically by alloy and laser in Fig. 2.

3. Discussion

3.1 Wavelength dependence of coupling

The measured values for coupling show a clear dependence upon the type of laser used in the welding. The main difference between the lasers is their wavelength, although some other differences exist and are discussed later in §3.3. Many of the physical processes inherent in the energy transfer are wavelength dependent, especially the simple wavelength dependence of the adsorption of laser light on clean metal surfaces. Hence it may be expected that the energy transfer in keyhole welds will follow this behaviour. This is seen in the strong dependence of the coupling on the laser wavelength; the use of continuous Nd:YAG lasers always providing the highest coupling values. This finding is also confirmed by the higher welding speeds available with the continuous Nd:YAG laser, as compared to the equally powered CO_2 laser.

3.2 The effect of pulsing upon coupling

The difference between the high coupling given by the continuous Nd:YAG laser and the lower coupling found when using pulsed Nd:YAG laser varied with alloy from 5 to 25 percentage points but was always significant. The lasers both delivered 5 kW of power, the 2 kW pulsed laser achieving this through a 40% duty cycle. Both lasers delivered the same power density and spot size.

The difference in coupling may be due to the time taken to form the keyhole during each pulse. The surface of the aluminium is highly reflective, adsorbing only ~6% of the incident light for this wavelength [14]. Until the keyhole forms, internal reflection does not take place and the energy transfer is inefficient. As the measured values for the coupling represent are averaged over a weld run, if a portion of each laser pulse is weakly absorbed, the overall coupling will be lowered as was observed experimentally.

Simon *et* al suggest that for pulsed Nd:YAG laser welding, keyholes can take of the order of 1 ms to form [15]. Thus for the 4 ms duration pulses used in the current work, the system may spend 25% of its time in a state of very low coupling, before a keyhole forms. Energy would be lost in this period. As the measured coupling in the pulsed laser welds was between 10 and 40% lower than that for the continuous welds, where the keyhole is maintained, this would support the suggestion that the time taken in each pulse to reform the keyhole accounts for the lower coupling in pulsed Nd:YAG welding.

3.3 Other effects upon coupling

The current work set out to study the dependence of coupling upon both laser and material properties. While the coupling showed a strong dependence upon laser wavelength, the dependence upon alloy properties was not so striking.

The clearest alloy effects are seen in the 7475 material, where the coupling is consistently the lowest of the five alloys, for all four lasers. This material was coated on both sides with thin layers of pure aluminium to prevent corrosion and this resulted in the material being visibly more reflective of light than other materials in this work. Surface modification has been shown to be able to greatly modify coupling in the laser welding of aluminium, for both conduction and keyhole welds [11]. Thus the low coupling in the 7475 material may have been due to the higher surface reflectivity of the pure aluminium surface.

However, the 7475 alloy was also the thinnest sheet (1.2 mm) included in the study. For the thickest material (3.2 mm for the 2219), the coupling was significantly higher than for the other materials for two of the laser types. This suggests that thickness of material is a factor in coupling. For the full penetration welds in this study, light will travel along the length of the keyhole and pass out the hole in the lower surface of the sheet, to be lost. The adsorption in this process will depend upon the length of the keyhole, as the keyhole is full of partially opaque plasma. It may also depend upon geometric considerations of the behaviour of the laser beam within the keyhole [16].

The thicknesses of the 5083, 6061 and 8090 materials were similar, between 1.5 and 2.0 mm; coupling values for these materials showed no clear trends other than the dependence upon laser wavelength. The 8090 material contained the easily vaporisable element lithium and can be welded at low heat inputs [17]. The clear presence of lithium in the plasma did not alter the coupling. This result suggests that the ease of laser welding of the 8090 alloy is due solely to its low thermal conductivity (0.0935 W mm^{-1} K^{-1} for 8090 [18] compared with 0.167 for 6061 [19]). This reduces energy losses by conduction, so that the evaporation required to form the keyhole and plasma occurs at lower power densities than in other alloys.

4 Conclusions

Coupling values for laser welding of several aluminium alloys by several laser sources have been successfully measured. The coupling was typically between 20 and 45 % depending upon laser and material parameters. The technique chosen allowed values to be obtained with reasonable accuracy, typically ±1-3 percentage points of the coupling value.

The coupling values obtained were clearly dependent upon the wavelength of the laser used for welding, with the shorter wavelength Nd:YAG lasers having the highest absorption.

The dependence of coupling upon alloy composition was small and certainly less than the dependence of coupling upon the sheet thickness. The similar values obtained for the coupling in the 8090 and 6061 alloys suggest that the ease of laser welding of the 8090 alloy is due to its low thermal conductivity, rather than because the high vaporisation rate and ease of ionisation of the lithium in 8090. It was possible that the coupling was altered by surface modification, as shown by the pure aluminium coating on the 7475 material.

The effect of other process parameters could also be determined. Pulsing the laser reduced coupling as the keyhole had to be reformed for each pulse. Similar reductions were found for melting efficiencies, energy was wasted as material was remelted [13].

Using the obtained values for the coupling, melting efficiencies could be determined and the overall process efficiency could be assessed. It was seen that many of the welds were carried out at close to the lowest possible heat inputs, limiting metallurgical damage and maximising processing speed. However, for some laser/material combinations, the low melting efficiencies suggest that welding speeds could be increased [13].

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Table 1 - Materials Parameters

Alloy	2219	5083	6061	7475	8090
Thermal conductivity ($W\ mm^{-1}\ K^{-1}$)	0.130	0.120	0.167	0.155	0.094
Thermal diffusivity ($mm^2\ s^{-1}$)	52.9	50.1	69.0	64.0	39.4
Density ($g\ mm^{-3}$)	0.00284	0.00266	0.0027	0.00280	0.00255
Specific heat ($J\ g^{-1}\ K^{-1}$)	0.864	0.900	0.896	0.864	0.93
Sheet thickness (mm)	3.17	1.94	1.52	1.19	1.65

Table 2 - Welding speeds in m min^{-1}

Laser Source	2219	5083	6061	7475	8090
Nd:YAG Pulsed	0.75	2.5	2.5		2.75
Nd:YAG Continuous	7.0	11	10	16	14
CO	0.4	1.75	1.25	4.0	3.5
CO_2	4.0	6.0	6.0	11	

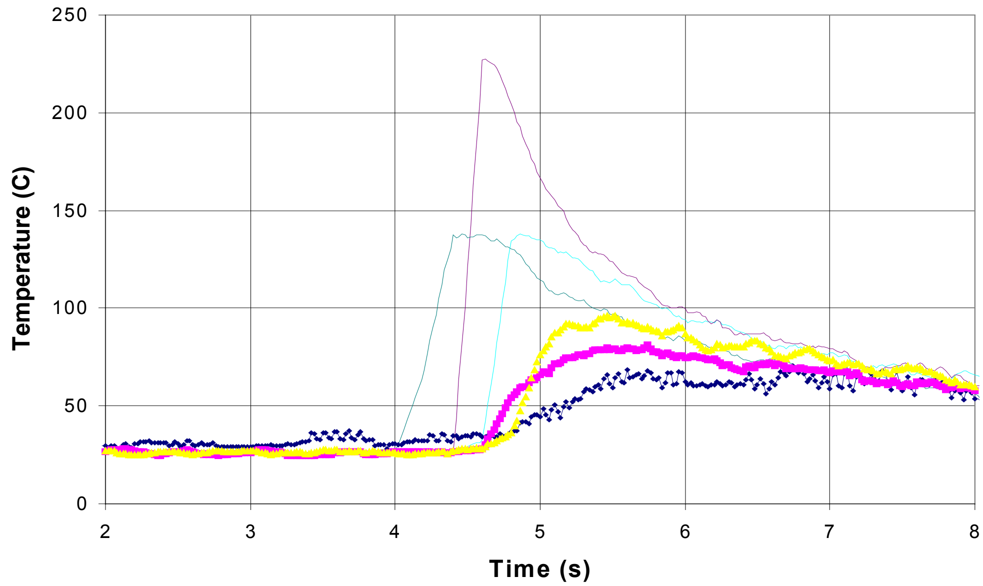
Table 3 - Calculated coupling values with 95% confidence limits

Laser Source	2219	5083	6061	7475	8090
Nd:YAG Pulsed	44 ±1.3	33 ±1.8	38 ±1.3		35 ±0.8
Nd:YAG Continuous	63 ±3.4	40*	46*	31 ±2.4	45*
CO	42 ±3.5	30 ±7.9	21 ±2.4	19 ±2.3	28 ±3.5
CO_2	22 ±0.6	20 ±1.2	19 ±3.3	18 ±2.6	

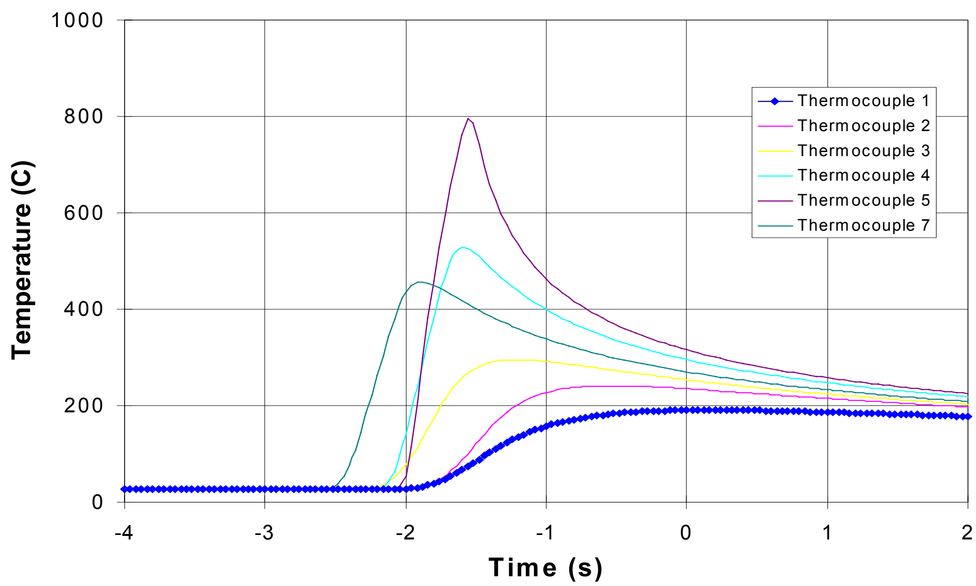
Table 4 - Number of readings for the calculated coupling values in Table 4

Laser Source	2219	5083	6061	7475	8090
Nd:YAG Pulsed	24	28	24		14
Nd:YAG Continuous	16	7*	24*	24	24*
CO	5	15	23	18	17
CO2	6	15	12	15	

* The data for these three laser/alloy pairings showed an anomalous temperature dependence, as described in [12]. Hence no qualitative confidence limits are given for these values as they were determined by linear extrapolation. However, from the curve fits, a value of ±5% would seem reasonable.



a)



b)

Figure 1

a) Experimental thermocouple data treated with a 100 reading moving. Data points collected every 0.04 seconds.

b) Cooling curves predicted using the Rosenthal equation, for six thermocouples in equivalent positions to those used experimentally near a pulsed Nd:YAG laser weld.

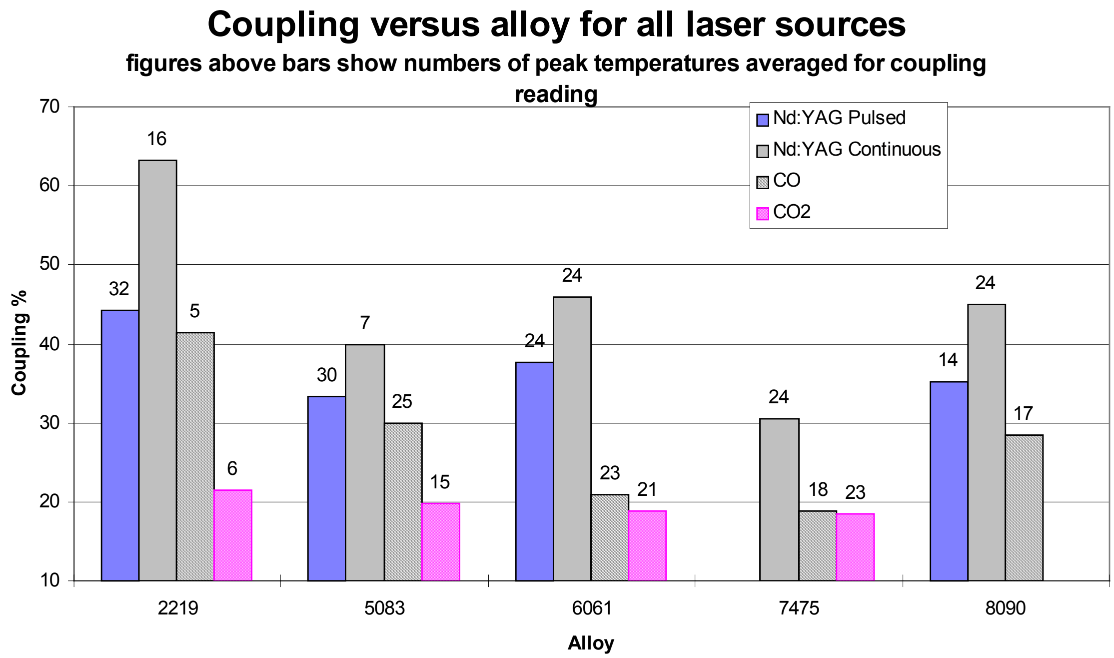


Figure 2

Average coupling values presented for each alloy