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Effect of Pulse Shapes on the Weldability of High Conductivity Copper C101 by Nd-YAG Laser

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Abstract

Similar lap joints of pure copper C101 thin sheets were welded using pulsed laser welding. The effect of laser welding parameters on mechanical properties was investigated. The experimental results revealed that sound defect-free joints could be obtained from similar copper-copper joints where the fracture occurs away from the weld line. The present work proposes improved design control for three different pulse shapes; rectangular (normal), ramped-down and modulated which are used to weld six different copper samples to achieve the optimum tensile-shear strength of the joints. Results showed that modulated pulse shape has the optimum in the shear-tensile test. Ramped-down pulse shape had a less significant effect on the strength of the copper joint when compared with the rectangular pulse shape. The relationship between the input and output parameters was obtained by employing Minitab software, and the Matlab software was used in order to reach the optimum solution. The genetic algorithm showed that the optimum magnitude achieved for the shear strength was 77.9 MPa, and the optimum input parameters were pulse energy of 39J, the pulse width of 8.5, frequency of 10Hz and linear speed of 160mm/min.

Keywords: Similar joint, Laser welding, Pulse shapes, Tensile shear test, Modulated pulse.

1. Introduction

Today, laser welding is a main process to achieve a reliable joint between similar and dissimilar materials because the process is clean, fast, and suitable for different geometry and high quality with less defects in the joints. On the other hand, this process is restricted for some materials like copper, aluminium, silver and gold due to high reflected energy from the bright surface of these materials [1].

The intensity of heat source in laser welding is about 10^6 Watt/cm^2 and this heat is focused on a small area. There are two modes in laser welding, one of them called conduction mode and the other is called keyhole mode. In conduction mode, there is less energy absorbed and more is conducted and also is beneficial for thin sheets and coupons. It is known, that most of welding processes require the enough heat to achieve the reliable joint and the welding engineer must calculate the exact amount of heat that's required to join the materials. More or less heat may reverse on the quality of the joint. Conduction mode is successful due to less heat penetration with the narrow heat affected zone, high stable of laser beam and less defects.

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Keyhole is suitable for heavy sections and the beam is fluctuated during the process and perhaps some defects are generated [2, 4].

Pure copper has high electrical and thermal conductivity and also has high corrosion resistance. Pure copper is easily welded by fusion and solid state welding processes because having more ductility and plasticity and not exposure to phase transformation with less residual stresses. In some applications, however, the copper needs more heat for achieving the joint because more heat is conducted by its own high thermal conductivity. The greatest electrical conductors, such as silver, copper, gold and aluminum reflect most lasers light and may absorb less than 5 percent of the incident radiation. Therefore, these metals are more easily welded by electron beam than by laser. Copper has low absorption percentages of 3%. This creates challenges trying to get this metal to sufficiently melt [5].

Due to the challenges to weld copper and its alloy by laser welding, several researchers worked to develop the technical methods to assist more heat absorbed by copper surfaces. Some researchers used the coating on copper surface by an element having low reflectivity. They found these elements may produce brittle intermetallic compounds and reduce the strength of the joint [6]. Some researchers used argon and oxygen gases to reduce the reflectivity of copper surface and increase the heat absorption from 4.89% to 16.10% when heating thin sheet from room temperature to melting point of pure copper Biro et al. [7]. Other researchers used dual laser beams and short wavelength to assist welding copper alloys. Engler et al. and Hess et al used two laser beams; green and infrared beam to improve the absorption of heat that required to laser weld of copper alloys [8, 9]. Govorov and Richardson used nanoparticles to increase the heat absorption that needed to weld copper alloy .These nano particles have a high surface area and absorb the light and transformed into thermal energy with high storage energy by nano particles [10]. Chi Chen et al. investigated the effect of copper base nanoparticles composite for improving the heat absorption to laser weld copper. An increase in tensile strength to 88% for copper base nanoparticles composite was established to compare with pure copper. The reflectivity reduced from 88% to 15%, and the weld efficiency increased to 50% with the incorporation of the composite absorber in laser welding of pure copper [11].

Yulong Chen et al. have developed a laser-arc hybrid technique for welding pure copper. They used a copper-silicon filler alloy (CuSi3) to improve the strength of the joint. The authors emphasized obtaining a high strength joint by solid solution strengthening of silicon in α-Cu alloy. The presence of Si in the filler alloy and using the arc in this technique make the joint is less in porosity and more bubbles migrated away from the weld zone, and thus showed a high strength of the joint [12]. Heider et al. indicated that the welding quality of copper alloy depends on the power modulated of laser pulses [13].

Most recent laser devices contain units to control the pulse shaping for welding and cutting processes. Suitable selection of pulse shape allows more control on the thermal cycle during heating and cooling before and after the solidification of a material and controlling the defects that occur during solidification. Likewise, the temperature gradient is reduced while using interpreted pulses and more uniform of the structure of weldment is obtained. For welding the metals with high reflectivity, the appropriate pulse shape enhances quick coupling between the workpiece and laser beam and good absorbers of laser light with less defects are detected.

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For changing the pulse shapes, it does not need to treat the surface of metals or use filler metal to enhance the absorption of laser light [14, 17].

As mentioned in [18], because of the low absorptivity of laser light and the high thermal conductivity, laser welding of copper still represents a research challenge. In [19], it was found that the weld produced by a green laser light had the best stability based on both the transition and weld depth fluctuation. Regarding the same weld depth, less laser power is needed because of better material absorption of green in comparison to infrared.

Jingquan Zhang et al [20] developed a new technique for copper welding using polarized fiber laser with applied pressure during laser welding. Two opened plates were used to make V-shaped configuration. The target of laser was applied along the V-shaped configuration, while the pressure was applied vertically by rolling. Multiple light reflections by laser energy were focused into the local welding area and produced sound joint.

Kangda Hao et al [21] used fiber laser-arc hybrid to join pure copper sheets. Two filler alloys $CuSi_3$ and $CuSn_6$ were used to improve the mechanical and metallurgical properties of the fusion zone. It was observed that silicon and tin elements can improve the morphology of weld zone to change the grains to column form and contribute to a positive impact on the strength and corrosion resistance of welds.

Diana Franco et al [22] used a wobble technique by fiber laser to solve the challenges that arise with laser welding of higher reflective pure copper. A circular band of grains in fusion zone was found. The join is free-defect and the wobble welding head provides a circular dynamic profile and improve the metallurgical bond. Amplitude and frequency can be optimized and additional befits can improve the control of the weld.

In the present study, three types of pulse shapes namely, rectangular, ramped-down and modulated were used to show the effect on the quality of joining high conductivity copper C101 by Nd-YAG Laser. Even though many researchers investigated the laser beam welding of copper, very few researchers reported on the pulse shapes. The proper selection of pulse shape enables greater control of the thermal cycle during heating and cooling before and after the solidification of material and the defects that arise during solidification. Thus, the main objective of this research is to enhance the weld quality of pure copper C101 during laser welding by applying a combination of pulse shapes and welding parameters.

2. Experimental Procedures

Similar copper (C101) of 0.45mm thick sheets were welded using a pulsed Nd-YAG laser system (GSI Lumonics JK702H) with a maximum average power of 350W and emitting at a 1.064µm wavelength as shown in Fig.1a. Copper was cut into sheets of 80mm x 30mm. Figure 2 illustrates the dimensions of the lap-joint for tensile shear testing of the similar copper joints. The composition of the copper C101-half hard was Pb. 0.005 wt.%, Bi., 0.001wt.% and Cu. 99.9wt.%. Prior to laser welding, the specimen coupons were polished with 1000 grit silicon carbide emery paper then cleaned with acetone. The coupons were supported with a welding fixture designed to hold up the sheets as shown in Figure 1b. Figure 1c shows the display controls that comprise eight keys with integral indicators which are primarily used for setting system laser parameters. In this research, the main parameter keys were selected such as height present (intensity) which refers to the flashlamp current during the laser pulse for welding, width which refers to the duration in milliseconds of a pulse and the rate (frequency) is an abbreviation for pulse repetition rate which signifies the number of laser pulses emitted each second also termed as recitation rate and frequency. These three parameters control the pulse energy in Joule.

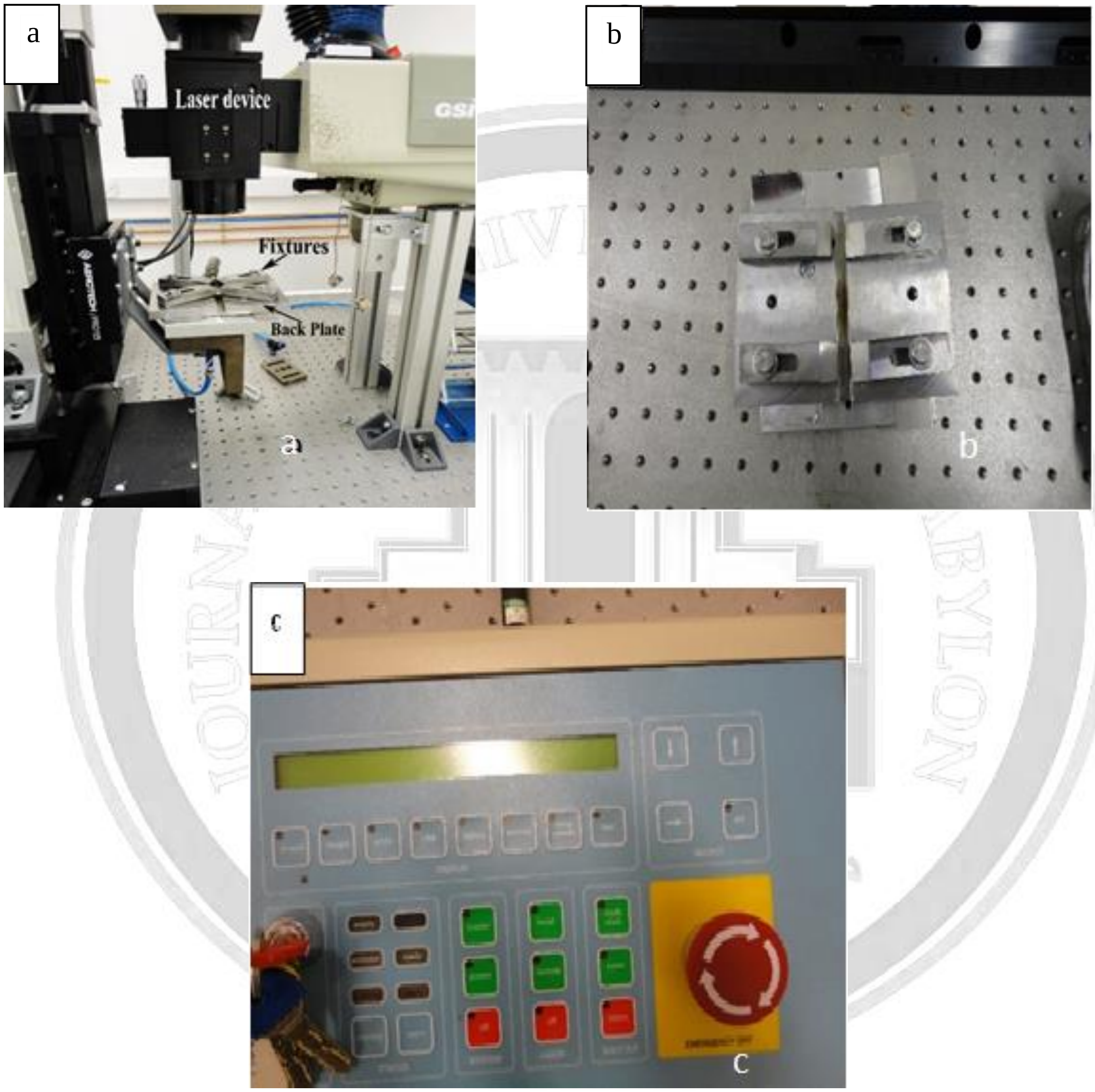

Fig1. Pulsed Nd-YAG laser system (a) Laser welding device (b) Fixtures support copper sheets (c) Display control of laser welding

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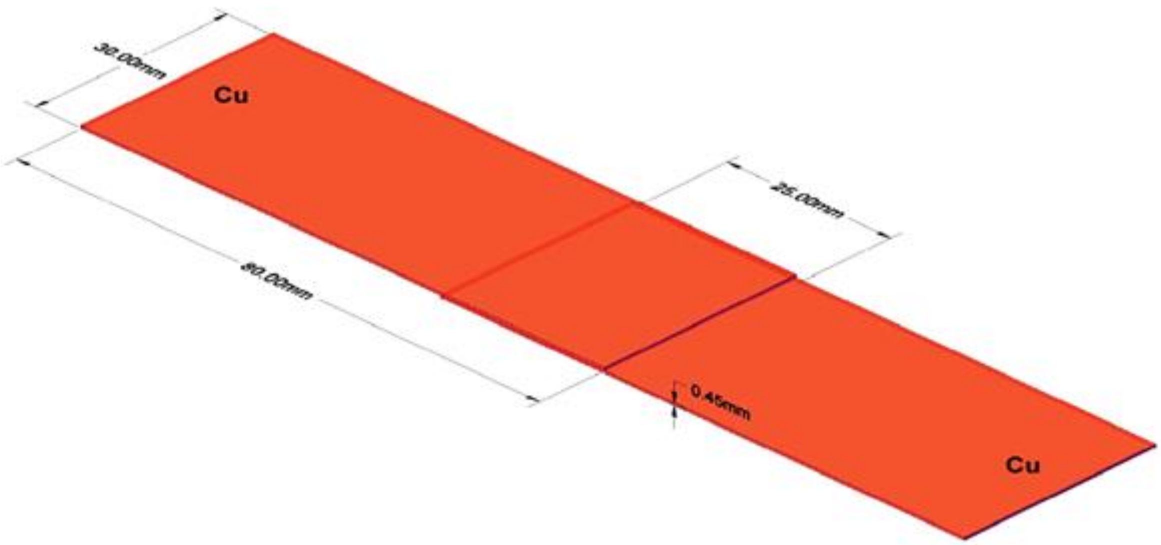

Fig 2. The geometry of copper sheets for laser welding

After laser welding, the samples were cut along their cross-section and ground and polished for metallurgical examinations. Optical microscopy was employed for analysis the changes in microstructure across the weld. Copper joints were etched in 100 ml distilled water; 10 ml ammonium hydroxide (25%) with a few drops of aqueous hydrogen peroxide (3%).

The normal pulse shape was utilized in these experiments. For applying the modes of pulse shapes to improve the weld joint, the stronger joint were selected to investigate the effects of pulse shaping on the resulting welds of C101 pure copper.

The setup of welding parameters subjected in this work for Cu-Cu laser welding is given in Table 1. These parameters were chosen as giving a stable welding process after undertaking trials. Pulse energy, pulse width and frequency were used as a variable parameter in this work. Then, tensile shear testing, optical microscopy and scanning electron microscopy were used to evaluate and characterize the weld.

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Table 1: The design of experimental parameters for Cu-Cu laser joint, achieved using ND:YAG laser welding method

No. of sample	Pulse Energy (J)	Pulse Width (ms)	Frequency (Hz)	Linear Speed (mm/min)
1	37	6.5	8	120
2	37	6.5	8	140
3	37	6.5	8	160
4	37	7.5	8	120
5	37	7.5	8	140
6	37	7.5	8	160
7	37	8.5	8	120
8	37	8.5	8	140
9	37	8.5	8	160
10	37	8.5	6	120
11	37	8.5	10	120
12	38	6.5	8	120
13	38	6.5	8	140
14	38	6.5	8	160
15	38	7.5	8	120
16	38	7.5	8	140
17	38	7.5	8	160
18	38	8.5	8	120
19	38	8.5	8	140
20	38	8.5	8	160
21	38	7.5	6	120
22	38	7.5	6	140
23	38	7.5	6	160
24	38	7.5	10	120
25	38	7.5	10	140
26	38	7.5	10	160
27	39	6.5	8	120
28	39	6.5	8	140
29	39	6.5	8	160
30	39	7.5	8	120
31	39	7.5	8	140
32	39	7.5	8	160
33	39	8.5	8	120

2.1 Pulse Shapes

Three different pulse shapes were used to weld similar copper after selected the laser parameter that gave optimum shear strength (test number 16). The laser device has many sectors to modulate the pulse shapes. The modes of pulse shapes are:

1. The standard pulse, 2. The step down pulse, and 3. The modulated pulse

Figure 3 shows the intensity vs. time curves for three pulse shapes that used in this study.

2.2 Optimization Analysis by Genetic Algorithm

The optimization process can be defined as the process of selecting the best individual from a group of feasible solutions. Several methods were employed for optimization, among them, is a genetic algorithm (GA). The Genetic algorithm is an optimization technique that depends on the Darwin theory, used to obtain the optimum solution. In this research, the population size was composed of 33 samples. Figure 3 presents the pulse shapes.

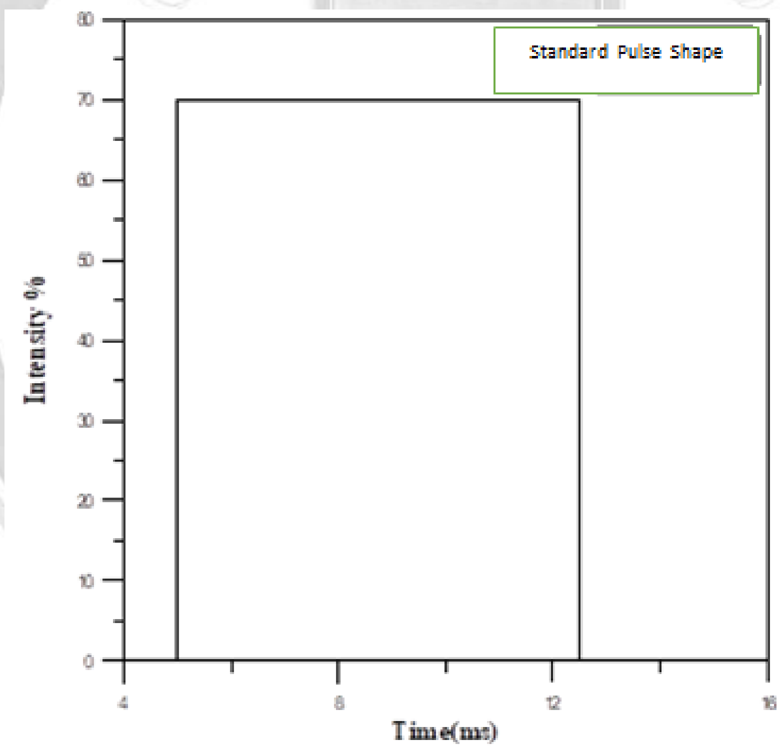

Fig 3. Pulse Shapes (a) Standard pulse (b) Step down pulse (c) Modulated pulse

The pulse energy, pulse width, frequency, and linear speed were taken as input or variables of the problem with 3 levels for each of them, whereas, the shear strength was taken as output parameter. The laser welding parameter of pulse energy, pulse width, frequency and linear speed were chosen as a major four controlled factors with their corresponding three levels to be investigated. Table 2 shows the input parameters that used in this study.

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Table2: The input parameters with their levels

No	Laser parameters	Unit	Levels Level 1	Level 2	Level 3
1	Pulse energy	J	37	38	39
2	Pulse width	ms	6.5	7.5	8.5
3	Frequency	Hz	6	8	10
4	Linear speed	mm/min	120	140	160

The regression or objective function of the shear strength was arriving by employing the MINITAB software as shown below:

$$\boldsymbol{SH = -454 + 12.59 \times pulse\ energy + 3.00 \times pulse\ width + 0.13 \times frequency + 0.088 \times speed}$$

3. Results and Discussion

Table 2 showed that the measured shear strength increases with welding speed and 140 mm/min is the optimum speed with respect to the other constant parameters. It was also observed that copper needs more energy input to achieve a durable joint. This is because the more laser light reflection from the copper surface and thus the amount of the energy absorbed is less. The overlapping of pulsed weld observed as a line on the surface of Cu-Cu as shown in Figure 3a. All samples were fractured outside the weld line near the start and finish points (see Figure 3b). The pure copper substrates were received in a cold worked condition and during laser welding some heat caused recovery or recrystallization of the grains and the formation of new grains. This process of re-crystallization or partial re-crystallization works to reduce the strength of the joint at the heat affected zone close to the weld line.

Figure 5 illustrates the microstructure of the nugget zone between the copper sheets after laser welding with an energy of 38 J, pulse duration of 7.5ms, frequency of 8Hz and linear speed of 140 mm/min. Uniform mixture occurs in the nugget zone between two sheets and no defects such as porosity and un-bonded area was observed throughout the joint. Epitaxial solidification is illustrated in Figure 5b and columnar grains formed by epitaxial solidification from the copper base metal grains at the fusion. Eventually, an epitaxial growth occurs in molten pool when the composition and the crystal structure are not altered. In this study the laser welding occurs without filler metal and the crystal structure remains un-changed. It is also observed from Figure 4b that the columnar grain growth in the direction perpendicular to pool boundary and it has the preferred direction ⟨100⟩ and this direction is easy growth that has less atomic packing. Narrow heat affected zone was formed between the fusion line and the base metal. Narrow width of HAZ is due to the high cooling rate of laser welding and more heat removed from the copper sheet.

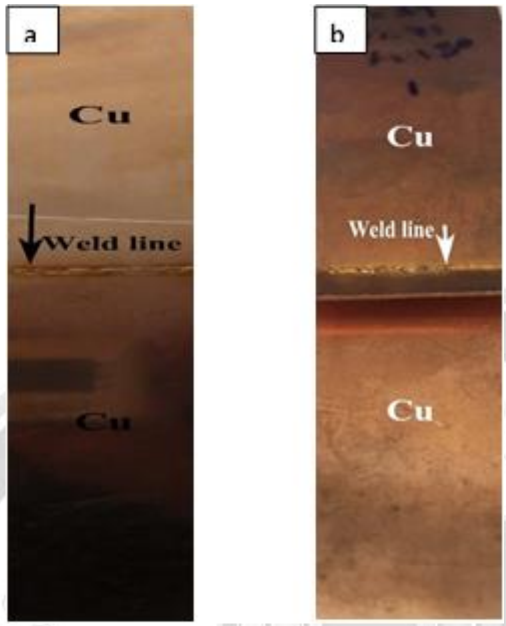
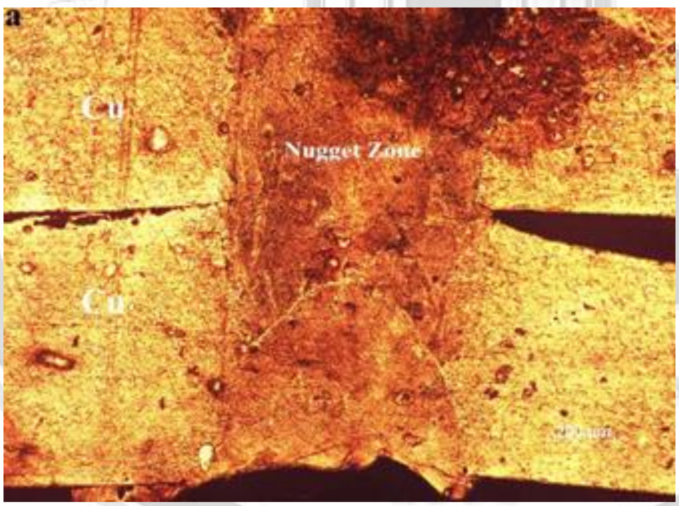


Fig 4. Lap joint of Cu-to-Cu sheets (a) before testing (b) after testing



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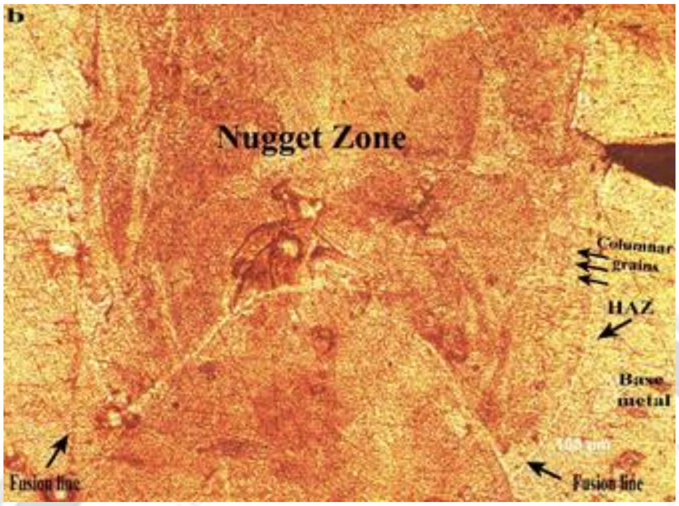
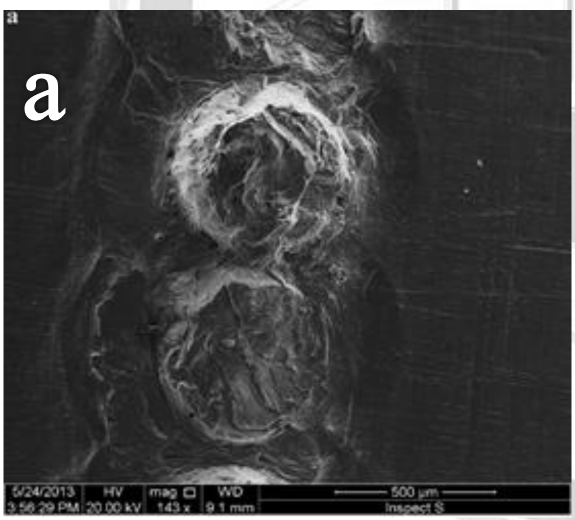
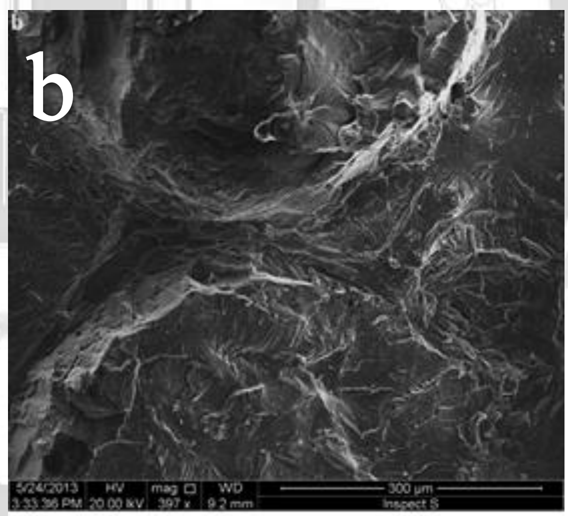


Fig 5. Microstructure of the Cu-Cu laser welded joint (a) Optical micrograph of the nugget zone, HAZ and the base metal (low magnification) (b) high magnification).

Scanning electron microscopy (SEM) shows the surface fracture of the copper sheet after shear test (Figure 6). It is observed that the pulse shape was as dimples and voids which refers to a ductile fracture of copper. Figure 6 also indicated the overlap between two pulses and more mixing between them.





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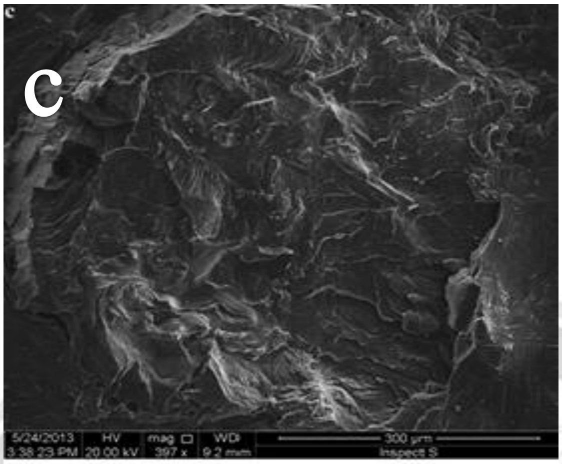

Fig 6. SEM micrograph of the surface copper fracture after shear test (a): three pulses (b): two pulses (c): one pulse

Table 3: The inputs and the output parameters for laser welding

Experiments No.	Pulse energy	Pulse width	Frequency	Linear speed	Shear strength
1	37	6.5	8	120	40
2	37	6.5	8	140	38.3
3	37	6.5	8	160	35.2
4	37	7.5	8	120	42.3
5	37	7.5	8	140	42.1
6	37	7.5	8	160	39.5
7	37	8.5	8	120	45
8	37	8.5	8	140	44.2
9	37	8.5	8	160	43.5
10	37	8.5	6	120	39
11	37	8.5	10	120	40
12	38	6.5	8	120	62
13	38	6.5	8	140	61.3
14	38	6.5	8	160	60
15	38	7.5	8	120	72
16	38	7.5	8	140	75.4
17	38	7.5	8	160	74
18	38	8.5	8	120	71
19	38	8.5	8	140	73
20	38	8.5	8	160	72.6
21	38	7.5	6	140	74.4
22	38	7.5	6	120	73.2
23	38	7.5	6	160	70.3
24	38	7.5	10	140	74

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25	38	7.5	10	120	72
26	38	7.5	10	160	73
27	39	6.5	8	120	60
28	39	6.5	8	140	63.1
29	39	6.5	8	160	67
30	39	7.5	8	120	58
31	39	7.5	8	140	59.4
32	39	7.5	8	160	60
33	39	8.5	8	120	57

3.1 Improving the weld quality

To improve the weld quality and achieve the maximum strength of C101 copper joints, a set of parameters were chosen. To overcome the difficulties for joining pure copper due to its high reflectivity and thermal diffusivity, three pulse shapes were used to control the thermal cycle of the process.

1. The rectangular pulse. This is the standard welding pulse shape. During this pulse, one shape is created by set the amount of intensity percent with constant duration time (7.5ms)
2. The ramped-down pulse. This pulse is interrupted to three parts during 7.5ms duration time. Intensity percent gradually decreases over time and allows more time to cool the solidified weld zone. The power of the laser decreased by 20% every 2.5ms.
3. The modulated pulse. This pulse shape is separated into three parts, each part consists of 2.5ms of power followed by a 0.5ms unload.

Maximum shear strength of the three pulse shape is listed in Table4 for three pulse shapes. According to previous research, they reported that both the ramped-down pulse and modulated pulse have a positive improve on the strength of the joint due to a probable decrease in defects within the weld and reduce the temperature gradient therefore an allowed to slowly cool the weldment with low thermal stresses.

3.2 The normal pulse shape

All results shown in Table 3 refer to the normal pulse shape. 1A and 1B in Table 4 denote the weld specimens in Table4 that used a normal pulse shape. The overall duration time was 7.5ms in this pulse shape.

Table 4: The Maximum shear strength of the three pulse shape

Sample	Pulse Shape	Tensile Shear Stress (MPa)
1A	Standard	72.5
1B	Standard	78.4
2A	Step Down	78.3
2B	Step Down	80.8
3A	Modulated	84.5
3B	Modulated	84.7

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3.3 The Step down pulse shape

2A and 2B denote the weld samples that used ramp-down pulse shape. Regular decrease in the power intensity is obtained by a certain amount at a set interval. It is clear from Figure 3 that 20% of energy supplied is decreased every 2.5 ms.

The 2B sample is stronger than the 1B sample by only 2.4 MPa. The ramp down pulse designed to alleviate the high reactivity of copper surface copper and allows more heat absorption that required for joining. Initially, the ramp down gives a high peak power in order to overcome the reflectivity of the copper quickly with the peak power. Then, peak power reduced gradually "ramping" down as the amount of energy absorbed by the metal increases. Moreover, gradual cooling from the high temperature of laser is necessary to accommodate the residual stresses that may be increased due to the high differential of temperature. Pulses shape in ramp down is more uniform than norm shape during the welding process and more regular of overlapping between two adjacent pulses as shown in Figure 6.

Clearly, samples 1A and 1B provide a lower strength in spite of a successfully joints being obtained. Also, more variation in the values of tensile shear strength observed between 1A and 2A. This deviation can be expected. One of the main problems for welding copper by photonic beams is its reflective bright surface. It needs more heat input to compensate the losses of heat by the high reflectivity of the copper to produce a sound joint. Hence, more heat applied by high intensity which in turn will cause a wide variation in values of weld strengths and less uniformity of pulses during laser welding as shown in Figures 6a and 6b).

3.4 The modulated pulse shape

3A and 3B samples were laser welded using the modulated pulse shape. This pulse shape supplied energy for 2.5ms followed by 0.5ms of zero energy; this is then duplicated 3 times per pulse. It is observed that the samples 3A and 3B had the greater strength welds of all the welds. The variation in strength values between specimen 3A and 3B is considerably lower than that between specimen 1A and 1B or 2Aand 2B. 3A and 3B only differ in strength by 0.2 MPa. Low deviation in values of strength of specimens in modulated pulse shape improved the reliability of the results and also signifies towards the weld being very uniformity.

The no energy spaces between the pulses in modulated pulse shapes allow avoiding over-heating in weld zone. Also, the alternative heating works as multi-passes and more stress relive during the sequence in heating. The distortion is less in modulated shape than other shapes. The modulated pulse shape has significant positive impact than other shapes because less energy applied for welding, stress relived during the sequence in heat and therefore more uniform interaction with less time between the workpiece and the laser beam. One disadvantage of the modulated pulse shape is it has taken addition time to complete the welding.

Another unique characteristic of the weld produced by the modulated pulse shape is the uniform and regular pulses during moving the heat source of the laser beam (see Figure 7 and Figure 8c). The three off time in modulating shape implies reducing the temperature gradient and reduces the thermal stresses during solidification of weldments.

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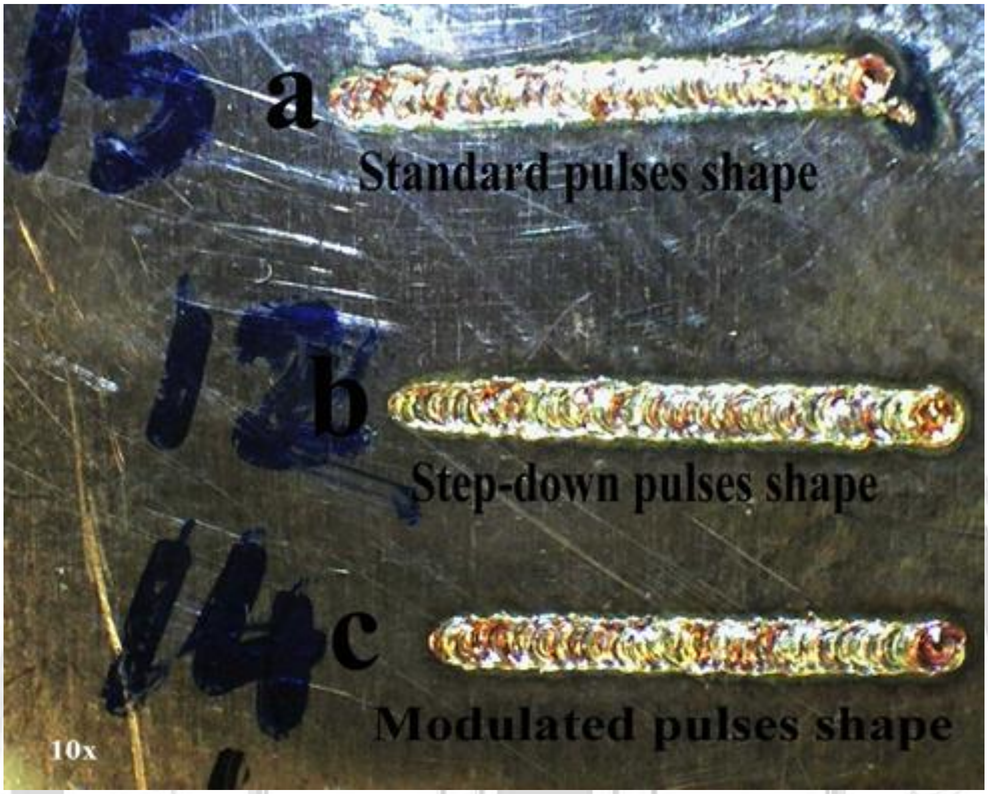
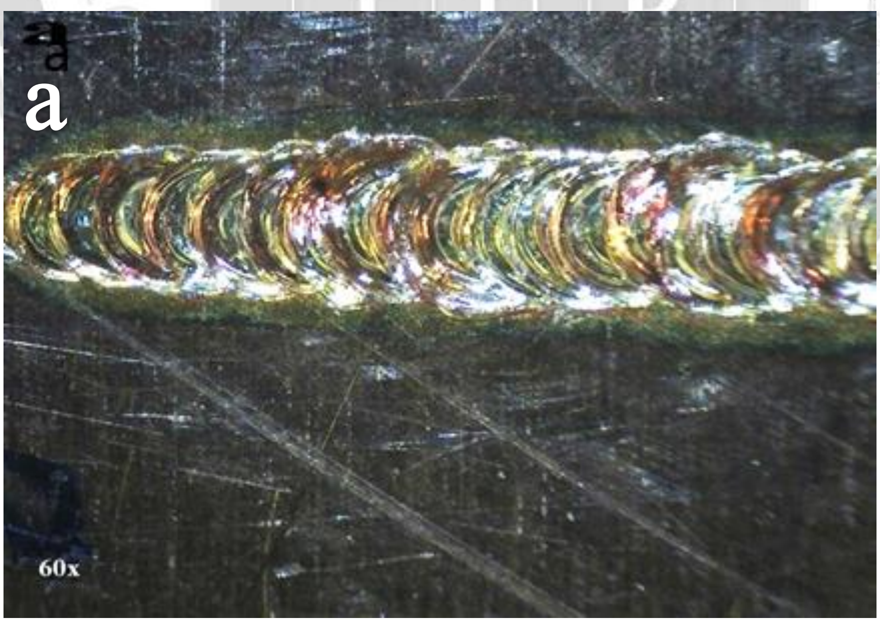


Fig 7. Pulse shapes at low magnification (a) Standard (b) Step down (c) Modulated



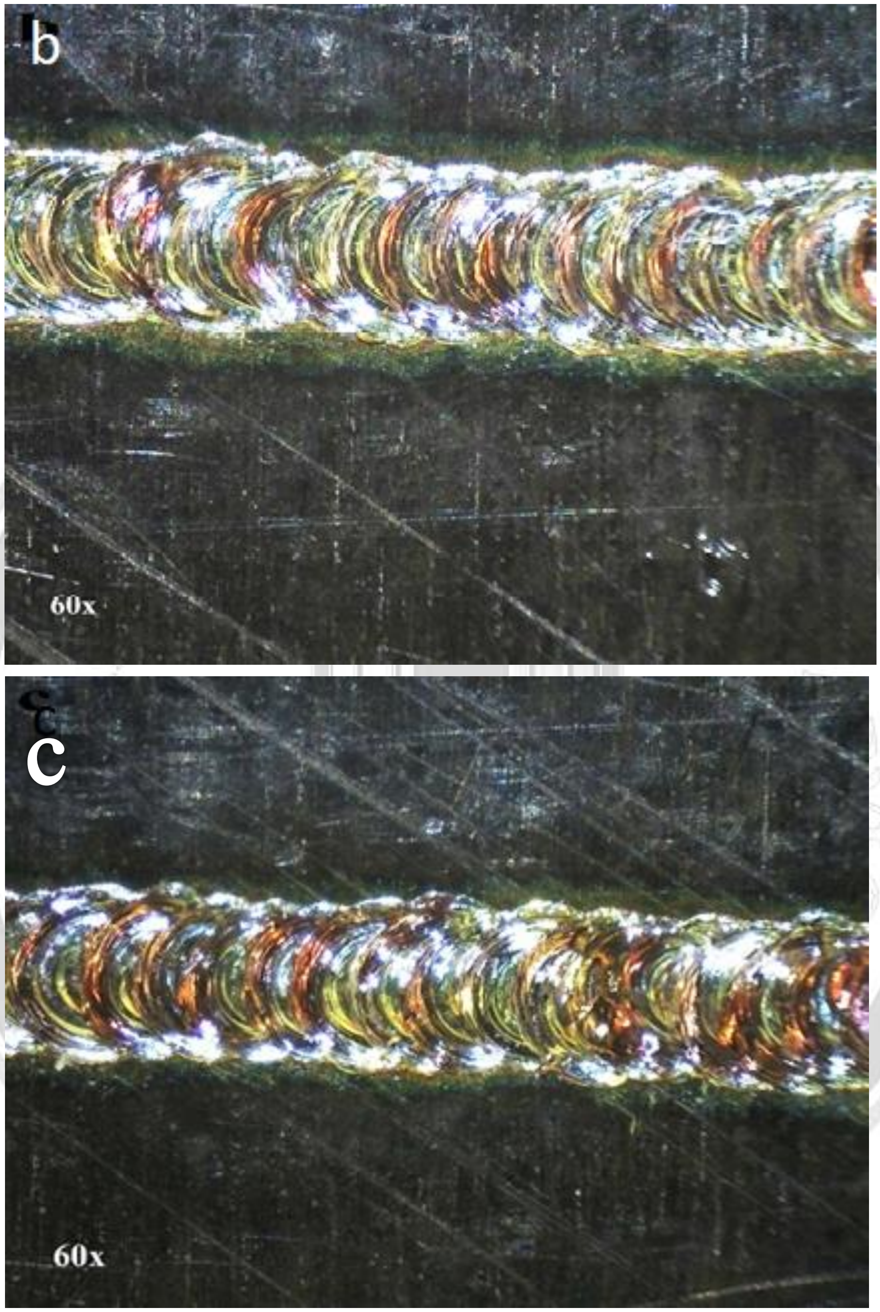


Fig 8. Pulse shapes at higher magnification (a) Standard (b) Step down (c) Modulated

3.5 Genetic algorithm parameters

The number of experiments that were conducted was 33, the selection process used was stochastic uniform, and the crossover type was heuristic, while mutation type was uniform with a probability of 0.01. Figure 9 shows that the optimum output value achieved for the shear strength

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was 77.89 MPa, while the optimum input parameters obtained were pulse energy of 39J, pulse width of 8.5 ms, frequency of 10Hz and a linear speed of 160mm/min as shown in Figure 10.

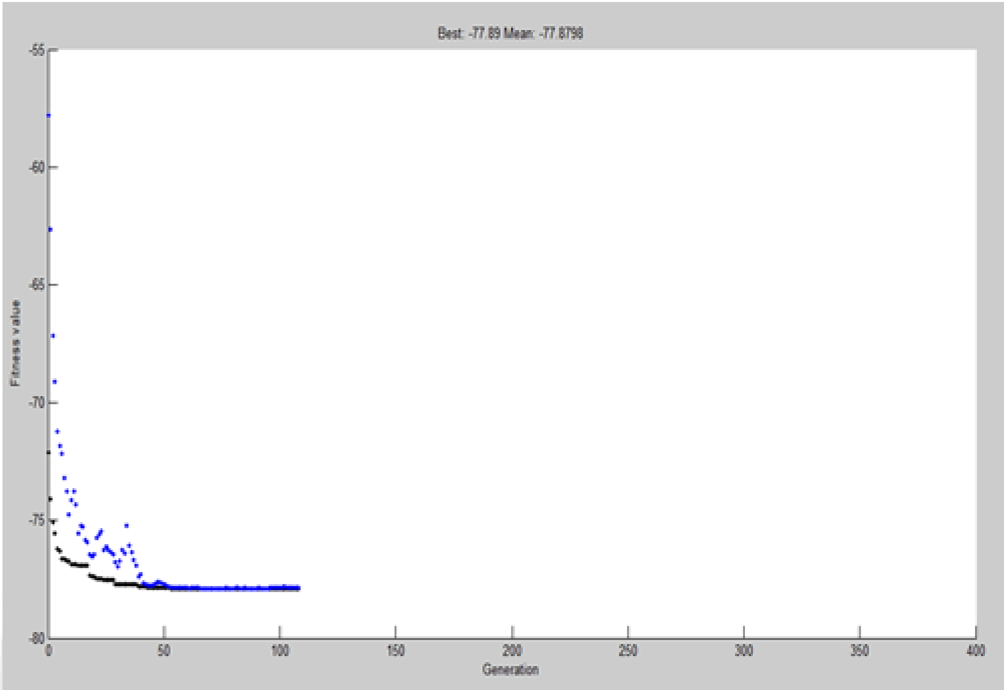

Fig 9. Optimum output value of shear strength in the genetic algorithm optimization

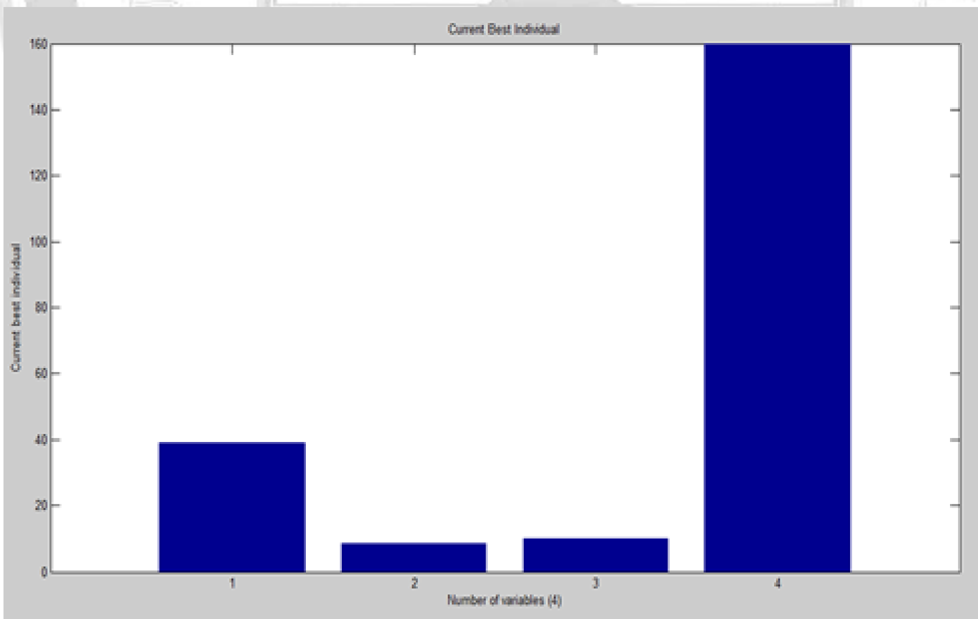

Fig 10. The best input parameters in genetic algorithm optimization.

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4. Conclusions

The effects of pulse shape on the quality of similar pure high conductivity copper C101 welds joined using the Nd-YAG laser have been evaluated over a range of power intensity, pulse width, frequency and linear speed. Three different pulse shapes have been used; normal (rectangular), ramped-down and modulated pulses. The modulated pulses have stronger strengths than ramped-down and normal pulses. All welds fractured out the interface between two sheets of pure copper. No defects observed in the nugget zone with all three pulse shapes. There was no significant difference indicated between normal and ramped-down pulses. More uniform of modulated pulses during welding than other pulses. The genetic algorithm showed that the optimum magnitude achieved for the shear strength was 77.9 MPa, and the optimum input parameters were pulse energy of 39J pulse width of 8.5ms, a frequency of 10Hz, and linear speed of 160mm/min.

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تأثير أشكال النبض على قابلية اللحام للنحاس عالي التوصيل C101 بواسطة ليزر Nd-YAG

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خلاصة

تم لحام وصلات تراكب مماثلة من صفائح رقيقة من النحاس النقي C101 باستخدام اللحام بالليزر النبضي. تم دراسة تأثير معاملات اللحام بالليزر على الخواص الميكانيكية. أظهرت النتائج التجريبية أنه يمكن الحصول على وصلات خالية من عيوب الصوت من وصلات نحاسية – نحاسية مماثلة حيث يحدث الكسر بعيدًا عن خط اللحام. يقترح العمل الحالي تحسين التحكم في التصميم لثلاثة أشكال مختلفة للنبض؛ مستطيلة (عادية)، منحدرة لأسفل ومعدلة وتستخدم في لحام ست عينات نحاسية مختلفة لتحقيق أقصى قوة شد وقص للمفاصل. أوضحت النتائج أن شكل النبضة المعدلة هو الأمثل في اختبار شد القص. كان لشكل النبضة المنحدرة تأثير أقل أهمية على قوة المفصل النحاسي عند مقارنته بشكل النبضة المستطيلة. تم الحصول على العلاقة بين معلمات الإدخال والإخراج من خلال استخدام برنامج Minitab، وتم استخدام برنامج Matlab للوصول إلى الحل الأمثل. أظهرت الخوارزمية الجينية أن المقدار الأمثل الذي تم تحقيقه لقوة القص كان 77.9 ميجا باسكال، وكانت معلمات الإدخال المثلى هي طاقة النبضة البالغة 39 جول وعرض النبضة 8.5 وتردد 10 هرتز والسرعة الخطية 160 ملم / دقيقة.

الكلمات الدالة: مفصل مماثل، لحام بالليزر، أشكال نبضية، اختبار قص الشد، نبض معدل.

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