

EFFECT OF PARAMETERS IN REPAIR WELDING OF PLASTIC MOLD STEEL WITH Nd: YAG LASER WELDING PROCESS

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Abstract

Laser welding is widely used across various industries, including automotive, aerospace, and jewelry manufacturing. Mold repair welding, in particular, has become a critical focus, aiming to efficiently restore molds to their original state before any damage occurs. This study investigates the parameters that influence weld integrity, specifically pulse frequency and pulse duration, while examining the macro and microstructural aspects of the welds and evaluating their hardness values. By employing a combination of plastic injection mold steel (AISI P20) and Nd: YAG laser welding, the research reveals that increasing these parameters expanded the weld bead, with optimal settings identified as a pulse frequency of 7 Hz and a pulse duration of 5, 6, and 7 ms, ensuring comprehensive welds while minimizing incomplete fusion defects. The heat input ranged from 116 to 468.3 J/mm, directly correlating with pulse duration and pulse frequency. The welds exhibited acicular martensitic structures, with coarse grains in the weld metal (WM) and fine grains in the heat-affected zone (HAZ) due to rapid cooling, resulting in increased hardness. The hardness values ranged from 320.4 to 413 HV.

Keywords: AISI P20; Nd: YAG laser welding process; Plastic mold steel; Repair welding

Introduction

The mold industry is a crucial supporting sector that caters to almost every type of manufacturing industry, as various manufacturing processes rely on molds to shape and define the quality and size of products. A well-made mold enables manufacturing industries to produce parts rapidly and in large quantities with standardized shapes and sizes, reducing losses incurred during manufacturing and enhancing competitiveness (Mack, 2000; Altan *et al.*, 2001; Poli, 2001; Swift and Booker, 2003).

Among the different materials used for molds, P20 steel is widely employed for making plastic injection molds due to its desirable properties, including rapid resistance to temperature changes, high strength at elevated temperatures, toughness, and wear resistance. However, prolonged usage of P20 steel molds can lead to deterioration, resulting in cracking, chipping, or surface damage, rendering the mold unusable.

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Repair welding of molds using the same material (P20) via laser welding is an effective method to restore molds to near-original condition. Laser welding offers several advantages, including the capability for automated welding, high welding speeds, minimal heat-affected zones, and the ability to weld in deep and intricate areas without distorting nearby workpieces (Dawes, 1992; Adams and Kwiatkowski, 1994; Silva *et al.*, 2008; Steen and Mazumder, 2010; Katayama, 2013; Fotovvati *et al.*, 2018). In Thailand, laser welding is extensively used in mold repair, automotive component manufacturing, and even jewelry or accessory production (Bridigum, 2008; Huda, 2016).

Despite its widespread use, there is a need for detailed studies on the specific parameters that influence weld integrity in the laser welding process, particularly for repair welding of plastic injection molds made of P20 steel. Previous research has primarily focused on the general advantages of laser welding and its applications in various industries. However, there is limited information on the optimal welding parameters, such as pulse frequency and pulse duration, their effects on the weld's macrostructural and microstructural characteristics, and the resulting hardness values (Preciado and Bohorquez, 2006; Buddery *et al.*, 2009; Kramár *et al.*, 2012; Caiazzo and Caggiano, 2018; Hekmatjou and Naffakh-Moosavy, 2018; Jiang *et al.*, 2019; Kumar *et al.*, 2023).

This study aims to address this research gap by investigating the effects of pulse frequency and pulse duration on weld integrity using Nd: YAG laser welding of AISI P20 steel. By examining both macrostructural and microstructural aspects of the welds and evaluating their hardness values, this research seeks to identify the optimal welding parameters that ensure comprehensive and defect-free welds. The findings of this study will provide valuable insights and guidelines for effectively utilizing these parameters in repairing plastic

injection molds, ensuring operational efficiency comparable to or close to the original condition before the damage occurred. Additionally, this research builds on previous work by providing a detailed analysis of the influence of specific laser welding parameters, thus contributing to the broader body of knowledge in the field of laser welding technology (Junkes *et al.*, 2020; Kapil *et al.*, 2020; Mack, 2000).

Materials and Methods

Experimental Setup

The Nd: YAG laser welding process was utilized to repair plastic injection mold steel (AISI P20). The experimental setup is depicted in Figure 1. The Nd: YAG laser emits pulsed light using the generated heat to melt the material. The laser operates in a square pulsed wave mode, with a nominal output power of 200 W and a peak power of 9 kW. The pulse duration range is 0.5-20 ms, and the pulse frequency range is 1-50 Hz. Argon gas was used as a shielding gas to reduce oxidation with a flow rate of 8 L/min. The welding speed was set to 50 mm/min (Table 1).

Materials

The base material used was plastic mold steel (AISI P20) with workpiece dimensions of 100×200 mm and 10 mm thickness. The chemical compositions were analyzed by an Energy Dispersive X-ray Fluorescence Spectrometer (ED-XRF) and are listed in Table 2. P20-grade steel welding wire with a diameter of 0.6 mm was used for welding. ED-XRF also analyzed the chemical composition of the welding wire. Furthermore, the research methodology was divided into several parts according to the research objectives as follows: 2.1 Parameter value investigation affecting welds, 2.2 Study of the metallurgical structure of welds 2.3 Heat input Calculation 2.4 Testing the hardness

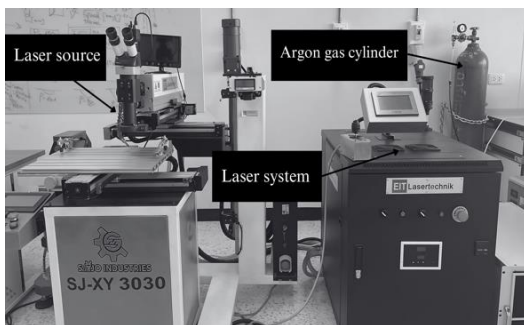


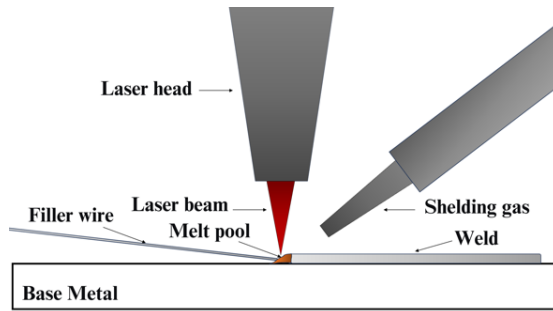
Figure 1. Experimental setup of Nd: YAG laser welding

Table 1. Experimental condition of the laser welding

Specification	Value
Laser mode	Square pulsed wave
Nominal output Power (W)	200
Peak power (kW)	9
Pulse duration range (ms)	0.5-20
Pulse frequency range (Hz)	1-50 Hz
Shielding gas	Argon
Gas flow rate (L/min)	8
Welding speed (mm/min)	50

Table 2. Chemical composition of plastic injection mold steel (AISI P20)

Plastic Injection Mold Steel AISI P20 (%mass)	
Aluminum (Al)	0.84
Vanadium(V)	0.03
Chromium (Cr)	1.37
Manganese (Mn)	1.13
Iron (Fe)	96.2
Nickel (Ni)	0.30
Copper (Cu)	0.09
Molybdenum (Mo)	0.20
Welding wire grade P20 (%mass)	
Aluminum (Al)	1.29
Vanadium(V)	0.04
Silicon (Si)	1.18
Manganese (Mn)	1.43
Iron (Fe)	89.27
Nickel (Ni)	0.59
Copper (Cu)	6.20

**Figure 2. Bead-on-plate welding with P20 steel**

of the weld, and 2.5 Analysis of the effects of parameters on welds using statistical methods.

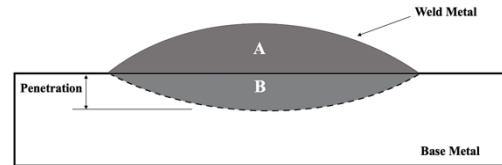
Study of Parameters Affecting Welds

Pulse duration (PD) and pulse frequency (PF) were varied. Preliminary experiments indicated that parameter values below the specified range did not melt the welding wire while exceeding the range was limited by machine constraints. Based on these findings, the study was conducted with PD values of 5, 6, and 7 ms and PF values of 5, 7, and 9 Hz (Srithorn and Saengsan, 2023). Bead-on-Plate Welding: The bead-on-plate welding method was used, as depicted in Figure 2. An appropriate laser welding machine current of 160 A was set for effective melting. Argon gas was used as a shielding gas with a flow rate of 8 L/min, and the welding speed was 50 mm/min.

Study of the Metallurgical Structure of the Welding

Welded specimens were prepared, cut along the cross-section using an EDM wire cut machine, mounted, and polished. Polishing was done using alumina powder with a particle size of 0.3 microns,

followed by etching with 2% Nital acid solution (Silva *et al.*, 2008). The macrostructure and microstructure of the welds were examined using optical microscopy and scanning electron microscopy (SEM).

**Figure 3. The dilution of the metal**

For the % dilution, which indicates the extent to which the original metal area mixes with the welding wire, increasing dilution alters the properties of the welded metal area. Dilution is calculated using Equation (1) and shown in Figure 3.

$$\% \text{ dilution} = \frac{B}{(A+B)} (100) \quad (1)$$

Where: A represents the area of the molten parent plate, and B represents the area enclosed by the bottom line.

Heat Input Calculation

The heat input calculation in this research, which involves welding with Nd: YAG laser welding process, is represented by Equation (2) (Kumar and Sinha, 2019). The current value is measured using a clamp meter in units of amperes (A).

$$HI = \left(\frac{P \times T \times f}{V} \right) \times \eta \quad (2)$$

Where: HI is the heat input into the workpiece (J/mm), P is the peak power (kW), T is the pulse duration (ms), f is the pulse frequency (Hz), V is the scanning speed (mm/s), and η is the welding efficiency, assumed to be 1 (or 100%) for practical purposes and to simplify calculations.

Testing the Hardness of the Weld

Vickers hardness tests were conducted using an FM-800 Vickers hardness tester. A pyramidal diamond-shaped indenter with an angle of 136° was used to apply a test load of 1,000 gf with a dwell time of 10 sec. Indentations were made at six points along the weld seam to create a microhardness profile, starting from the HAZ, moving to the WM, and descending to the BM, with 100 μ m between points (Figure 4).

The micro vickers hardness test aims to compare the hardness of the weld metal (WM), heat-affected zone (HAZ), and base metal (BM) using different experimental parameters.

Statistical Analysis of Parameter Effects on Welding Characteristics

Statistical parameter analysis using Minitab software to analyze statistical data, demonstrating the relationship between each variable in welding. It analyzes the 27 factorial experiments at a confidence level of 95% ($P\text{-Value} < 0.05$), considering pulse duration factors of 5, 6, and 7 ms and frequency factors of 5, 7, and 9. The analysis is conducted based on Pareto Chart graphs showing whether Factor A (pulse duration) influences Factor B (pulse frequency), along with an examination of Normal Probability Plot graphs for data distribution. Versus Fits graphs examine data dispersion from the mean, indicating data variability as a measure of data deviation. Histogram and versus-order graphs also observe continuous distribution patterns, assessing data independence, as shown in Figure 5.

By following this detailed methodology, the study aimed to investigate the optimal welding parameters for repairing plastic injection molds made of AISI P20 steel using the Nd: YAG laser welding process. The experimental setup and procedures were designed to ensure reproducibility and accuracy in the results.

Results and Discussion

Impact of Parameters on Weld Profile

Figure 6 displays weld beads obtained with different pulse durations (PD) and pulse frequencies (PF) using an Nd: YAG laser welding process. Each sample demonstrates the impact of varying these parameters on the weld characteristics.

The effect of welding parameters on the weld was determined by setting parameters and calculating the average weld width, as shown in Figure 7. The average weld height was 437 μm , while the average weld width was determined to be 1,855 μm , and the average % dilution of the metal was calculated to be 32.43% according to Equation (1).

The average width of the weld for each parameter is observed. It is found that increasing the pulse duration (PD) and pulse frequency (PF) leads to a corresponding increase in the weld width (Srihorn and Saengsan, 2023), as shown in Figure 7. An example of the bead-on-plate weld characteristics using laser welding and similar macrostructure features is shown in Table 3. Moreover, there is a close similarity in the average

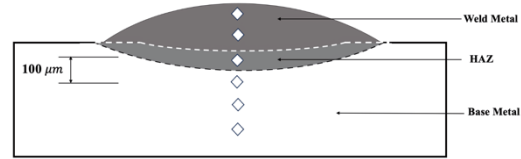


Figure 4. The position of the hardness test points

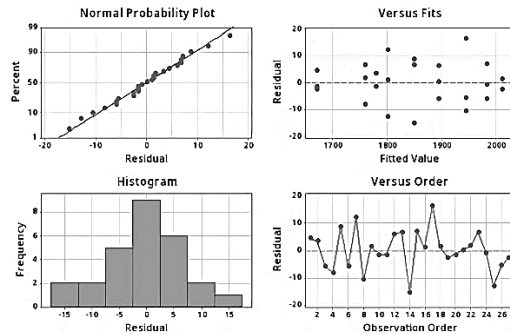


Figure 5. Residual plots analysis graph

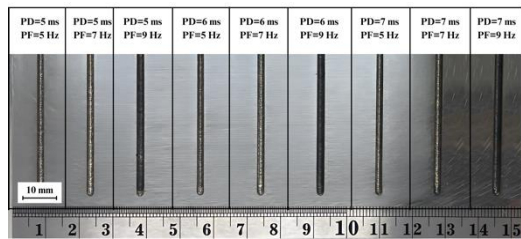


Figure 6. Shows the welding characteristics obtained from pulse duration (PD) and pulse frequency (PF)

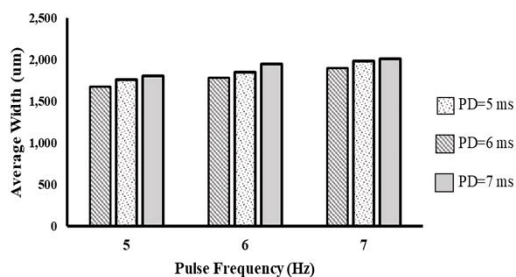


Figure 7. The average width of the weld for each parameter

%dilution, with an average of 32.43 and a standard deviation of 2.79.

Increasing Pulse Duration (PD) leads to wider weld beads due to the higher amount of energy delivered per pulse, resulting in more material melting. Similarly, increasing Pulse Frequency (PF)

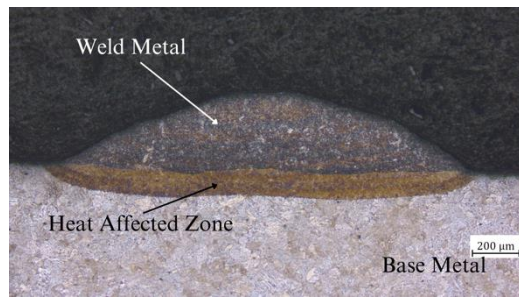


Figure 8. Macrostructure of the workpiece with a pulse duration of 7 ms and pulse frequency of 7 Hz, examined under a microscope

Table 3. Bead-on-plate welding and macrostructure of complete welds

Parameters	Bead-on plate	Macrostructure
PD=5 ms PF=7 Hz		
PD=6 ms PF=7 Hz		
PD=7 ms PF=7 Hz		

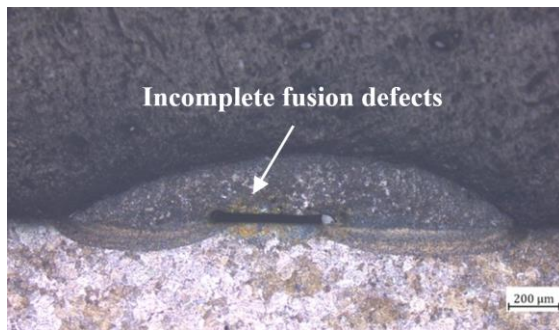


Figure 9. The characteristics of welds with incomplete fusion defects

Table 4. Heat input values corresponding to various parameters

No	Peak power (kW)	Scanning speed (mm/s)	PD (ms)	PF (Hz)	Heat input (J/mm)
1	5.3	1.2	5	5	116
2	6.7	1.2	5	7	204.8
3	7.5	1.2	5	9	295.9
4	5.7	1.2	6	5	150.0
5	7.2	1.2	6	7	262.5
6	8.2	1.2	6	9	387.5
7	6.2	1.2	7	5	187.8
8	7.7	1.2	7	7	329.1
9	8.8	1.2	7	9	468.3

also results in wider weld beads as the number of pulses per second increases, thus increasing the overall heat input. The combined effect of higher pulse duration and higher pulse frequency maximizes the energy input, resulting in the widest weld beads. The image shows that both pulse duration and frequency significantly influence the weld characteristics, and their effects are cumulative.

Macrostructure analysis of the welds was conducted using a microscope, providing magnified images of the weld structure produced by various welding parameters, as shown in Figure 8, magnified 50X. This image reveals the regions of the Weld Metal (WM), Heat-Affected Zone (HAZ), and Base Metal (BM). The HAZ appears narrower and smaller than the weld metal region (Adams and Kwiatkowski, 1994; Katayama *et al.*, 2013; Fotovvati *et al.*, 2018).

While examining the macrostructure under a microscope, researchers observed welds. They found that these complete welds occurred when the pulse duration (PD) was set between 5 and 7 ms and the pulse frequency (PF) was 7 Hz. Furthermore, defective welds were observed to occur at parameters where the pulse frequency was set at

5 and 9 Hz, indicating incomplete fusion defects. (Vedani, 2004; Silva *et al.*, 2008), as shown in Figure 9. These parameters are inappropriate and will not be considered in the weld hardness testing.

Effects of Heat Input on Welded Workpieces

When calculating the heat input into the welded workpieces, with parameters related in Table 4, it is found that the heat input for all nine experiments ranges between 116.0-468.3 J/mm. It is observed that there is a direct correlation with both pulse duration and pulse frequency, where an increase in these parameters increases heat input. Therefore, the parameters affecting laser welding are pulse duration and pulse frequency. In this experiment, the optimal welding conditions yield a heat input of 204.8 J/mm (PD=5, PF=7), 262.5 J/mm (PD=6, PF=7), and 329.1 J/mm (PD=7, PF=9), respectively.

Metallographic Microstructure Analysis

Metallographic examination at the microscopic level of the workpiece, conducted after various testing processes and using scanning electron microscopy (SEM), yields microstructure images, as shown in Figure 10. The weld metal (WM) microstructure and the heat-affected zone

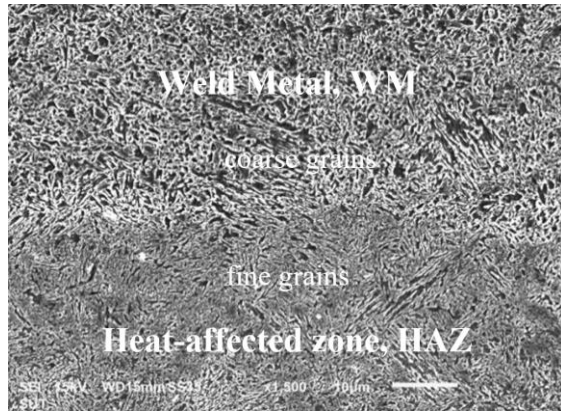


Figure 10. The weld metal (WM) microstructure and the heat-affected zone (HAZ)

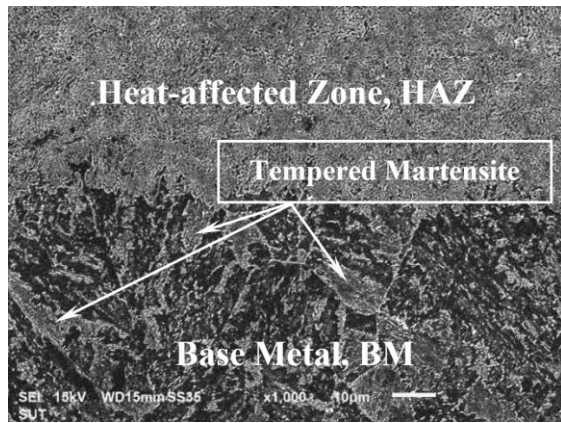


Figure 11. Shows the microstructure of the base metal (BM) and the heat-affected Zone (HAZ)

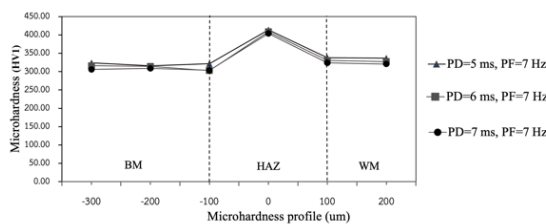


Figure 12. Microhardness profile of the welds under different parameters

(HAZ) are depicted. The weld metal (WM) exhibits an acicular martensitic structure characterized by coarse grains (Li *et al.*, 2018), while the heat-affected zone (HAZ) shows an acicular martensitic structure with fine grains, primarily due to rapid cooling.

Figure 11 shows the heat-affected zone (HAZ) microstructure and the base metal (BM) of AISI P20 plastic mold steel magnified 1,000 times. It reveals

a tempered martensite structure (Silva *et al.*, 2008). The HAZ shows a transition from the coarse-grained structure of the WM to finer grains. This fine-grained structure results from the thermal gradient experienced in the HAZ, where the metal is heated to temperatures below the melting point but high enough to cause recrystallization and grain refinement upon cooling. The rapid cooling in this zone leads to the formation of fine acicular martensite. The base metal (BM) appears unaffected by the welding heat, resulting in minimal to no alteration in the microstructure of the AISI P20 plastic mold steel.

Hardness testing results of the welds

Hardness testing results of the welds were obtained using a Micro Vickers hardness test to compare the hardness of the weld metal (WM), heat-affected zone (HAZ), and base metal (BM). The tests were conducted with pulse durations (PD) set at 5, 6, and 7 ms and a pulse frequency (PF) set at 7 Hz, with measurements taken at six points along the weld. The average hardness values of the welds, as shown in Figure 12, are consistent with those in Table 5. The HAZ with PD = 5 ms and PF = 7 Hz exhibited the highest hardness, with the weld metal being harder than the base metal. However, hardness testing was not performed for welds with pulse frequencies set at 5 and 9 Hz due to incomplete fusion, rendering these parameters unsuitable, as shown in Figure 9.

Table 5. Results of the average hardness testing of the welds

Parameters	Average hardness (HV1.0)		
	WM	HAZ	BM
PD=5 ms PF=7 Hz	337.2	413.8	320.4
PD=6 ms PF=7 Hz	328.9	408.7	311.0
PD=7 ms PF=7 Hz	322.4	403.8	306.0

Table 5 and Figure 12 show that as the pulse duration increases, it leads to a corresponding increase in heat input. Higher heat input values result in lower cooling rates, affecting the hardness. This is evidenced by the fact that the hardness at a pulse duration of 7 ms is lower than at pulse durations of 6 and 5 ms, respectively. All hardness values exhibit a base metal (BM) tempered martensite microstructure. The heat-affected zone (HAZ) displays a microstructure of fine-grained acicular martensite, while the weld metal (WM)

Table 6. The value obtained from the analysis using MINITAB software

Source	DF	F-Value	P-Value
Model	8	485.92	0.000
Linear	4	959.47	0.000
Pulse	2	543.28	0.000
Frequency	2	1,375.67	0.000
2-Way Interactions	4	12.37	0.000
Pulse*Frequency	4	12.37	0.000
Model Summary			
S	R-sq	R-sq (adj)	R-sq (prwd)
8.85515	99.54%	99.33%	98.96%

exhibits a microstructure of coarse-grained acicular martensite, as illustrated in Figures 10 and 11.

The highest hardness values in the HAZ are consistent with the rapid cooling effect, which increases the hardness due to the formation of fine martensitic structures (Vedani, 2004). The observed decrease in hardness with increased pulse duration is due to lower cooling rates from higher heat input, leading to softer microstructures, as also reported by Silva *et al.* (2008).

The appropriate hardness values for both WM and HAZ are within the range of 30-34 HRC (302-336 HV 1.0 kg) (Silva *et al.*, 2008). Table 5 and Figure 12 shows that the parameters recommended for all three welding adaptations have suitable hardness values, making them applicable for repairing plastic injection molds.

Statistical Analysis Results of Parameters Impact on Welds

The analysis of weld width was conducted by considering two factors: pulse duration and pulse frequency. Weld width was measured according to the experimental design conditions, totaling nine experiments, with each experiment repeated three times to determine the main factors significantly affecting weld width. Statistical analysis of factors A (pulse duration) and B (pulse frequency) at a 95% confidence level revealed that the main factors affecting the experimental response or weld width were factors A (pulse duration) and B (pulse frequency), as they had P-values less than 0.05. Furthermore, the combined effects of these factors were analyzed, and it was found that the interaction factor A*B (pulse duration * pulse frequency) also had a P-value less than 0.05, indicating that these combined factors influenced the weld width in the experiment.

Statistical values of weld width were analyzed using Minitab 19 software. The decision-making coefficients were analyzed for variance concerning the experimental response. The decision-making coefficient during the experiment was 99.54%,

and after adjustment, it was 99.33%, as shown in Table 6. This high coefficient indicates the reliability of the response values resulting from the experimental factors. A decision-making coefficient approaching 100% signifies greater reliability.

This analysis demonstrates the significant impact of pulse duration and pulse frequency on weld width and their interaction, thereby ensuring the reliability and validity of the experimental results.

Conclusions

This research investigated the influence of various welding parameters on the weld profile of plastic injection mold steel (AISI P20) using an Nd: YAG laser and P20 grade steel wire (0.6 mm diameter). Both macrostructural and microstructural examinations were conducted on the workpieces. The metallographic analysis of the macrostructure revealed that the heat-affected zone (HAZ) was narrower and smaller in dimension than the weld metal (WM) area, indicating a localized thermal impact from the laser welding process.

At the microstructural level, the base metal (AISI P20 steel) maintained a tempered martensite structure with negligible changes in hardness, suggesting minimal microstructural alterations. In contrast, the weld metal (WM) exhibited acicular martensitic structures with coarse grains, while the HAZ featured fine grains due to rapid cooling, resulting in higher hardness in the HAZ compared to the WM.

The heat input to the welded workpieces, ranging from 116.0 to 468.3 J/mm, was directly proportional to pulse duration and pulse frequency. Increased pulse duration and frequency led to higher heat input, thereby affecting the weld profile and characteristics. The study found that increasing the pulse duration and frequency resulted in a wider weld profile. These two parameters had a combined effect on the weld profile.

Optimal welding parameters were identified as a pulse frequency of 7 Hz and pulse durations between 5 to 7 ms, which achieved complete welds without incomplete fusion defects. These settings produced welds that closely matched the standard hardness values for P20 plastic injection molds.

In conclusion, the optimal welding parameters for Nd: YAG laser welding of AISI P20 steel are a pulse frequency of 7 Hz and pulse durations between 5 and 7 ms. These parameters ensure complete, defect-free welds with appropriate hardness for repairing plastic injection molds. The findings underscore the significance of controlling pulse duration and frequency to achieve

desired weld characteristics and structural integrity. This conclusion is supported by Adams and Kwiatkowski's investigation, which demonstrated the critical impact of laser welding parameters on weld quality, and Fotovvati *et al.*'s review, which detailed the influence of process parameters on melt-pool dynamics and microstructure formation (Adams and Kwiatkowski, 1994; Fotovvati *et al.*, 2018).

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References

- Adams, J.T. and Kwiatkowski, J.J. (1994). Nd-YAG laser welding of the fiber optic connector to the header shell on the 2SL actuator EG and G Mound Applied Technologies, Miamisburg, OH (United States). No. MLM-3790. <https://doi.org/10.2172/10122837>
- Altan, T., Lilly, B., and Yen, Y.C. (2001). Manufacturing of dies and molds. *CIRP Annals*, 50(2):404-422. [https://doi.org/10.1016/S0007-8506\(07\)62988-6](https://doi.org/10.1016/S0007-8506(07)62988-6)
- Bridigum, T. (2008). *How to Weld*. 1st ed. Motorbooks, 208p.
- Buddery, A., Dargusch, M.S., StJohn, D.H., Drennan, J., and Nabulsi, S. (2009). Laser welding of titanium and its alloys for medical applications: Current knowledge and future direction. *Materials Science Forum*, 618-619:291-294. <https://doi.org/10.4028/www.scientific.net/MSF.618-619.291>
- Caiazzo, F. and Caggiano, A. (2018). Investigation of laser welding of Ti alloys for cognitive process parameters selection. *Materials*, 11(4):632. <https://doi.org/10.3390/ma11040632>
- Dawes, C. (1992). *Laser Welding*. Woodhead Publishing, 258p.
- Fotovvati, B., Wayne, S.F., Lewis, G., and Asadi, E. (2018). A review on melt-pool characteristics in laser welding of metals. *Advances in Materials Science and Engineering*, 2018(1):920718. <https://doi.org/10.1155/2018/4920718>
- Hekmatjou, H. and Naffakh-Moosavy, H. (2018). Hot cracking in pulsed Nd: YAG laser welding of AA5456. *Optics and Laser Technology*, 103:22-32. <https://doi.org/10.1016/j.optlastec.2018.01.020>
- Huda, Z. (2016). *Welding and Joining Processes*. Materials Processing for Engineering Manufacture, 462p.
- Jiang, D., Alsagri, A.S., Akbari, M., Afrand, M., and Alrobaian, A.A. (2019). Numerical and experimental studies on the effect of varied beam diameter, average power and pulse energy in Nd: YAG laser welding of Ti6Al4V. *Infrared Physics and Technology*, 101:180-188. <https://doi.org/10.1016/j.infrared.2019.06.006>
- Junkes, R., Howarth, J.L.L., Becker, D., and Bond, D. (2020). Properties evaluation of semi-crystalline and amorphous polymers injected in AISI P20 molds repaired by welding. *Matéria (Rio de Janeiro)*, 25(03):e-12786. <https://doi.org/10.1590/s1517-707620200003.1086>
- Kapil, S., Legesse, F., Negi, S., Karunakaran, K.P., and Bag, S. (2020). Hybrid layered manufacturing of a bimetallic injection mold of P20 tool steel and mild steel with conformal cooling channels. *Progress in Additive Manufacturing*, 5:183-198. <https://doi.org/10.1007/s40964-020-00129-3>
- Katayama, S. (2013). Introduction: fundamentals of laser welding. In: *Handbook of laser welding technologies*. Woodhead Publishing Series in Electronic and Optical Materials, p. 3-16. <https://doi.org/10.1533/9780857098771.1.3>
- Kramár, T., Michalec, I., and Kovacoc, P. (2012). The laser beam welding of titanium grade 2 alloy. *GRANT J*, 1:77-79.
- Kumar, P. and Sinha, A.N. (2019). Effect of heat input in pulsed Nd: YAG laser welding of titanium alloy (Ti6Al4V) on microstructure and mechanical properties. *Welding in the World*, 63:673-689. <https://doi.org/10.1007/s40194-018-00694-w>
- Kumar, U., Chattopadhyaya, S., Das, A.K., Seikh, A.H., Sharma, S., Dwivedi, S.P., Nagai, K., Kumar, A., Agrawal, A., and Singh, S. (2023). Effect of pulsation in microstructure and mechanical properties of titanium alloy-annealed welded joints at different temperatures. *Photonics*, 10(4):372. <https://doi.org/10.3390/photonics10040372>
- Li, H.X., Qi, H.L., Song, C.H., Li, Y.L., and Yan, M. (2018). Selective laser melting of P20 mould steel: investigation on the resultant microstructure, high-temperature hardness and corrosion resistance. *Powder Metallurgy*, 61(1):21-27. <https://doi.org/10.1080/00325899.2017.1368965>
- Mack, W.C. (2000). *Worldwide Guide to Equivalent Irons and Steels*. 4th ed. ASM Material Data Series, ASM International, Materials Park, OH.
- Poli, C. (2001). *Design for Manufacturing: a Structured Approach*. Butterworth-Heinemann. Elsevier Science & Technology Books, 130p.
- Preciado, W.T. and Bohorquez, C.E.N. (2006). Repair welding of polymer injection molds manufactured in AISI P20 and VP50IM steels. *Journal of Materials Processing Technology*, 179(1-3):244-250. <https://doi.org/10.1016/j.jmatprotec.2006.03.101>
- Silva, B., Pires, I., and Quintino, L. (2008). Welding technologies for repairing plastic injection moulds. *Materials Science Forum*, 587-588:936-940. <https://doi.org/10.4028/www.scientific.net/MSF.587-588.936>
- Silva, B., Pires, I., Quintino, L., and Miranda, R. (2008). New welding procedures for repairing H13 and P20 tool steels. In: *5th Luso-Mozambican International Engineering Congress*.
- Srithorn, J. and Saengsan, K. (2023). The study of parameters affecting weld bead by welding SS400 grade carbon steel materials with Nd: YAG laser welding process. In: *The Conference of Industrial Engineering Network (IE NETWORK 2023)*, May 11-12, 2023, Brighton Grand Hotel Pattaya, Chonburi, Thailand, p. 83-84.
- Steen, W.M. and Mazumder, J. (2010). *Laser Material Processing*. 4th ed. Springer, 558p. <https://doi.org/10.1007/978-1-84996-062-5>
- Swift, K.G. and Booker, J.D. (2003). *Process Selection: From Design To Manufacture*. Elsevier, 316p. <https://doi.org/10.1016/B978-0-7506-5437-1.X5000-8>
- Vedani, M. (2004). Microstructural evolution of tool steels after Nd-YAG laser repair welding. *Journal of Materials Science*, 39:241-249. <https://doi.org/10.1023/B:JMSC.0000007750.16970.4e>