Laser Spot Welding and Efficiency Consideration

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Laser spot welding is beneficial when welding small and/or electrical components where a small heat-affected zone is required. The modeling of heat transfer analysis carried out until now omits thermal efficiency analysis of the process involved. This may become important when optimization and cost effectiveness of the welding process is concerned. Consequently, the present study was conducted to develop expressions relevant to the welding efficiencies based on the first and second laws of thermodynamics. The study is extended to include an experimental investigation into the welding process to relate the first- and second-law efficiencies with mechanical properties of the resulting welds.

Keywords efficiency analysis, laser spot welding

1. Introduction

Laser spot welding is a versatile tool for welding small components. It is particularly useful in cases where localized heating is desired. These instances include welding glass to metals, interconnections of leads in dedicated heat-sensitive semiconductor circuitry, dissimilar metals for electrical connections, and so forth. In such cases, laser spot welding can be competitive with conventional techniques such as resistance welding. When spot welding is required, a single laser pulse may be suitable, provided that good metallurgical joints with small heat-affected zones are produced after the welding process.

Two types of spot welding are common: conduction and penetration. The conduction mode involves power intensities sufficiently low to cause melting, but not high enough to vaporize the metal. Consequently, penetration is limited to about one-half of the top surface weld diameter. As a result, conduction laser spot welding is well suited to weld materials less than 0.5 mm thick. At high laser power intensities vaporization occurs, and the vapor pressure and surface tension flow promote formation of a cavity within the weld pool. This condition requires a penetration weld. Ideally, the laser welding process can be optimized around some specific measurable characteristics. Objective characteristics such as penetration, weld strength (tensile or shear), or leak rate (for hermeticity) are desirable quantities for optimization because the mean and standard deviation for a sample can be determined easily. However, subjective characteristics such as weld shape or cosmetic quality are difficult to optimize in conjunction with measurable characteristics. A weld spot diameter is a good indication of the laser pulse parameters used. In some instances, the optical system may produce large spot sizes, which require peak power intensity out of the normal operating range of the laser. This typically occurs with a large focal length lens where there is insufficient melting, even at the highest-rated peak power (Ref 1). One significant investigation of laser spot welding involved the use of a neodymium:yttrium-aluminum-garnet (Nd:YAG) laser to weld electrical wires to metal sheets (Ref 2). This study showed that pulsed Nd:YAG lasers could be used effectively in welding electrical components.

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Surface deformation resulting from laser spot welding was investigated by Segalman and Krieg (Ref 3). They modeled the welding process including room-temperature mechanical properties of the weld joint to study the isotropic kinematic/plastic behavior of the resulting welds. They concluded that the plastic deformation occurred during the heating due to thermally induced residual stresses. The spot welding of aluminum sheets with YAG laser was investigated by Watanabe and Yoshida (Ref 4). They simulated the heat transfer process and developed an empirical formula for weld strength. On the other hand, weld quality in pulsed Nd:YAG laser welds was investigated by Bransch et al. (Ref 5). In assessing the weld quality, they developed a split-specimen technique, which enabled evaluation of the weld quality accurately and faster than traditional metallurgical techniques involving sectioning, polishing, and etching. However, more comprehensive work on laser spot welding was carried out by Yilbas et al. (Ref 6). They showed that the weld strength increased considerably when using an inert gas in the welding ambient, and controlling the surface evaporation improved the weld strength.

To date, thermal analyses carried out for laser welding have addressed the temperature and thermally induced stress fields, but have ignored the thermal efficiency analysis of the welding processes (Ref 3, 6). Therefore, efficiency analysis of the welding process can be beneficial in minimizing laser energy and reducing cost in the welding process. Consequently, the present analysis was conducted to predict the thermal efficiency of the laser spot welding of sheet metals; that is, first- and second-law thermodynamic efficiencies were conducted. The study was extended to include an experimental investigation into laser spot welding of aluminum, nickel, and steel sheets at different thicknesses. To achieve this, an Nd:YAG laser was used. Tensile testing of the resulting welds was carried out to correlate the thermal efficiencies with the tensile properties of the resulting welds.

2. Experimental

The experimental apparatus is shown in Fig. 1. An Nd:YAG laser of output energy in the range of 10 to 21 J with a nominal pulse length of 1.48 ms giving output power intensity of the order of 100 GW/m^2 was used to irradiate the workpieces. An energy power meter was used to measure the instantaneous laser output power and energy. A nominal focal length of 51 mm focusing lens was used to focus the laser beam.

Austenitic type 302 steel, aluminum 1100, and nickel 200 sheets of different thicknesses were used as workpieces. Table 1 gives the laser and workpiece parameters. The samples were cut in size so that they could be easily mounted on the tensile testing machine. All the workpieces were cleaned ultrasonically before the melting process. To examine the fusion depth and heat-affected zone, the workpieces were mounted and ground down to a welding diameter. Microphotography of the resulting weld cross sections was carried out using an optical microscope. Tensile testing was carried out for the resulting welds. Figure 2 shows the direction of tensile forces in the tests.

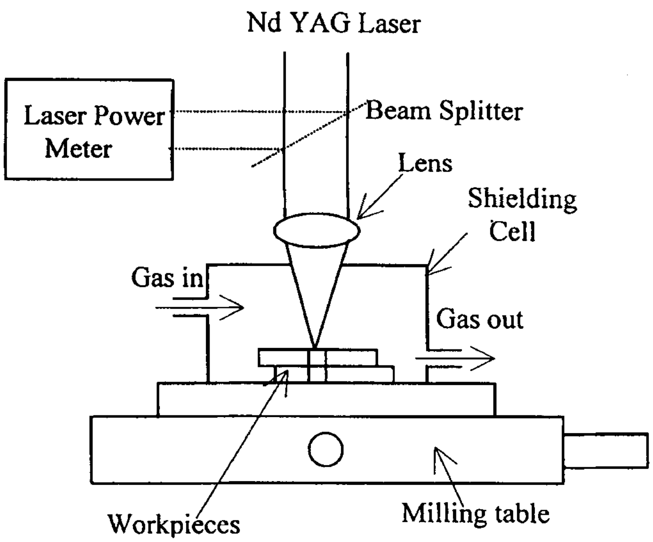

Fig. 1 Experimental apparatus

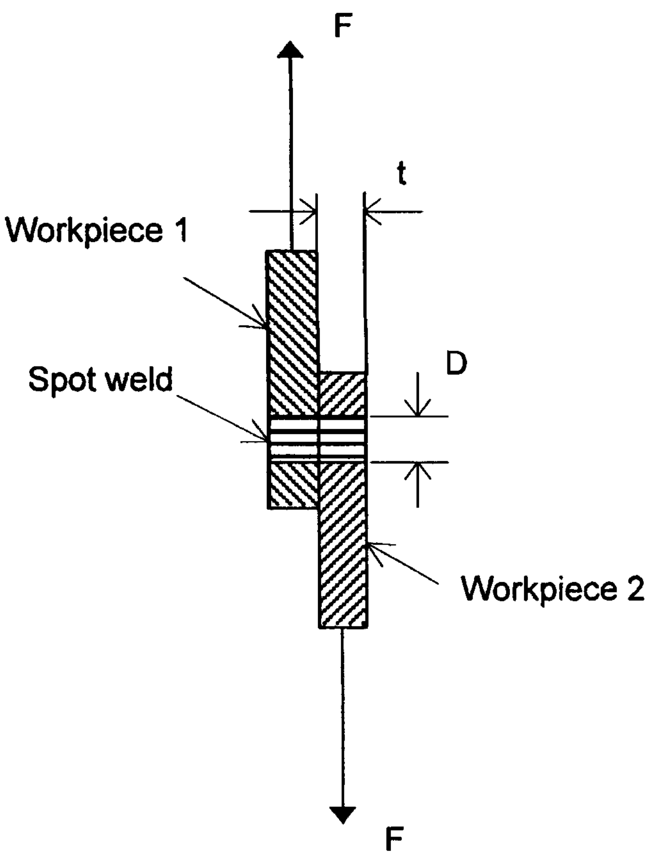

Fig. 2 Cross-sectional view of a spot weld and tensile forces acting on the workpieces

3. First-Law Efficiency

Cross-sectional view of a spot weld is shown in Fig. 2 (each workpiece thickness is t and spot diameter is D). The energy required to melt the first material at the top is:

$$E_1 = m_1 \left[\int_{T_0}^{T_m} (C_p)_1 \, dt + L_m \right] \quad \text{(Eq 1)}$$

where m_1 is the mass of spot weld, which is $m_1 = (\pi D^2/4) \cdot t \cdot \rho$.

The empirical formula for heat capacity at constant pressure for each material is given by Lynch (Ref 7) as:

$$C_p = a + (b \times 10^{-3})T + (c \times 10^{-6})T^2 + (d \times 10^5)/T^2 \quad \text{(Eq 2)}$$

The coefficients a, b, c, d and some thermodynamic properties of the materials used are given in Table 2. The melting temperature T_m, the reference temperature T_0, and the heat of transition L_m are also given by Lynch (Ref 7). Similar equations can be written for material 2 as written for material 1. Then, the first-law efficiency can be defined as:

$$\eta = \frac{E_1 + E_2}{E_0} \quad \text{(Eq 3)}$$

where E_0 is the energy provided by the laser beam to the workpieces.

Table 1 The levels of workpiece thickness and laser output energy

Levels	1	2	3	4
Thickness, mm	0.3	0.5	0.8	1
Laser output energy, J	13	15	17	20

Table 2 Some thermodynamic properties of the materials used

	Melting point, K	Specific heat capacity, (J/kg · K)	Density, kg/m³	*a*	*b*	*c*	*d*
Aluminum	932	38	2710	4.94	2.96	...	...
Nickel	1726	460	8900	4.06	7.04	...	...
Steel	1800	510	7930	10.3	...	...	...

4. Second-Law Efficiency

Using a similar approach carried out for the first-law efficiency, available energy used during spot welding of material 1 can be determined as:

$$(E_1)_{\text{available}} = m_1 \left[\int_{T_0}^{T_m} (C_p)_1 \, dT + L_m - T_0 \left(\int_{T_0}^{T_m} \frac{(C_p)_1}{T} dT + S_m \right) \right] \quad \text{(Eq 4)}$$

where S_m is the transition entropy given by Lynch (Ref 7). Similarly for material 2, $(E_1)_{\text{available}}$ may be replaced with $(E_2)_{\text{available}}$. The second-law efficiency may be written as:

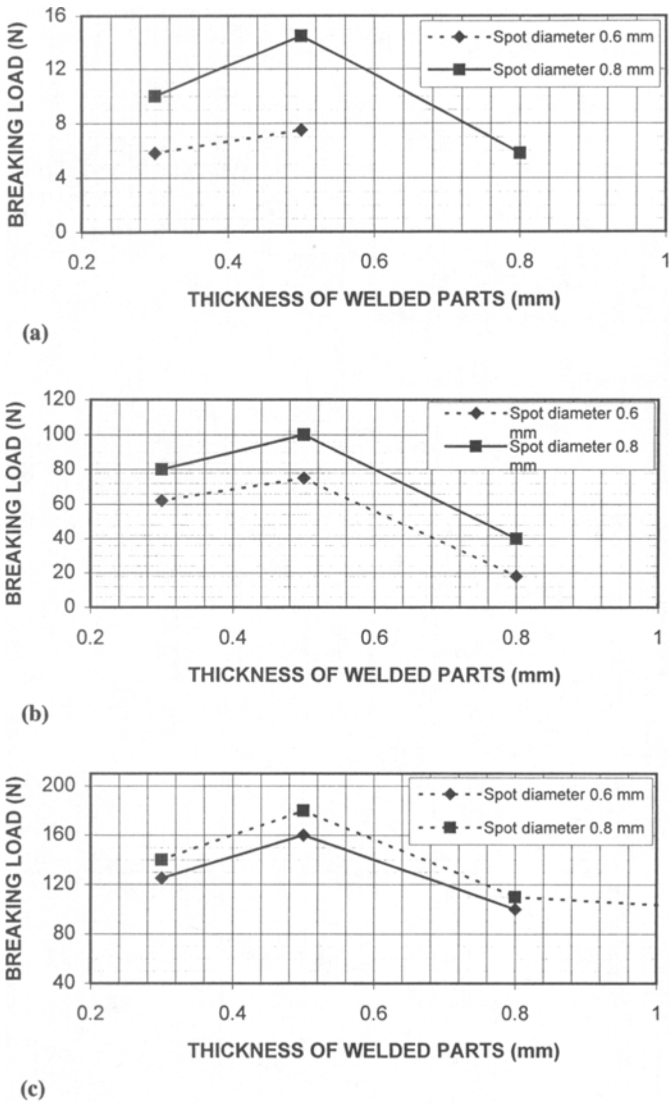

Fig. 3 Breaking loads of the spot welds with thickness for various spot diameters. (a) Aluminum, (b) nickel, and (c) steel workpieces

$$\eta_{II} = \frac{(E_1)_{\text{available}} + (E_2)_{\text{available}}}{E_0} \quad \text{(Eq 5)}$$

where E_0 is the laser energy and is considered to be available energy.

5. Results and Discussion

Figure 3 shows the tensile test results for welds obtained for aluminum, nickel, and steel workpieces at different thicknesses. The breaking load decreases at the upper end of the thickness. This effect is significant in the cases of nickel and steel. It should be noted that nickel and steel have higher thermal diffusivity than aluminum; consequently, small surface plasma may develop, which in turn improves the bonding in the weld zone. In this case, the surface plasma acts as a heat source enhancing the mass removal rate and allowing more laser energy to penetrate the material (Ref 8). On the other hand, when the size of the surface plasma increases, it absorbs the incident laser beam and reduces the laser energy reaching the workpiece. This may be the case occurring for thick samples, because it was reported that the recoil pressure at the interaction zone increases for thicker materials, which in turn increases the mass removal rate from the workpiece material (Ref 9).

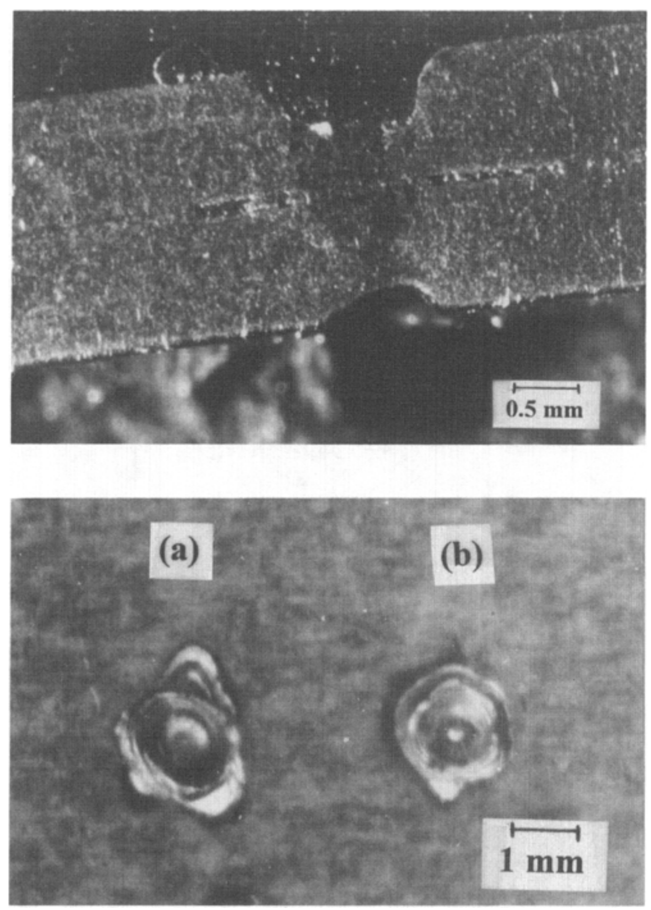

Fig. 4 Photographs of laser weld cross section and (a) top and (b) bottom view of a typical weld

When comparing breaking loads with respect to different spot diameters, a large spot diameter (0.8 mm) results in a low breaking load. This may be because the energy intensity available at the workpiece surface becomes less; therefore, the full penetration of the laser beam may not be achieved; that is, the sound weld may not be obtained. Figure 4 shows a typical cross section of the resulting weld. It is evident that the small craters were generated at the upper and lower surfaces of the weld materials. This is because mass removal rate resulted from the recoil pressure (Ref 10). It should be noted that this mass removal process can reduce the material available at the weld pool, hence allowing more laser beam energy to reach the inner part of the weld material. In addition, the recoil pressure developed in this region pushes the sheet metal in the weld region, providing improved mechanical contact.

First-law efficiencies are shown in Fig. 5 for aluminum, nickel, and steel workpieces. In general, the first-law efficiency increases as the diameter of the spot weld increases. This is because the energy requirement for a large diameter weld is high. Therefore, E_1 and E_2 in Eq 3 increase, which in turn results in attainment of high first-law efficiency (η_1). This is also true for the thick samples; that is, as the weld thickness increases, the first-law efficiency increases. On the other hand, as the thickness increases, the weld strength in Fig. 3(a) reduces, and at thicknesses greater than 0.8 mm welding ceases. In this case, laser energy output, which is 20 J, is not sufficient to melt the material for the completion of the welding process. It is also true that when the weld diameter increases, the energy intensity available for full penetration of both sheet metals becomes less; therefore, the weld strength drops. It should also be

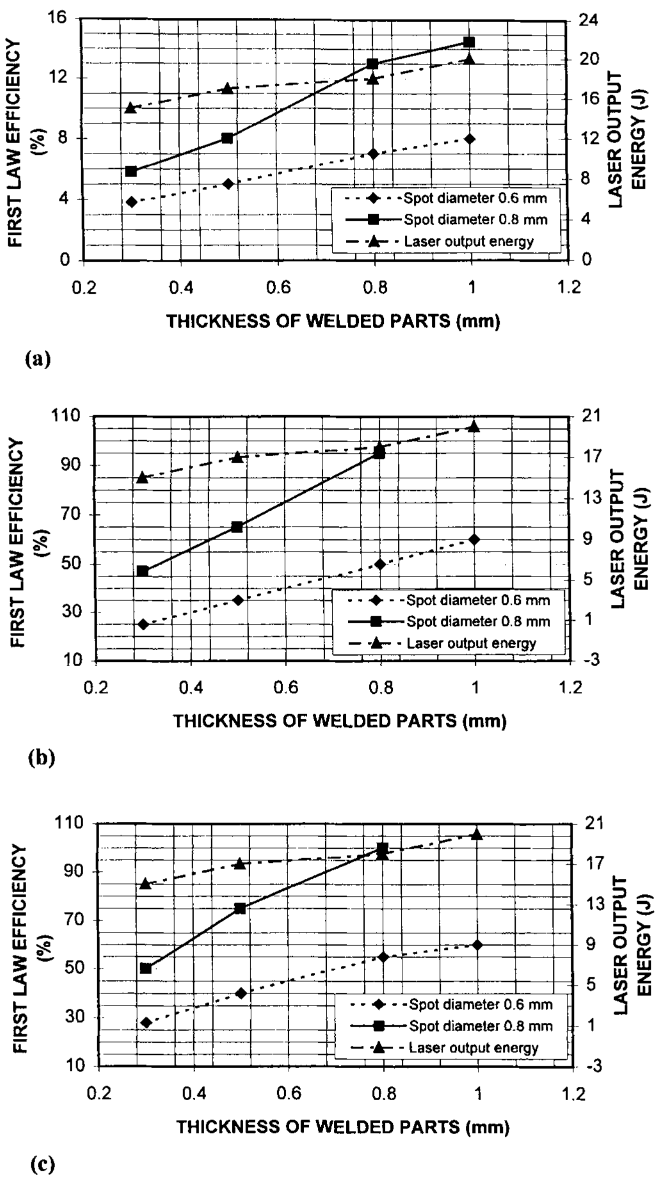

Fig. 5 First-law efficiencies and laser output energy. (a) Aluminum, (b) nickel, and (c) steel workpieces

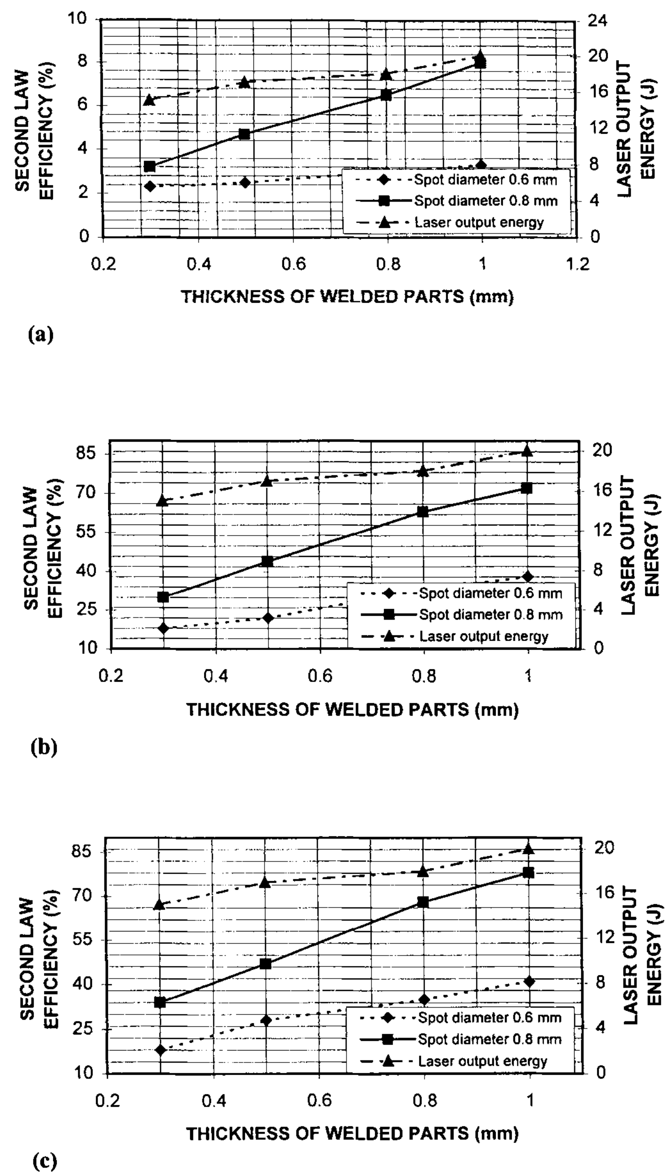

Fig. 6 Second-law efficiencies and laser output energy. (a) Aluminum, (b) nickel, and (c) steel workpieces

noted that using oxygen in the welding region triggers a high-temperature exothermic reaction, which in turn provides excess energy for improved penetration. In this case, the material removed from the top and bottom weld pools increases. When considering the material properties, it is evident that materials having high specific heat and latent heat of melting results in high first-law efficiency. This is evident from Eq 3. Consequently, the first-law efficiency is highest in the case of steel, followed by nickel and aluminum, respectively.

Figure 6 shows the second-law efficiencies corresponding to aluminum, nickel, and steel. In general, second-law efficiency increases as the thickness of the welded parts and the diameter of the spot weld increase. The behavior of the second-law efficiency with workpiece thickness and the weld spot diameter is similar to that obtained for the first-law efficiency. It is evident that second-law efficiency corresponding to steel is highest, followed by nickel and aluminum, respectively. It should be noted that the laser output energy is set to increase with increasing thickness of the welded parts. This is due to the energy required to achieve a sound weld.

When comparing the first- and second-law efficiencies, it is evident that the second-law efficiencies are lower than the first-law efficiencies. This may be because the laser beam source is considered a clean energy source; consequently, Eq 3 gives higher values than Eq 5; that is, the denominator of both equations are the same, but the numerator of Eq 3 is greater than that of Eq 5.

6. Conclusions

Tensile test results indicate that as the workpiece thickness increases, the weld strength decreases. However, welding improves at a certain thickness of the workpiece. When the diameter of the weld spot increases, the weld strength decreases. In this case, energy intensity available for full penetration of the workpieces may not be sufficient, which in turn results in partial melting of the workpiece material. The first-law analysis reveals that the first-law efficiency increases as the workpiece thickness increases. In addition, an increase in the diameter of the laser spot weld increases the first-law efficiency. These arguments are also true for the second-law efficiencies. However, it is evident from the tensile tests that the weld strength drops at a certain workpiece thickness and above, even though the first- and second-law efficiencies improve. Therefore, a relationship may exist between the weld strength and thermal efficiencies of the welding process; in this case, for a sound weld the thermal efficiency may not be maximum.

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