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Experimental investigation of WEDM process parameters for the machining of as-built and heat-treated SLM AlSi10Mg

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Abstract

Although additive manufacturing (AM) technology offers significant advantages in terms of geometric complexity and material efficiency, the lack of optimization in post-processing procedures of advanced alloys such as AlSi10Mg, which are widely used in high-precision sectors including aerospace, automotive, and defense, remains a major limitation for sustainable production. Despite the superior mechanical properties of AlSi10Mg alloys, such as their lightweight and high strength, their machinability is not compatible with all processing techniques. This limitation directly affects the surface quality, mechanical performance, and production efficiency of components fabricated by AM. Therefore, in the present study, we systematically investigate the effects of heat treatment and Wire Electrical Discharge Machining (WEDM) input parameters on AlSi10Mg alloys. The specimens, produced by selective laser melting (SLM) and heat-treated via furnace cooling (FC), were analyzed to evaluate the influence of WEDM process parameters. An L9 orthogonal array of the Taguchi method was utilized to model these effects. Pulse-on time, pulse-off time, and wire feed rate were considered as control parameters. Material removal rate (MRR) and Surface roughness (R_a) were evaluated as response variables. Microstructural and surface characteristics of the samples were examined to evaluate the effects of process parameters. The results indicated that FC heat treatment improved microstructural homogeneity, surface quality, and machinability. According to the ANOVA results, pulse-on time was identified as the dominant factor governing both MRR and R_a , while wire feed rate showed a secondary but consistent influence, particularly on MRR. This research provides experimental data for optimizing post-processing operations by revealing the combined effects of heat treatment and WEDM parameters on AlSi10Mg alloys.

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1. Introduction

Additive Manufacturing (AM) technologies have gained significant importance in manufacturing over the past few years. This technology provides design flexibility with its layer-by-layer production method, minimizing material waste while potentially increasing production speed. One advantage of AM over traditional manufacturing methods is its ability to produce complex geometries directly. Selective Laser Melting (SLM) is a widely preferred method among metal-based AM technologies, especially for producing lightweight, high-strength materials such as AlSi10Mg alloys (Yılan et al., 2024). However, parts produced via SLM often exhibit machinability issues, including surface roughness and internal stresses. These challenges necessitate post-processing to improve machinability and the final part quality (Galati et al., 2023).

During AM processes, especially when manufacturing complex geometries, support structures must be added to the parts. These support structures are crucial for processing overhanging features and completing the production process. However, these structures must be carefully removed during post-processing. Improper or incomplete removal can lead to mechanical damage or unwanted defects in the part (Jiang et al., 2018). In this context, Wire Electrical Discharge Machining (WEDM) technology is an ideal solution for precisely cutting support structures in SLM-produced AlSi10Mg alloys. WEDM enables high-precision cutting of these structures without damaging the workpiece, ensuring no imperfections are left behind. As a result, WEDM has become an essential method for post-processing AMed parts in recent years (Şentürk et al., 2025).

In the literature, the effects of WEDM process parameters on surface roughness and material removal rate (MRR) have been widely studied for AM-produced AlSi10Mg parts (Murali Krishnan et al., 2025). (Franczyk et al., 2021) examined the WEDM processing of AlSi10Mg alloys, using samples produced by SLM and casting methods. Their study investigated the effects of SLM laser scanning speed and WEDM current amplitude on surface roughness, showing that SLM-produced parts exhibited better surface quality than cast samples. (Vaidyaa et al., 2021) optimized the multi-objective WEDM parameters for AlSi10Mg alloys, achieving maximum microhardness (478 VHN) and minimizing surface roughness (4.33 μm) with a discharge current of 12 A, discharge voltage of 42 V, and pulse-on time of 12 μs . Validation tests confirmed that the predicted results matched the experimental data with 98% accuracy. Additionally, white layer analysis revealed that microhardness increased near the HAZ region and that surface quality improved by 15.25%. (Calignano and Mercurio, 2024) has conducted studies on improving the surface roughness of AlSi10Mg alloy, which is widely used in the production of lightweight components in the aerospace and automotive sectors, after fabrication by powder bed AM technologies, using WEDM. During AM production, components are placed on the platform and supported by support structures made of the same material to ensure stability. These support structures stabilize overhanging surfaces and reduce thermal stresses. When the structure permits, the part can be directly fixed to the build platform, eliminating the need for additional support structures and allowing mechanical removal, resulting in suitable surfaces for assembly. Based on the literature, this study investigates the combined effects of heat treatment followed by furnace cooling and WEDM process parameters on the machinability of SLM-produced AlSi10Mg alloys. Specifically, the effects of processing parameters such as pulse-on time, pulse-off time, and wire feed rate on material removal rate (MRR) and surface roughness (R_a) are experimentally examined using the Taguchi L9 orthogonal design method. Furthermore, microstructure evaluations, surface morphology analyses, X-ray diffraction (XRD) analysis, and microhardness measurements are conducted to support the experimental findings. As a result, this study provides valuable experimental data for optimizing post-processing strategies for AlSi10Mg components produced by AM.

2. Materials and methods

2.1. Feedstock powder, SLM, and heat treatment processes

The ERMAK A461 AlSi10Mg alloy powder used in this study, with a particle size range of 15–50 μm , was supplied by ERMAKSAN (Türkiye). To evaluate the suitability of the feedstock powder for the SLM process, its morphological characteristics and chemical composition were analyzed.

The morphology and chemical composition of the AlSi10Mg powder were characterized using scanning electron microscopy (SEM) coupled with energy-dispersive X-ray spectroscopy (EDS), as presented in Fig. 1. As shown in Fig. 1a and 1b, the powder particles exhibit a predominantly spherical morphology with smooth surfaces, which is favorable for uniform powder spreading and stable melting behavior during the SLM process.

The EDS spectrum and elemental analysis shown in Fig. 1c confirm that aluminum (Al), silicon (Si), and magnesium (Mg) are the main constituent elements of the AlSi10Mg powder. Minor amounts of Fe, Ni, Cu, and Zn were also detected, which fall within the typical compositional range of AlSi10Mg alloys. The presence of C and O signals in the EDS spectrum is attributed to the graphite tape used during SEM sample preparation.

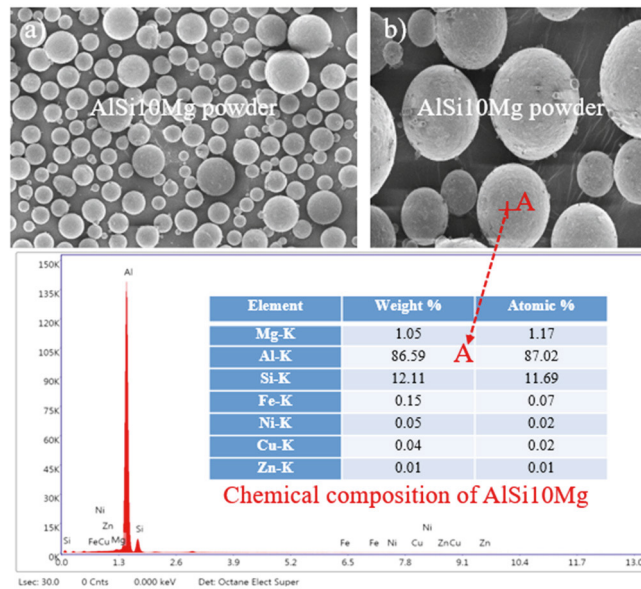


Fig. 1. (a) 200 $\times$ magnification, (b) 1000 $\times$ magnification SEM images of AlSi10Mg; and (c) the EDS point analysis of AlSi10Mg alloy powder.

In this study, AlSi10Mg specimens were manufactured using a powder bed fusion (PBF)–based SLM process. During fabrication, a thin layer of AlSi10Mg powder was uniformly spread over the build platform, and a laser beam was selectively scanned over the powder bed according to a predefined scanning strategy. The powder particles were melted and consolidated layer by layer to produce the specimens. All SLM processes were carried out under an argon protective atmosphere to prevent oxidation.

For the experiments of this paper, the following parameters were applied:

- Laser beam power of 320W.
- Scanning speed of 800mm/s.
- Layer thickness: 30 μm .
- Hatch spacing: 100 μm .
- Laser spot diameter: 85 μm .

After the SLM process, the fabricated specimens were divided into two groups. One group was retained in the as-built condition, while the other underwent a post-processing heat treatment. A solution heat treatment (SHT) followed by furnace cooling (FC) was applied using a Protherm Furnaces PLF 130/3 furnace (Alser Technic Ceramic Inc.). The specimens were held at 525 $^{\circ}\text{C}$ for 2 h, after which the furnace was turned off, and the samples were allowed to cool slowly within it. This cooling procedure corresponds to FC.

2.2. WEDM parameters and experimental methods

WEDM is a non-contact machining process in which material is removed by controlled electrical discharges between a continuously fed wire electrode and the workpiece. The localized electro-thermal energy generated within a narrow spark gap causes melting and vaporization of the material, while the machining zone is continuously immersed in a dielectric fluid. In this study, WEDM experiments were carried out on both as-built and heat treated specimens using an Ultracut-F1 CNC Wire-EDM machine. The WEDM machine, the schematic representation of the machining process, and the machining zone during operation are illustrated in Fig. 2(a), Fig. 2(b), and Fig. 2(c), respectively. All machining experiments were performed under identical processing conditions to enable a direct comparison of the machining behavior of as-built and heat-treated specimens. Deionized water was used as the dielectric fluid, and a 0.25 mm-diameter brass wire electrode was used throughout the experiments.

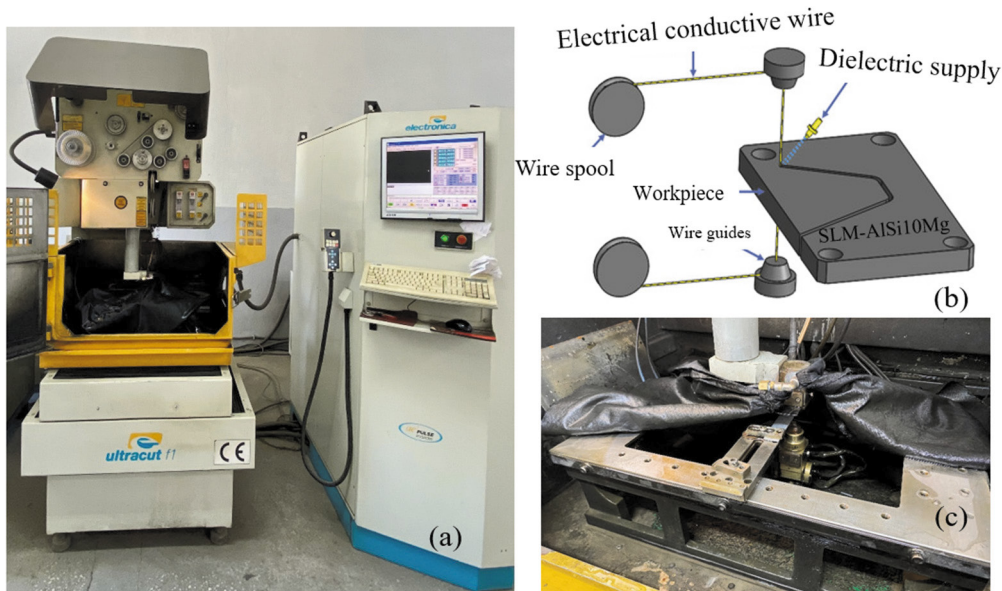


Fig. 2. (a) Experimental setup (b) A schematic illustration of the process (c) Machining process

The experimental design was established using a Taguchi L9 orthogonal array. Wire feed speed (A), pulse off time (B), and pulse on time (C) were selected as the control parameters, each considered at three different levels. The Taguchi experimental layout was generated using Minitab 19 statistical software. The selected WEDM parameters and their corresponding levels employed in the L9 orthogonal array are presented in Table 1.

Based on this experimental design, 9 experimental runs were conducted for each specimen condition. The experimental runs applied to both as-built and heat-treated SLM-AISI10Mg samples are summarized in Table 2. To ensure the reliability of the experimental procedures, the tests for each parameter combination were repeated three times, and the average values were used to evaluate the consistency of the results. This approach enabled a more accurate and repeatable assessment of the effects of different WEDM parameters on the machining performance.

2.3. Measurement of MRR, R_a , and machined surface characterization

Material removal rate (MRR) is one of the most important response parameters for evaluating machining performance, as it is directly related to productivity, surface integrity, and manufacturing efficiency. In the present study, MRR was selected as a key indicator to assess the machinability of both as-built and heat-treated specimens under different WEDM process conditions.

Table 1. WEDM parameters for experiments.

Parameters	Code	Level 1	Level 2	Level 3
The variable parameters				
Wire feed speed (m/s)	A	6	7	8
Pulse off time (μ s)	B	55	58	61
Pulse on time (μ s)	C	110	115	125
The constant parameters				
Peak current (Amps)			0.25	
Wire tension (N)			1	
Dielectric flushing pressure (bar)			1.96	
Servo voltage (V)			30	
Servo feed (mm/min)			10	

Table 2. Experimental runs for as-built and heat treated AlSi10Mg specimens.

#run	Factors		
	Wire feed speed (m/s)	Pulse off time (μ s)	Pulse on time (μ s)
R1	6	55	110
R2	6	58	115
R3	6	61	125
R4	7	55	115
R5	7	58	125
R6	7	61	110
R7	8	55	125
R8	8	58	110
R9	8	61	115

MRR values were determined for each experimental run using the weight-loss method. After each machining operation over a constant cutting length, the specimens were carefully cleaned and dried with compressed air to remove any residual dielectric fluid. The initial and final weights of the specimens before and after machining were measured using a high-precision digital weighing balance with a resolution of 0.1 mg.

MRR was calculated based on the difference between the initial and final weights of the specimen and the corresponding machining time, as expressed in Eq. (1) (Hosalli et al., 2025):

$$MRR = \frac{W_i - W_f}{t}, g/min \quad (1)$$

where W_i and W_f denote the initial and final weights of the specimen, respectively, and t represents the machining duration. This procedure ensured accurate, repeatable determination of MRR values across all experimental conditions.

The surface quality of the WEDM-cut samples was evaluated using a Zygo ZeGage 3D non-contact optical profiler together with the Advanced Texture Application software. Surface roughness (R_a) measurements were performed directly on the cut surfaces in order to assess the machinability of the material after WEDM processing. For each specimen, measurements were taken from three different locations along the machined surface, and the average R_a

value was reported to improve measurement reliability and minimize local surface effects.

Microstructural characterization was conducted on both as-built and heat-treated specimens. Prior to analysis, the samples were ultrasonically cleaned and then subjected to sequential grinding and polishing to remove surface scratches. After polishing, all specimens were etched for 20 s using Keller's reagent prepared with a volumetric ratio of HF, HCl, HNO₃, and H₂O as 1:1.5:2.5:95. Following the etching process, the microstructural features and surface morphologies of both specimen groups were examined using a field emission scanning electron microscope (FE-SEM, Zeiss Gemini 500). X-ray diffraction (XRD) analyses were performed to determine the phase composition and crystallographic structure of both as-built and furnace-cooled SLM- AlSi10Mg specimens. The measurements were carried out using a Cu-tube PANalytical Empyrean X-ray powder diffractometer. During the XRD measurements, the tube voltage and current were set to 40 kV and 30 mA, respectively. Diffraction patterns were recorded over a 2θ scanning range of 20° – 110° with a step size of 0.02° . The obtained diffraction data were analysed using Match! 3 software to identify and interpret the phase constituents of the samples. Microhardness measurements were performed on both as-built and heat-treated specimens using a Micro-Vickers hardness tester. For each specimen, 10 indentations were made at different locations on the surface, and the average value was reported as the microhardness.

3. Results and discussion

3.1. Experimental analysis and optimization for MRR

Table 3 presents the Taguchi response analysis results for the MRR obtained from as-built and heat-treated specimens. The relative influence of the Wire-EDM control parameters was evaluated using delta statistics, defined as the difference between the maximum and minimum mean response values for each factor. For both material conditions, pulse-on time exhibits the strongest influence on MRR, ranking first with delta values of 0.856 for as-built and 0.838 for heat-treated specimens. Wire feed speed is identified as the second-most-influential parameter, with delta values of 0.574 and 0.489, respectively. In contrast, pulse-off time has the least effect on MRR and ranks third in both material conditions. The consistency of the parameter ranking indicates that the dominant machining mechanism governing material removal remains unchanged for as-built and heat-treated specimens, although the absolute MRR values differ due to the applied post-heat treatment.

Table 3. Taguchi analysis: MRR for different factors.

Response variable	As-built SLM- AlSi10Mg			Heat-treated SLM- AlSi10Mg		
Factors	A	B	C	A	B	C
1	3.319	3.693	3.224	2.709	3.130	2.562
2	3.705	3.611	3.614	3.037	2.958	2.981
3	3.893	3.614	4.080	3.198	2.856	3.400
Delta	0.574	0.082	0.856	0.489	0.274	0.838
Rank	2	3	1	2	3	1

Figure 3 presents the experimental MRR results and the corresponding signal-to-noise (S/N) ratio analyses for as-built and heat-treated specimens. Figure 3(a) shows the MRR values obtained for as-built series under different experimental conditions. The MRR varies approximately between 1.40 g/min and 1.65 g/min, with the minimum at R1 and the maximum at R7. This variation indicates that MRR is highly sensitive to changes in machining parameters that directly affect the discharge energy.

The average S/N ratios for MRR of as-built specimens are illustrated in Fig. 3(b) using the larger-is-better criterion. Based on the S/N analysis, pulse-on time is identified as the most dominant parameter influencing MRR, with a contribution ratio of 67.03%. This is followed by wire feed speed, which accounts for 30.76%, whereas pulse-off time has a very limited influence, accounting for only 1.09%. These results demonstrate that increasing pulse-on time significantly enhances material removal by increasing the effective discharge energy.

Figure 3(c) presents the MRR results for heat-treated specimens. Compared to the as-built condition, a systematic reduction in MRR is observed for all experimental runs. The MRR values range from approximately 1.32 g/min to 1.54 g/min, with the highest MRR again obtained under the R7 condition. This behavior indicates that heat treatment followed by FC reduces the overall material removal capability while preserving the relative trends among the machining parameters.

The S/N ratio analysis for heat-treated specimens is shown in Fig. 3(d). Similar to the as-built condition, pulse-on time remains the most influential parameter, contributing 67.54%, followed by wire feed speed at 23.99%. The contribution of pulse-off time increases to 8.08%, although it still remains less influential than the other parameters. The results show that heat treatment followed by furnace cooling decreases the MRR. However, the relative influence of the machining parameters remains unchanged, and pulse-on time remains the dominant parameter controlling MRR.

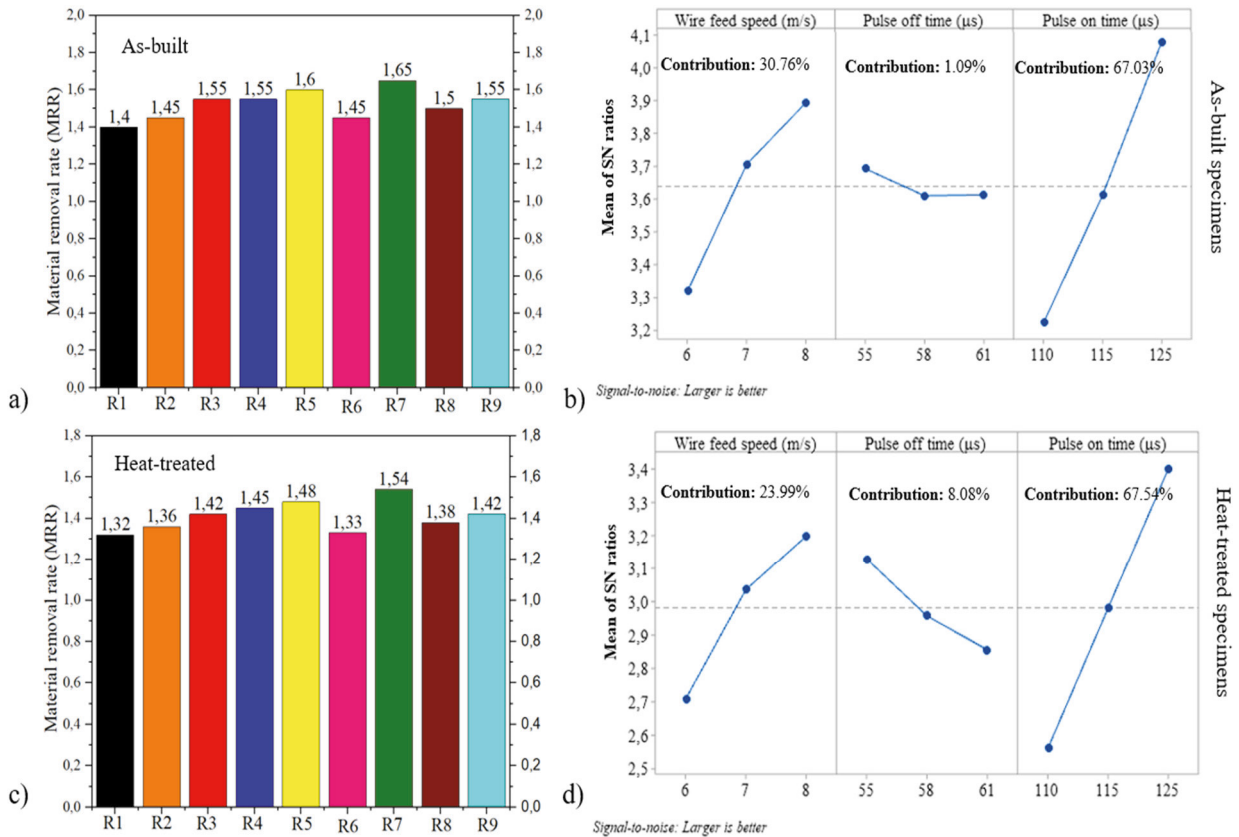


Fig. 3. a) MRR values of as-built series, b) Average S/N Ratios for as-built specimens in MRR, c) MRR values of heat-treated SLM-AISI10Mg and d) Average S/N Ratios for heat-treated SLM-AISI10Mg in MRR.

Table 4 summarizes the analysis of variance (ANOVA) results for the mean MRR of as-built and heat-treated specimens. The statistical significance of the WEDM control parameters was evaluated at a 95% confidence level ($\alpha = 0.05$) based on the p-values and F-statistics.

For the as-built specimens, wire feed speed (WF) and pulse-on time (T_{on}) exhibit statistically significant effects on MRR, with p-values of 0.034 and 0.016, respectively. Among the investigated factors, T_{on} shows the strongest influence, evidenced by the highest F-value of 61.00, followed by WF with an F-value of 28.00. In contrast, pulse-off time (T_{off}) does not present a statistically significant effect on MRR within the investigated range ($p = 0.500$, $F = 1.00$). The model's adequacy is supported by a high coefficient of determination ($R^2 = 98.90\%$) and an adjusted R^2 of 95.60%.

For the heat-treated specimens, all three parameters are statistically significant, with p-values of 0.015 for WF, 0.044 for T_{off} , and 0.006 for T_{on} . Similar to the as-built condition, T_{on} remains the dominant parameter with the highest F-value ($F = 180.14$), indicating a markedly stronger sensitivity of MRR to T_{on} after heat treatment followed by FC. WF also shows a significant contribution ($F = 64.00$), while T_{off} becomes statistically significant ($F = 21.57$). The ANOVA model for the FC condition demonstrates high reliability, as indicated by $R\text{-sq} = 99.63\%$ and $R\text{-sq}(\text{adj}) = 98.50\%$. Overall, the ANOVA results confirm that T_{on} governs MRR for both material conditions, while heat treatment followed by FC increases the statistical significance of T_{off} .

Table 4. ANOVA for Means of MRR.

As-built specimens						Heat-treated specimens			
Source of Variance	DF	Adj SS	Adj MS	F	P	Adj SS	Adj MS	F	P
WF	2	0.015556	0.007778	28.00	0.034	0.009956	0.004978	64.00	0.015
T_{off}	2	0.000556	0.000278	1.00	0.500	0.003356	0.001678	21.57	0.044
T_{on}	2	0.033889	0.016944	61.00	0.016	0.028022	0.014011	180.14	0.006
Error	2	0.000556	0.000278			0.000156	0.000078		
Total	8	0.050556				0.041489			
Significance		$R\text{-sq}=98.90\%$	$R\text{-sq}(\text{adj})=95.60\%$			$R\text{-sq}=99.63\%$	$R\text{-sq}(\text{adj})=98.50\%$		

Combining the Taguchi response analysis (Table 5), S/N ratio evaluation (Fig. 3), and ANOVA results (Table 4), it is confirmed that pulse-on time is the dominant parameter governing the MRR for both as-built and heat-treated specimens. Based on the MRR response, the optimal WEDM parameter combination is identified as A3–B1–C3, corresponding to the highest wire feed speed, the lowest pulse-off time, and the highest pulse-on time levels.

3.2. Experimental analysis and optimization for R_a

Table 5 presents the Taguchi response analysis results for surface roughness (R_a) obtained from as-built and heat-treated specimens. The relative influence of the control parameters on R_a was evaluated using delta statistics, defined as the difference between the maximum and minimum mean S/N ratio values for each factor.

Table 5. Taguchi analysis: R_a for different factors.

Response variable	As-built specimens			Heat-treated specimens		
Factors	A	B	C	A	B	C
1	-5.701	-6.205	-5.706	-6.767	-7.332	-6.784
2	-7.206	-6.851	-6.659	-8.159	-7.775	-7.603
3	-7.917	-7.767	-8.458	-8.898	-8.717	-9.437
Delta	2.216	1.562	2.751	2.130	1.384	2.653
Rank	2	3	1	2	3	1

For as-built specimens, the pulse-on time exhibits the strongest influence on R_a , ranking first with a delta value of 2.751. This indicates that variations in pulse-on time lead to the most pronounced changes in surface roughness. The wire feed speed is identified as the second most influential parameter with a delta value of 2.216, whereas the pulse-off time shows the lowest effect on R_a , ranking third with a delta value of 1.562. A similar trend is observed for heat-treated specimens. Pulse-on time remains the dominant factor affecting R_a , with the highest delta value of 2.653. Wire feed speed again ranks second with a delta value of 2.130, while pulse-off time exhibits the lowest contribution to surface roughness, with a delta value of 1.384.

The consistent ranking obtained for both material conditions indicates that the governing mechanism controlling surface roughness does not change with heat treatment followed by FC. Although the absolute S/N ratio values differ

due to the applied post-heat treatment, pulse-on time remains the primary parameter influencing R_a , followed by wire feed speed, while pulse-off time has a comparatively minor effect.

Figure 4 presents the surface roughness (R_a) results obtained for as-built and heat-treated specimens together with the corresponding signal-to-noise (S/N) ratio analyses. Figure 4(a) shows the R_a values measured under different experimental conditions for as-built specimens. The R_a values range approximately from 1.41 to 2.80 μm . The minimum surface roughness is obtained under the R1 condition (1.41 μm), whereas the maximum R_a value is recorded at the R7 condition (2.80 μm). These variations indicate that surface integrity is highly sensitive to changes in the WEDM processing parameters.

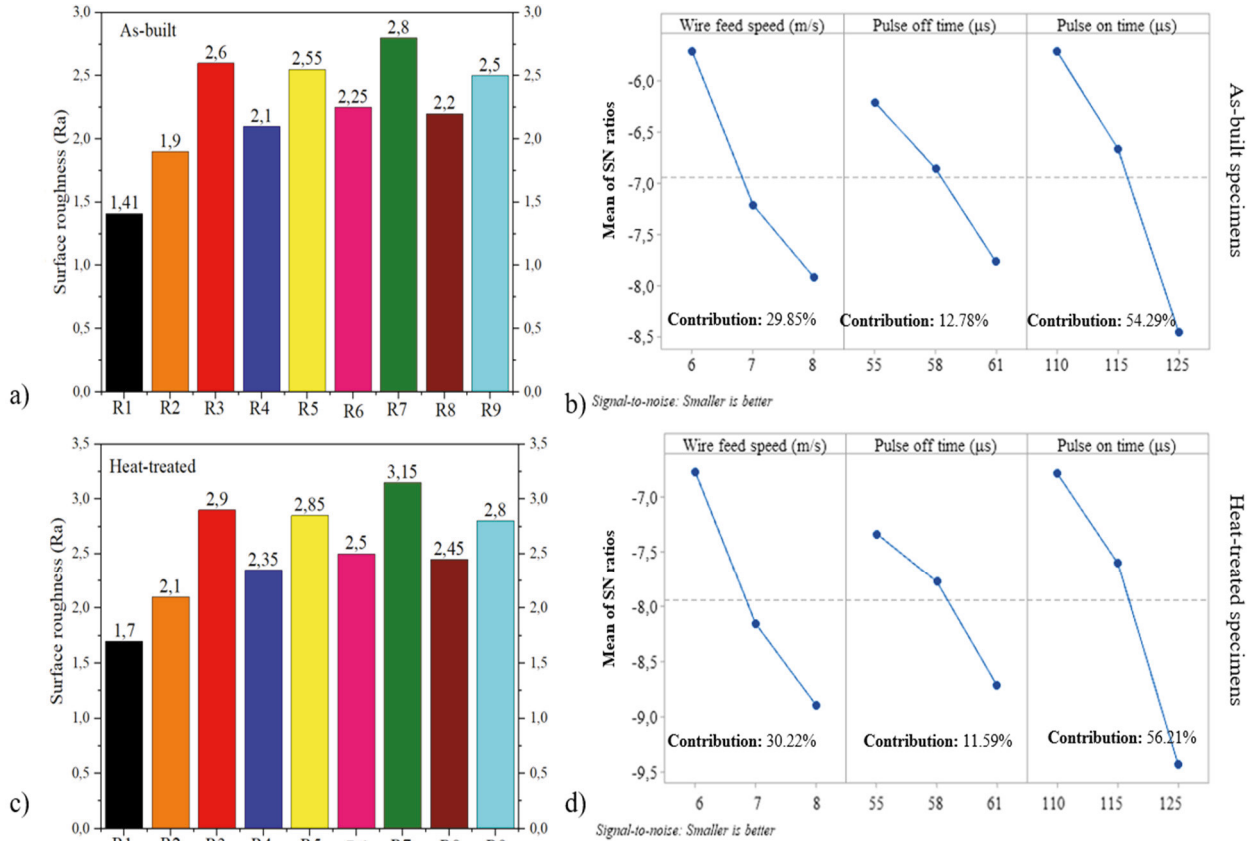


Fig. 4. a) R_a values of as-built SLM-ALSi10Mg, b) Average S/N Ratios for as-built SLM-ALSi10Mg in R_a , c) R_a values of heat-treated SLM-ALSi10Mg, and d) Average S/N Ratios for heat-treated SLM-ALSi10Mg in R_a .

The average S/N ratios for R_a of as-built series are illustrated in Figure 4(b) based on the “smaller-is-better” criterion. According to the contribution analysis, pulse-on time is identified as the most dominant parameter affecting R_a , with a contribution ratio of 54.29%. This is followed by wire feed speed with a contribution of 29.85%, while pulse-off time exhibits a comparatively lower contribution of 12.78%. The S/N trend clearly indicates that increasing the pulse-on time from 110 μs to 125 μs results in a pronounced deterioration in surface quality, whereas lower pulse-on times yield smoother machined surfaces.

Figure 4(c) presents the R_a values obtained for heat-treated specimens. In this case, the R_a values range approximately from 1.70 μm to 3.15 μm . The lowest R_a value is again observed at the R1 condition (1.70 μm), while the highest surface roughness is measured at the R7 condition (3.15 μm). Compared to the as-built specimens, a systematic increase in R_a is observed for all experimental runs, indicating that heat treatment by FC adversely affects the surface finish, although the overall trend across the experimental conditions remains similar.

The S/N ratio analysis for R_a of heat-treated specimens is shown in Figure 4(d). Pulse-on time remains the most influential parameter, accounting for 56.21% of the contribution. Wire feed speed ranks second, contributing 30.22%, while pulse-off time contributes 11.59% to the overall variation in R_a . These results confirm that surface roughness is predominantly governed by pulse on time, while wire feed speed plays a secondary role. This optimal condition corresponds to the highest S/N ratio levels observed in Fig. 4(b) and Fig. 4(d). Overall, Figure 4 clearly reveals that pulse-on time is the controlling parameter for surface roughness in both as-built and heat-treated specimens. Although heat treatment followed by FC increases R_a values, the relative influence order of the machining parameters on surface roughness remains unchanged.

Table 8 presents the analysis of variance (ANOVA) results for the mean surface roughness (R_a) obtained from as-built and heat-treated specimens. The ANOVA results were used to evaluate the statistical significance of the machining parameters on R_a at a 95% confidence level.

For the as-built SLM- AlSi10Mg specimens, T_{on} exhibits the highest contribution to R_a variation, with an F-value of 18.26, indicating that T_{on} is the most influential parameter governing surface roughness. WF shows a moderate influence, with an F-value of 10.04, whereas T_{off} has a relatively minor effect on R_a , as reflected in its lower F-value of 4.33. Although none of the parameters strictly meet the $p < 0.05$ significance criterion for the as-built, T_{on} exhibits a borderline statistical significance ($p = 0.05$) and remains the dominant factor controlling surface quality according to the Taguchi analysis. The high coefficient of determination ($R^2 = 97.03\%$) confirms that the developed model reliably represents the experimental data.

In the case of heat-treated specimens, T_{on} becomes statistically significant with a p-value of 0.034 (< 0.05) and the highest F-value of 28.58, thereby confirming its governing role on surface roughness after heat treatment followed by FC. WF shows a secondary influence ($F = 15.37$), while T_{off} again exhibits the least effect ($F = 5.89$). The high R^2 value of 98.03% further indicates a strong correlation between the selected parameters and the R_a response. Based on the combined evaluation of the Taguchi response analysis, S/N ratio trends (Fig. 4), and ANOVA results (Table 6), the parameter combination A1-B1-C1 yields the lowest surface roughness within the investigated parameter range. This optimized condition corresponds to a low WF, a short T_{off} , and a short T_{on} , resulting in reduced discharge energy per pulse and improved surface finish during the WEDM process.

Table 6. ANOVA for Means of R_a .

Source of Variance	As-built specimens					Heat-treated specimens			
	DF	Adj SS	Adj MS	F	P	Adj SS	Adj MS	F	P
WF	2	0.40722	0.20361	10.04	0.091	0.48667	0.24333	15.37	0.061
T_{off}	2	0.17556	0.08778	4.33	1.888	0.18667	0.09333	5.89	0.145
T_{on}	2	0.74056	0.37028	18.26	0.052	0.90500	0.45250	28.58	0.034
Error	2	0.04056	0.02028			0.03167	0.01583		
Total	8	1.36389				1.61000			
Significance		R-sq=97.03%	R-sq (adj)=88.11%			R-sq=98.03%	R-sq (adj)=92.13%		

Figure 5 presents the three-dimensional surface topography of the as-built and heat-treated samples machined under identical WEDM conditions ($WF = 6 \text{ m/s}$, $T_{\text{off}} = 55 \text{ }\mu\text{s}$, $T_{\text{on}} = 110 \text{ }\mu\text{s}$), corresponding to the optimal parameter set identified for minimum surface roughness (R_a). As shown in Fig. 5a, the machined surface of the as-built specimens exhibited a relatively uniform topography with moderate height variations. However, localized surface peaks and valleys remain observable, indicating residual surface irregularities resulting from rapid melting solidification cycles during the WEDM process. These features are consistent with the SEM observations (Fig. 8a), where resolidified debris and globular structures contribute to local roughness variations.

In contrast, the heat-treated specimen (Fig. 5b) displayed a smoother, more homogeneous surface profile, with reduced height fluctuations and a more evenly distributed surface texture. The attenuation of sharp surface asperities suggests that heat treatment promoted a more stable discharge–material interaction during WEDM. This behavior can be attributed to stress relaxation and microstructural homogenization induced by the heat treatment, which reduces the material's susceptibility to localized melting instabilities. The observed differences in surface topography are in

good agreement with the quantitative R_a measurements presented in Fig. 4, where the heat-treated specimens consistently exhibited slightly higher R_a values but maintain similar parametric trends compared to the as-built condition. Moreover, the smoother height distribution in the heat-treated condition supports the MRR findings (Fig. 3), indicating that although heat treatment followed by FC slightly reduced material removal efficiency, it enhanced surface stability during machining. Overall, the 3D surface topography analysis confirms that the optimized WEDM parameters effectively minimize surface roughness for both material conditions, while heat treatment followed by FC contributes to a more uniform surface morphology. These results demonstrate that the combined optimization of heat-treatment and machining parameters is critical for balancing surface quality and material-removal behavior in SLM-AlSi10Mg alloys.

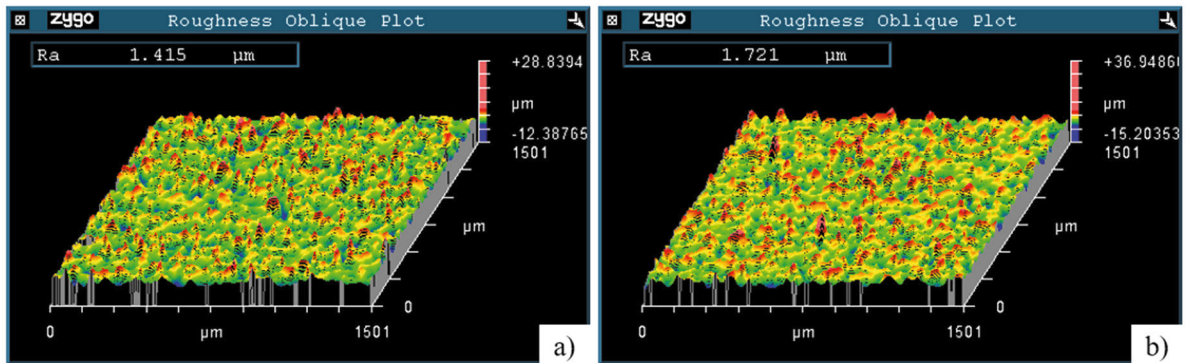


Fig. 5. 3D surface topography of SLM-AlSi10Mg parts machined with the same process parameters ($WF = 6\text{ m/s}$, $T_{\text{off}} = 55\text{ }\mu\text{s}$, $T_{\text{on}} = 110\text{ }\mu\text{s}$) a) as-built and b) heat-treated condition.

3.3. XRD analysis

In the present study, the XRD technique was employed to identify the crystallographic phases of as-built and heat-treated specimens, as shown in Fig. 6. The diffraction patterns are dominated by α -Al peaks, confirming that the primary matrix retains the face-centered cubic (FCC) structure characteristic of aluminum. The main α -Al reflections are observed at approximately $2\theta \approx 38.5^\circ$ (111), 44.7° (200), 65.1° (220), and 78.2° (311), which are consistent with standard Al diffraction data. In addition to the α -Al matrix, diffraction peaks corresponding to crystalline Si are detected at around $2\theta \approx 28.5^\circ$, 47.3° , and 56.2° , indicating the presence of Si-rich phases within the microstructure. The relative intensity of the Si peaks is slightly higher in the heat-treated condition, suggesting reduced Si solubility in the α -Al matrix due to prolonged thermal exposure during cooling.

Moreover, weak but distinguishable diffraction peaks corresponding to the Mg_2Si phase are observed, particularly in the heat-treated specimens. The detection of Mg_2Si indicates partial precipitation of Mg and Si during solidification and subsequent cooling, which is consistent with the Al–Si–Mg alloy system processed under SLM conditions. The presence of Mg_2Si is attributed to the thermal history imposed by the cooling strategy rather than surface-related or post-processing effects. Comparative analysis of peak intensities reveals variations in the relative dominance of the Al (111) and Al (200) reflections between as-built and heat-treated series samples, implying changes in preferred crystallographic orientation (texture). These variations indicate that the applied cooling strategy influences phase stability and crystallographic orientation without introducing any additional secondary phases. Overall, the XRD results confirm that the phase constitution of the SLM-AlSi10Mg alloy consists primarily of α -Al, Si, and minor Mg_2Si phases, and that heat treatment followed by FC mainly affects peak intensity and phase prominence rather than altering the fundamental phase structure (Zhang et al., 2024).

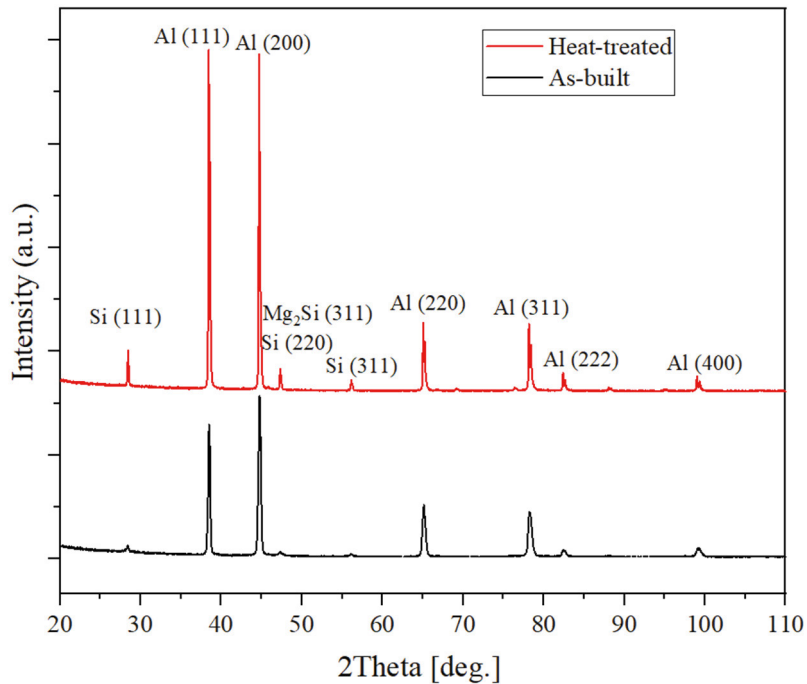


Fig. 6. XRD pattern analysis of AlSi10Mg SLM samples.

3.4. Microstructure analysis

Fig. 7 presents the SEM images and corresponding EDS elemental maps of the as-built and heat treated specimens. In both conditions, Al is observed as the dominant matrix phase, while Si is distributed within the Al matrix in discrete regions. The Mg distribution appears generally uniform; however, a slight reduction of Mg intensity within the Al matrix is observed for the heat-treated specimen. This behavior can be attributed to the formation of Mg_2Si precipitates during heat treatment by FC, which promotes elemental redistribution without introducing additional phases, in agreement with the XRD results.

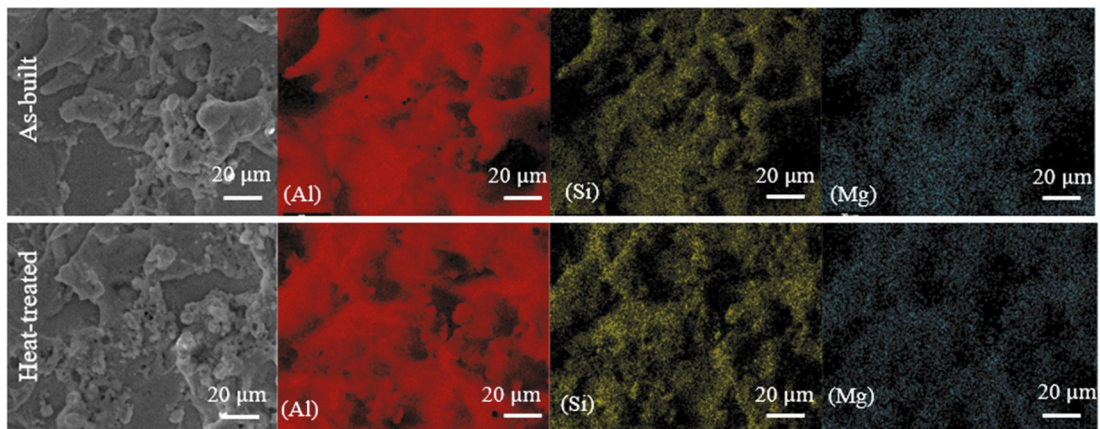


Fig. 7. SEM images showing the EDS maps of specimens in (a) as-built and (b) heat-treated conditions.

Figure 8 shows SEM micrographs of the cut surfaces of the as-built and heat-treated specimen after the WEDM process. For the as-built condition (Fig. 8a), the machined surface exhibits resolidified debris, globules, microcracks, and localized voids. These surface features are associated with the high thermal gradients and rapid melting–solidification cycles occurring during WEDM. The presence of globules and resolidified debris indicates partial reattachment of molten material to the surface, while microcrack formation is mainly attributed to repetitive thermal stresses induced by rapid heating and cooling.

In contrast, the heat-treated series sample (Fig. 8b) displays a comparatively more stable surface morphology. Although craters and resolidified debris are still observed, their distribution appears more uniform, and the occurrence of globules and microcracks is noticeably reduced. The formation of relatively larger but fewer craters in the heat-treated condition suggests a modified interaction between the discharge energy and the thermally stabilized microstructure. The reduced tendency for microcrack formation can be related to stress relaxation and microstructural homogenization achieved through heat treatment followed by FC. Overall, the SEM observations indicate that the surface integrity achieved after WEDM is strongly influenced by the initial microstructural state of the SLM- AlSi10Mg alloy. The as-built samples exhibit more pronounced surface defects such as globules, voids, and microcracks, whereas heat treatment followed by FC yields a more uniform surface morphology with fewer localized defects. These microstructural differences are consistent with the machining performance results, in which the optimal parameters for lower surface roughness (R_a) and improved MRR are closely associated with reduced surface irregularities and enhanced surface stability.

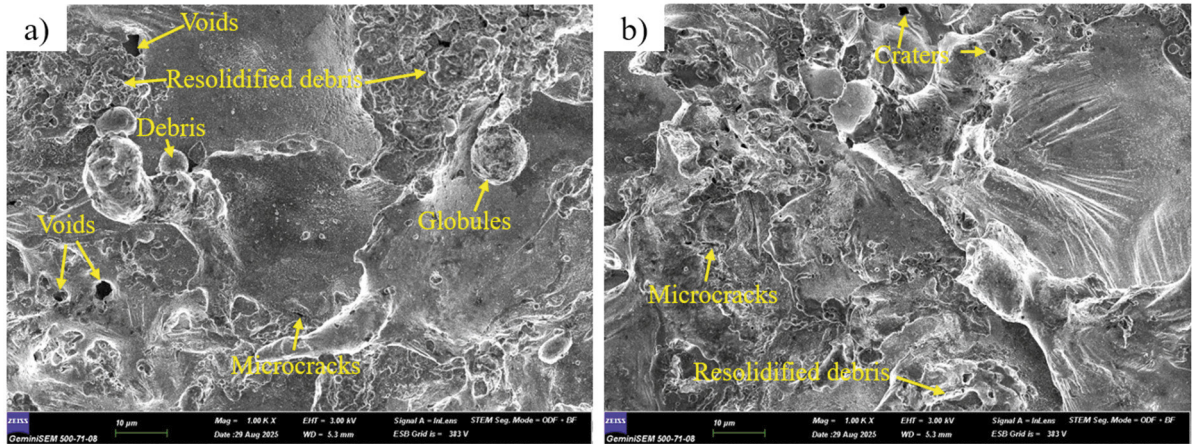


Fig. 8. SEM micrographs of the cut surfaces of SLM- AlSi10Mg samples after WEDM: (a) As-built and (b) heat-treated conditions.

3.5. Microhardness analysis

The microhardness of the SLM- AlSi10Mg samples was measured using the Micro-Vickers hardness test, and the hardness values were calculated according to Equation (2). The measurements were performed on the as-built and heat-treated specimens, and the results are presented in Fig. 9.

$$HV = \frac{1.854P}{D_1 \times D_2} \quad (2)$$

where P represents the applied load, and D_1 and D_2 correspond to the diagonal lengths of the indentation.

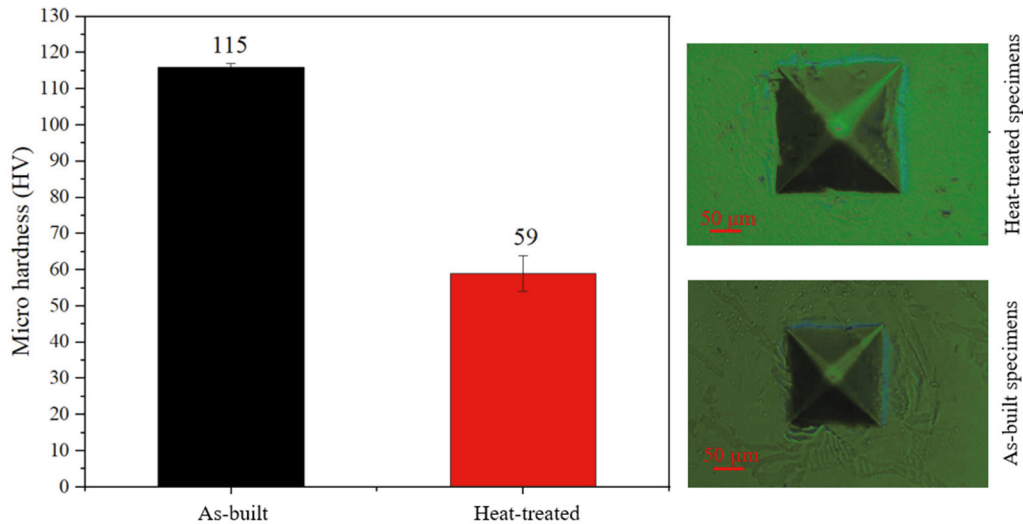


Fig. 9. Micro hardness of as-built and heat-treated SLM-AlSi10Mg specimens.

The as-built specimens exhibited an average Vickers hardness of 115 HV. After heat treatment followed by FC, the hardness decreased significantly. The heat-treated specimens showed an average hardness of 59 HV, corresponding to a 48.63% reduction compared to the as-built condition. This reduction in hardness is associated with stress relief and microstructural coarsening induced by the slow FC rate, which promotes grain growth and reduces dislocation density.

4. Conclusions

This study systematically investigated the influence of furnace cooling heat treatment and Wire Electrical Discharge Machining (WEDM) process parameters on the machinability and surface integrity of AlSi10Mg alloys produced by Selective Laser Melting (SLM). The primary objective was to evaluate how the interplay between post-processing thermal cycles and discharge energy levels affects the material removal performance and final surface quality of additively manufactured components. The analysis of the experiments carried out leads to the following conclusions:

- Pulse-on time (T_{on}) was identified as the most statistically significant parameter governing both MRR and surface roughness (R_a) for both as-built and heat-treated material conditions.
- The heat treatment resulted in a substantial reduction in microhardness from 115 HV to 59 HV, representing an approximately 48.63% decrease attributed to stress relief and microstructural coarsening.
- Heat-treated specimens exhibited a systematic reduction in material removal rate compared to the as-built condition; however the maximum material removal rate achieved was 1.65 g/min for as-built and 1.54 g/min for heat-treated specimens under the A3-B1-C3 parameter setting.
- Optimal surface quality yielded the lowest R_a values of 1.41 μm for as-built specimens and 1.70 μm for heat-treated series.
- SEM analysis confirmed the presence of typical WEDM defects such as micro-cracks, globules, and craters; however, heat treatment was found to promote a more stable surface morphology and reduce the density of micro-cracks.
- XRD diffraction patterns indicated that while the primary α -Al matrix remained unchanged, heat treatment enhanced the visibility of the crystalline Si phase and the precipitation of Mg_2Si .
- Analysis of variance and Taguchi optimization confirmed the high reliability of the experimental results, with

developed regression models showing R-squared values exceeding 97%.

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