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Nd:YAG Laser Welding of Stainless Steel 304 for Photonics Device Packaging

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Abstract

Although pulsed Nd:YAG laser welding has been widely used in microelectronics and photonics packaging industry, a full understanding of various phenomena involved is still a matter of trials and speculations. In this research, an ultra compact pulsed Nd:YAG laser with wavelength of 1.064 µm has been used to produce a spot weld on stainless steel 304. The principal objective of this research is to examine the effects of laser welding parameters such as laser beam peak powers, pulse durations, incident angles, focus point positions and number of shots on the weld dimensions: penetration depth and bead width. The ratio of the penetration depth to the bead width is considered as one of the most critical parameters to determine the weld quality. It is found that the penetration depth and bead width increase when the laser beam peak power, pulse duration and number of shot increase. In contrast, the penetration depth decreases when the laser beam defocus position and incident angle increase. This is due to the reduction of the laser beam intensity causing by the widening of the laser spot size. These experimental results provide a reference on an optimal laser welding operations for a reliable photonics device packaging. The results obtained shows that stainless steel 304 is suitable to be used as a base material for photonics device packaging employing Nd:YAG laser welding technique.

*Keywords:*Nd:YAG laser welding, photonics device packaging, penetration depth, laser material processing.

1. Introduction

Laser welding has been widely used in the manufacturing industry especially in the fabrication of small components for photonics, electronics, aerospace, biomedical, micro-electro-mechanical systems (MEMS), micro-

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electro-optomechanical systems (MEOMS) and other applications [1, 2]. The state-of-the art of the pulsed Nd:YAG laser spot welding for photonics device packaging has been introduced by Marley [3], which utilizes the laser for high precision joining and alignment. The advantages of laser welding over conventional fusion welding processes include precise welds with a high aspect ratio, narrow heat affected zone (HAZ), very little thermal distortion, ease of automation, high welding speed, enhanced design flexibility, clean, high energy density, low heat input and an efficient process [4, 5, 6]. One of the key features of laser welding is the ability to weld without filler materials and it offers distinct advantages [6]. Laser welding is a liquid-phase fusion process. It joins metals by melting the interfaces and resulting the mixing of liquid molten metal. Then, it solidifies on the removal of the laser beam irradiation [7]. The desired material for this application requires a low thermal conductivity or a higher electrical resistivity [8]. The lower the thermal conductivity of a material the more likely it is to absorb laser energy. For this reason, several weldable grades of steel and stainless steel are ideal for laser welding. The low carbon austenitic stainless steel (300 series steel) which has carbon level less than 0.1% produces good quality welds and reliable weld performance [9,10]. Hence, in this study a stainless steel 304 is used as a base material for laser welding. It has been reported that other types of stainless steel were studied by researchers. For instance, Mousavi and Sufizadeh investigated stainless steel 321 and 630 [11], while Beretta studied stainless steel 420 [12], for the application of pulsed Nd:YAG laser welding.

This research aims to examine the effects of laser welding parameters such as laser beam peak power, pulse duration, incident angle, focus point position and number of shot on the welding dimensions which are represented by penetration depth and bead width. The ratio of the penetration depth to the bead width in the laser weld spot is considered as one of the most critical parameters to determine the weld quality [13]. For photonics device packaging applications, most of the welds are of butt or lap joints which require the penetration depth to be larger than the bead width. Moreover, for miniature packages that contain sensitive coupling components, the penetration depth should be large enough to achieve strong attachment. At the same time, the bead width should be small to minimize the HAZ and hence prevent the damage to the sensitive optical components [14]. Despite the pulsed Nd:YAG laser welding has been widely used in microelectronics and photonics packaging industry, a full understanding of various phenomena involved is still a matter of trials and speculations [15]. Thus, these experimental results provide a reference on optimal laser welding operations for a reliable photonics device packaging.

2. Experimental Setup

In this research, a Unitek Miyachi LW10E ultra compact pulsed Nd:YAG laser with wavelength of 1.064 μm is used to produce a spot weld on stainless steel 304. The energy per pulse output is in the range of 1 to 20 J, the maximum laser beam peak power is 3.5 kW and the longest pulse duration is 10.0 ms. The experimental setup consists of the laser source, fiber optics delivery system, and focusing lenses with focal length of 100.00 mm as illustrated in Fig. 1. The optical fiber cable transmits the laser beam to the welding specimen through the focusing lenses inside the lens housing. The laser welding system is also equipped with an aiming diode laser beam, which simplifies positioning of the laser spot on the stainless steel 304 specimen. The penetration depth and bead width of a laser spot weld was produced by controlling variation of pulsed Nd:YAG laser welding parameters. Each parameter affected the profile of penetration depth and also the bead width. The measurements of the penetration depth and bead width were taken using Optical Microscope, Charge Couple Devices (CCD) video camera operated by VideoTest 5.0 software and Matrox Inspector 2.1 measurement software.

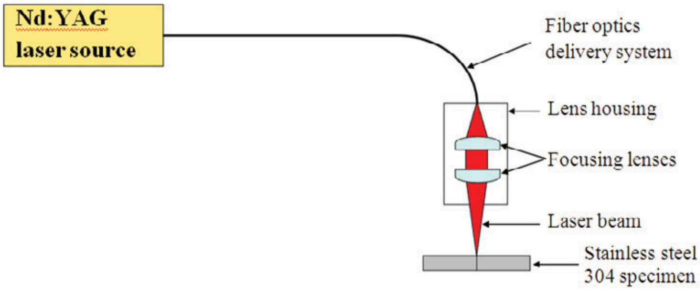

Fig. 1. Nd:YAG laser experimental setup to produce a spot weld on stainless steel 304 specimen.

By referring to the experimental setup in Fig. 1, an accurate one dimensional model to estimate the penetration depth was developed based on the energy balance at the welding front and the heat conduction equation. This model is capable of predicting the optimum penetration depth by controlling several laser beam parameters as shown in Equation (1) [16],

$$d = \frac{\sqrt{1-\sin^2(\theta)}\,(1-R)\,Pt}{\pi r^2 \rho \left[L_m + c\left(T_m - T_0\right) \right]} \tag{1}$$

where d is the penetration depth, P is the laser beam peak power, t is the laser beam pulse duration, θ is the laser beam incident angle in respect to the material surface normal, r is the laser spot radii, R is the material surface reflectivity, L_m is the latent heat of fusion, ρ is the material density, c is the material specific heat capacity, T_0 is the ambient temperature and T_m is the melting temperature of the material. The theoretical results from this model provide the validity of the experiment result.

3. Analysis of the pulsed Nd:YAG laser spot weld

The profiles for the penetration depth and bead width produced by the pulsed Nd:YAG laser beam were captured by an optical microscope and depicted in Fig. 2 and Fig. 3. The element composition of the stainless steel 304 specimen was analyzed using the Energy Dispersive X-ray (EDX) spectrometer and the result illustrated in Fig. 4 shown it is consisting of iron (Fe) 69.59 wt%, chromium (Cr) 18.33 wt% and nickel (Ni) 12.08 wt%.

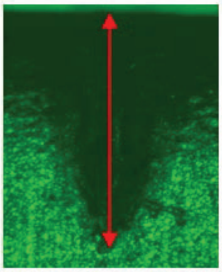

Fig. 2. Cross-section of a spot weld produced by 2.5kW laser beam peak power and 2.5ms pulse duration. The penetration depth is labelled by the vertical line.

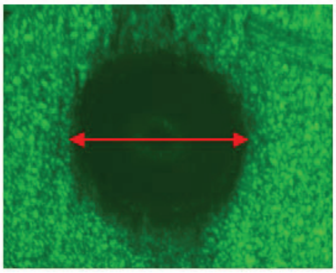

Fig. 3. Top view of a spot weld produced by 2.5kW laser peak power and 2.5ms pulse duration. The bead width is labelled by the horizontal line.

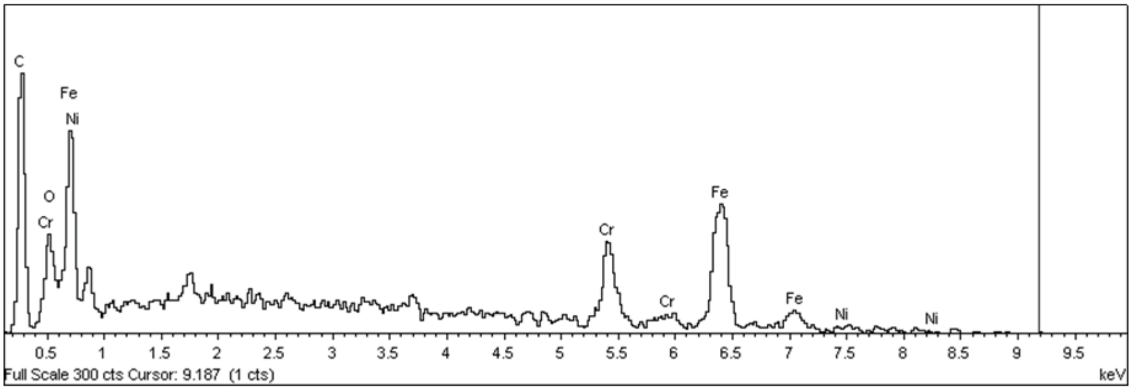

Fig. 4. Energy Dispersive X-ray analysis for element composition of stainless steel 304.

The results of weld dimensions (weld penetration depth and weld width) for different laser beam peak powers are illustrated in Fig. 5. The results display an increase in penetration depth and bead width with an increase in the laser beam peak power. The deepest penetration depth produced is 1.31 mm and the largest bead width is 0.57 mm when laser beam peak power is set at 3.5 kW. When laser beam peak power is reduced to 0.5 kW, the reading of penetration depth and the bead width are only 0.36 mm and 0.24 mm. The linear gradients of penetration depth and bead width are 0.301 and 0.10, respectively. These values show the laser beam peak power is almost 3 times more effective on the penetration depth rather than the bead width. This suggests that the laser beam peak power is a reliable parameter to control the desired penetration depth. It is observed in Fig. 6 that the penetration depth and bead width increases when the pulse duration is increased. From the Fig. 6, linear gradient of penetration depth and bead width are 0.0039 and 0.035, respectively. Only slight difference is noted and this means that the pulse duration has no significant effect either on penetration depth or bead width. As compared with the effect of laser peak power, the pulse duration is a much more better parameter to control the desired bead width.

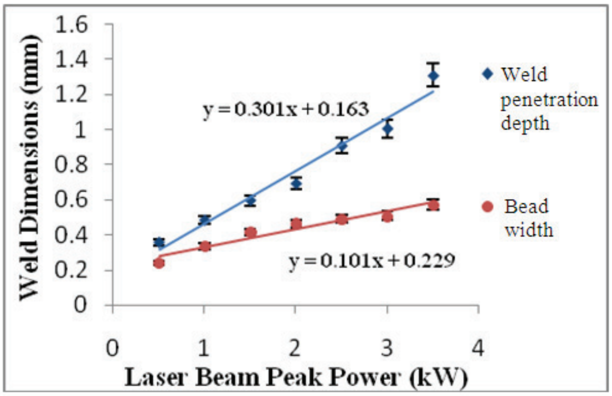

Fig. 5. Characteristics of a spot weld dimensions as a function of laser peak powers conducted by 2.5 ms pulse duration with laser beam incidence is vertical in respect to the surface normal.

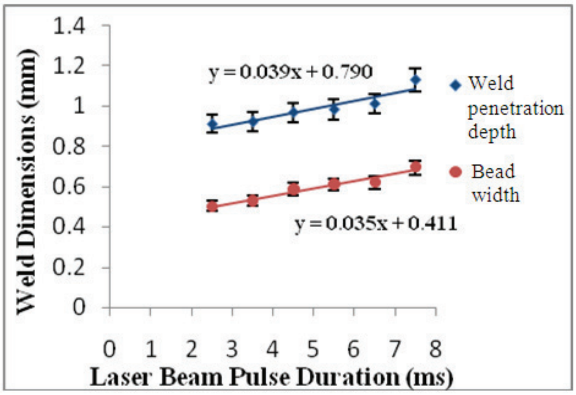

Fig. 6. Characteristics of a spot weld dimensions as a function of laser pulse durations conducted by 2.5 kW laser peak power with wavelength of 1064 nm.

Laser beam can be defocused by moving the focus point position forward or backward from the specimen surface. Fig. 7 depicts that the penetration depth decreases significanly when the laser beam focus point position is moved from 0 to 4.0 mm with respect to the specimen surface. After 4.0 mm, the penetration depth decreases gradually untill 6.0 mm and there is no penetration depth that can be traced after 6.0 mm. Otherwise, when the focus point position is moved forward or backward, the bead width increases. But after 6.00 mm, there is no more bead width and only the sign of burning can be observed on the welding surface. As the focus point position is moved forward or backward from the specimen surface, the laser spot size increases. This will reduce the intensity of the laser beam which is given by, $I_0=P/ \pi r^2$. Here, P is the laser beam peak power and r is the laser spot radius. It indicates that the intensity of laser beam is negatively proportional with r^2. Hence, the laser beam does not have sufficient intensity to penetrate the material. As illustrated in Fig. 8, it is observed that the penetration depth and bead width changes with the laser beam incident angle. As the laser beam incident angle increases, the laser spot becomes elliptical and wider. Hence the bead width also becomes elliptical and wider. The wider laser spot will reduce the intensity of the laser beam. This will result in a decrease of the penetration depth. However, when the laser beam incident angle is increased, the reflectivity of material surface drops due to the influence of light polarization. When the reflectivity drops, it will transport more laser energy into the welding material. Hence, it will increase the penetration depth. It can be seen that when weld penetration depth at angle of incidence of 45 degrees is much higher than that at 25 degrees. But, even though the reflectivity of the material surface drops greatly at 65 degrees, the penetration depth is only 0.82 mm because laser beam is less intense due to the significant increases in the laser spot area for a slight increase of the incident angle.

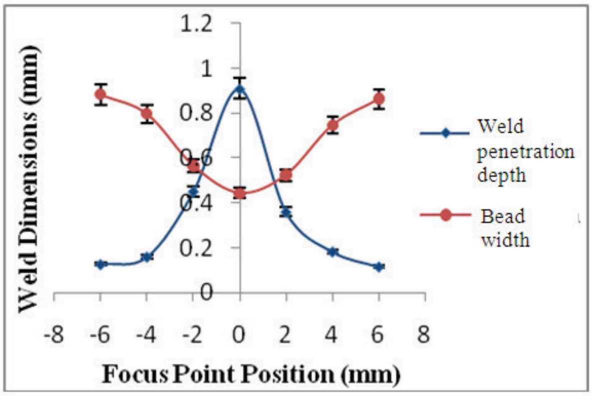

Fig. 7. Characterictics of a spot weld dimensions when Nd:YAG laser spot is positioned forward and backward from the stainless steel 304 surface with 2.5 kW laser peak power and 2.5 ms pulse duration.

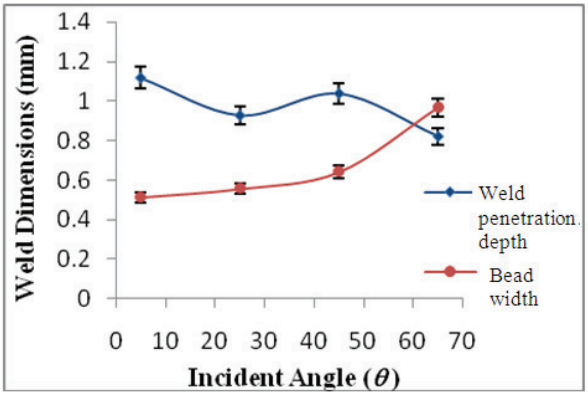

Fig. 8. Characterictics of a spot weld dimensions when Nd:YAG laser spot incident angle is varied with respect to the stainless steel 304 surface normal by employing 2.5 kW laser peak power and 2.5 ms pulse duration.

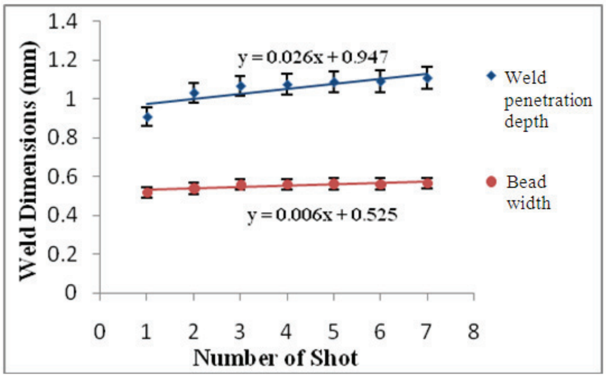

Fig. 9. Spot weld produced by 2.5 kW laser peak power, 2.5 ms pulse duration with laser beam incidence is vertical in respect to the surface normal and laser focus point is on the stainless steel 304 surface, while the laser beam shot numbers are varied.

In Fig. 9, it can be seen that the penetration depth increases slightly with the number of shots. The penetration depth for the first and seventh pulse shots are 0.91 mm and 1.11 mm. When the first shot is applied it produces a shallow concave hole on the specimen surface. This is due to the material ablation produced by laser pulse pressure when it strikes the material surface. Then, when the second shot is given, it is able to go towards the bottom of the concave hole. The second shot weld penetration depth is similar to the first shot but with an increase in the depth of the concave hole. The first and seventh shot produce 0.52 mm and 0.57 mm of weld width. The difference is relatively small because the same laser beam parameters are used for each shot.

4. Conclusion

From the results, it is found that the penetration depth and bead width increase when the laser beam peak power, pulse duration and number of shot are increased. It is found that the laser peak power is more effective to produce the deeper penetration depth rather than the bead width. Otherwise, the laser beam pulse duration is an accurate parameter to control if the desired bead width is required rather than the penetration depth. As the focus point positions are placed forward and backward from the stainless steel 304 specimen surface, the laser spot size increases. This leads to the reduction of the laser beam intensity. Hence, the penetration depth decreases. The increase of the laser spot size will increase the bead width. When the laser beam incident angle is varied, the bead width also changes due to the widening of the laser spot size. The penetration depth depends on the both widening laser spot size and material surface reflectivity that drops due to the influence of light polarization. The penetration depth increases slightly with the number of shots due to the material ablation produced by laser pulse pressure when it strikes the specimen surface. In conclusion, these experimental results provide a reference on an optimal laser welding operations for a reliable photonics device packaging.

5. Acknowledgement

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