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OPTIMIZATION OF SURFACE FINISH OF PLASMA METAL DEPOSITED STAINLESS STEEL 316L PARTS BY UTILIZATION OF PLASMA BEAM REMELTING (PBR) AND TAGUCHI METHODOLOGY

The study aimed to optimize the Plasma Beam Polishing process for 316L stainless steel components to reduce anisotropy and poor surface roughness using statistical analysis. An experimental design investigated the impacts of managing factors on surface roughness, with scanning speed having the ultimate impact, followed by beam power and energy density.

For lower values of plasma energy density and scanning speed, and a focal location without changes on the metal surface, there was a strong tendency for the estimated *Ra* to drop with increasing laser power. The process parameters were changed throughout a broad range of values, making it challenging to model the dependent variable across the whole range of experimental trials. The study supports the potential of PBP as a post-processing method for additive manufacturing components.

Keywords: Metal Additive manufacturing; High beam energy; ANOVA; Surface roughness; Plasma Beam Remelting (PBR)

1. Introduction

In recent decades, additive manufacturing technologies have significantly transformed the manufacturing concept and production principles in various industries. AM technology has numerous advantages such as improved efficiency, especially for low-volume production, increased design flexibility, and reduced reliance on moulds and specialized equipment [1,2]. ASTM has classified widely used AM processes into seven categories, namely directed energy deposition, sheet lamination, powder bed fusion, material extrusion, binder jetting, material jetting, and VAT photopolymerization [3].

Metal additive manufacturing (MAM) builds three-dimensional metal parts by adding material layer by layer using specialized machines. It enables complex geometries, reduced waste, and precise production of metal components for various industries. Metal additive manufacturing (MAM) methods encompass procedures such as electron beam melting (EBM), direct metal deposition (DMD), wire arc additive manufacturing (WAAM), and selective laser melting (SLM). These methods differ primarily in energy source, material type, and precision of the operation mechanism employed. Such variations result in the acquisition of a diverse set of core and outer characteristics [4].

SS316L is a widely studied metallic alloy utilized in additive manufacturing due to its remarkable properties such as ductility, weldability, corrosion and oxidation resistance, biocompatibility, and relatively low cost. However, the inferior surface quality of metal created components has made it difficult for industry developers to disseminate this technology to actual industrial operations [5]. Various mechanical, thermal, or chemical surface modification techniques can be employed as a postprocessing step to enhance surface roughness and other characteristics [6].

Laser polishing utilizes laser energy to improve surface texture, appearance, and overall quality of a material. In this process, a laser beam is directed onto the surface of the material, heating and melting a thin layer. The controlled heating and melting process smoothens surface irregularities, removes imperfections, and refines the surface, resulting in a polished and refined finish. Laser polishing is commonly used in industries like aerospace, automotive, and manufacturing to enhance the appearance and functionality of metallic components and other materials. Furthermore, LP improves repeatability, flexibility, reliable monitoring, and automation, and multiple textures may be created over the same portion [7]. Researchers investigated a novel laser-polishing method was developed and compared metal AM components that are manufactured using AISI 420 stainless steel fabricated through selective laser sintering. The

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technique demonstrated considerable reductions in surface roughness, with *Ra* values decreasing by up to 80% [8]. The ability of the laser-polishing (LP) process to develop the external roughness an AM Inconel 718 alloy components was demonstrated, with manufactured roughness of over 6.98 µm which was decreased to under 0.10 µm using LP [9].

However, Materials having a high reflectivity, on the other hand, are difficult to process with laser polishing. In the early 21st century, electron beam polishing gained popularity as a surface treatment technique, with significant contributions from Sodick Co., Ltd. [10]. Recent studies have shown that the purpose of plasma beams for surface treatment of metals is a promising substitute to traditional high-energy beam methods, including conventional laser beams [11]. After applying plasma beam treatment for three consecutive rounds, the initial surface roughness value of AISI 304 stainless steel was 5.11 µm *Ra*, and after the process, it was reduced to 0.55 µm *Ra*, without any significant alteration in the chemical composition [12]. Plasma beam, within the WAAM classification of ASTM additive manufacturing, can serve as a direct metal deposition process, offering an extra advantage. This implies that the equipment can be employed for both additive manufacturing and post-processing tasks [13].

To the best of authors knowledge, they have used a design experiment tool for the first time in the plasma beam re-melting process parameters. This method of manufacturing could offer a more efficient approach to improving surface roughness beyond what has been reported previously, with normal surface roughness rates of less than 5 microns. The plasma beam remelting process has the capability to generate components with a wide range of applications, particularly for the 316L alloy.

2. Methodology

2.1. Materials and methods

For this experiment, the material used as the workpiece was stainless steel 316L. The specimens were cut into square pieces measuring 50×50×10 mm. The top surface of the sample was machined using electro discharge machining (EDM) to accomplish a specific irregularity. The specimens were first treated with acetone and dried before the polishing procedure.

Taguchi is a popular pattern of experiments that has been extensively utilized in engineering analysis. It entails creating an experimentation schedule with the goal of gathering data in a precise approach. Similarly, the experimental data is analysed using the mean and analysis of variance in this study [14].

The experimental apparatus for plasma additive manufacturing has been built locally (PAM). The experimental configuration for the plasma system used in the study consisted of plasma power source from EWM Germany and 3-axis manipulator system, and an elective wire feeding system operated by a computer, as per the designed configuration. Fig. 1 demonstrates the configuration of the plasma system used in the study. A commercially available software program «Kay,» provided by Delft Spline Systems in the Netherlands was used to control the scanning speed, axis manipulation, and plasma power during the trials. The surface was remelted in an open environment therefore provided with local shielding, creating an argon environment around it. To achieve shielding and generate plasma during the remelting process, two separate argon gas cylinders were utilized. The gas flow rate for shielding was maintained at a constant of 4 l/min, while for pilot arc creation, it was set at 0.5 l/min. During the experiment, the space between the plasma torch and the workpiece, known as the standoff gap, was consistently set at 3 mm. In all trials, nozzles with a diameter of 0.8 mm were used for uniformity. To maintain consistency, each trial was conducted three times, and the most favourable results were recorded.

2.2. Experimental details

The SS316L plate (workpiece) that had already undergone EDM pre-processing and was installed on the worktable before the experiments began. For the experiment, a 90° angle was maintained between the plasma torch and the workpiece.

Fig. 1. Plasma beam remelting [15]

Preliminary tests were carried out, and plasma power and travel speed were varied within a certain range. chosen based on the outcomes of previously published research. Based on previously published findings, The Ar gas flow rate was modified and applied at various levels for both plasma generation and shielding purposes. The material's top surface is remelted to a depth of roughly 0.5 mm, and the melted material is then solidified again to achieve a smoother surface. Adequate plasma power was used to soften the surface peaks and fill up the valley's depth.

The intention was to employ a single-pass approach to achieve enhanced surface roughness. The study aimed to validate the influence of the plasma beam on external roughness by conducting energy density scans at different scan speeds. The remelting process was conducted horizontally. Based on the diameter of the beam 0.80 millimetres, the step-over 10 mm was chosen as the separation to prevent overlap. in between two successive passes. A diagram of the plasma beam remelting approach is shown in Fig. 3.

2.3. Process Parameters and Design

A sequence of straightforward linear tracks makes up the tests performed on a planer surface. A total of 27 tests were conducted, altering the plasma power (P_e) between 298 to 336 W. In the study, the travel speed (W_f) was varied between 10 to 150 mm/min. Track melt and subsequent surface shape in this process are significantly influenced by plasma power and travel speed. Finding the ideal parametric combination to provide a low roughness (R_a) value was the major goal of the test trials. The processing parameters were combined with variations in travel speed and plasma power as shown in TABLE 1.

The roughness of the surface of each sample (remelted track) was measured using a portable surface roughness tester model SJ from Mitutoyo. The roughness parameters for 2D representation were observed using the SJ interface software. SEM analysis was conducted on specific samples using the TASCAN MIRA 3 model. Vickers hardness testing equipment was employed to measure the micro-hardness of both polished and unpolished regions, with measurement of displacement and loading forces during the test. The holding time for the test was set at 10 seconds, and both loading and unloading periods were 5 seconds each. The surface roughness of the untreated sections, measured at 13.852 µm, is presented in Fig. 2.

2.4. Scanning Pattern

The creation and realisation of the scanning route planning throughout the plasma process is another crucial problem. The scan route has long been the subject of research since it is crucial to the plasma beam remelting procedure.

In this research work, we used unidirectional scan pattern to know its effect as schematically represented in Fig. 3. The topology of workpieces is found the various effect of parameters and it helps to find the optimal parameters for surface remelting.

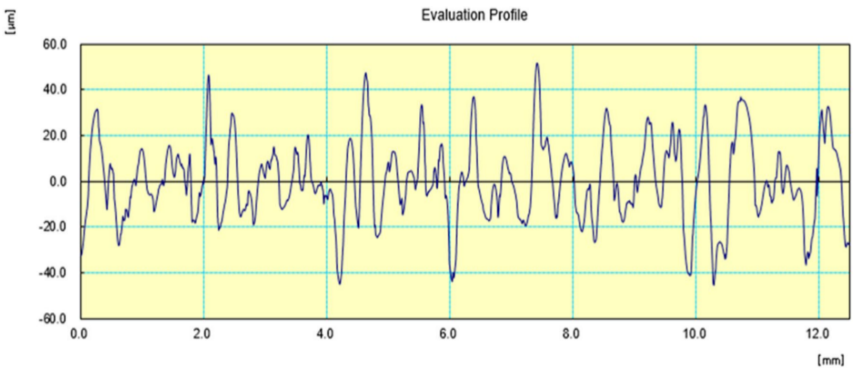


Fig. 2. Initial surface roughness [16]

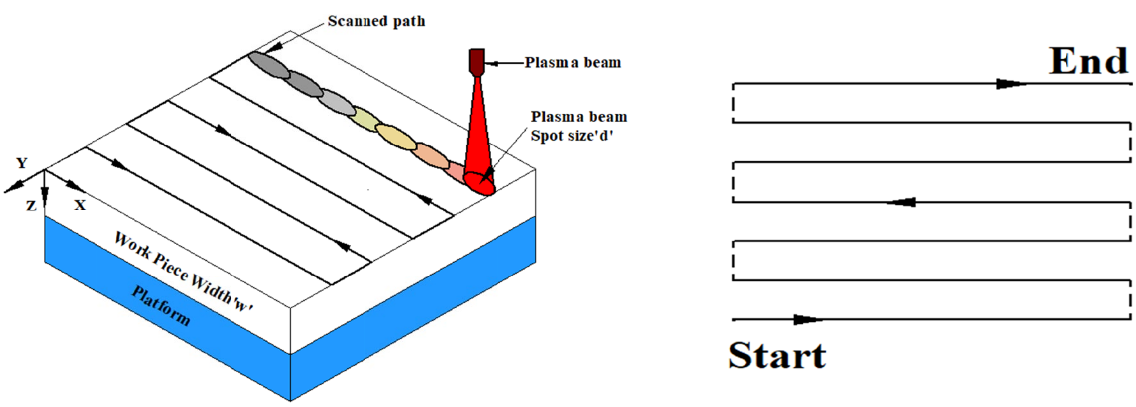


Fig. 3. Scanning pattern used

2.5. Surface characterization

Typically, a standard surface finish (or flatness) comprises three main components: primary texture, also referred to as roughness, secondary texture, sometimes identified as waviness, and form defects. The measurement commonly used to characterize the cross-section of an external profile is the Centre Line Average (*Ra*). *Ra* is calculated by summing the areas above and below a mean line and then dividing that total by the assessment length [17].

$$Ra = \text{sum of the regions above as well as below the mean line / Length of assessment} \quad (1)$$

For accurate profile readings, the traverse length must be greater than the end-to-end distance [18]. This procedure is repeated up to the quantified roughness and evaluation length decrease within the specified limits in the table. The researchers analysed and evaluated similar results of the surface quality in powder-mixed die sinking EDM using *Ti* powder. These findings will serve as a crucial basis for confirming the significance of the optimal HV results. The study revealed that the surface layer quality under optimal conditions is excellent, which greatly enhances the durability of die/molds [19].

3. Results and discussion

The aim of the experimental procedure was to examine the relationship between various process parameters including current, voltage, velocity, and plasma power. The first stage used an ANOVA technique conducted to assess the consequences of relationship between the variables. Each variable along with their interactions were also assessed. The equation (2) $P_i = (1 - Ra, i/Ro) \times 100$ was used to calculate the performance index, where Ra, i/Ro represents the percentage reduction in the original roughness achieved by polishing the surface [20]. The second stage included running numerous linear regressions to determine the inter-parameter correlations. The outcomes include surface roughness (*Ra*) and Microhardness (HV). Experiments were carried out twice, and the results were averaged for the sake of this study, TABLE 1 displays the relevant information.

3.1. Analysis of variance results

ANOVA may be used to evaluate experimental data and determine the effect of a particular input parameter. A set of experimental results were obtained in the study of plasma remelting. TABLE 1 shows ANOVA findings for various surface

TABLE 1

The experimental PBR processes parameters and results regarding energy density, surface roughness, and microhardness

Sl. No	Current in (A)	Voltage in (v)	Travel Speed (mm/min)	Plasma Power (W)	Surface Roughness (microns)	Micro hardness (HV)	Plasma power "P_e" in Watts	Travel speed "W_f" in mm per Min	Plasma beam energy "E_p" in (J/mm)
1	12.4	23	60	285.2	11.998	12.055	299	150	1.99
2	12.4	23	80	288.2	12.245	11.145	299	140	2.14
3	12.4	23	100	292.2	12.561	10.745	299	130	2.30
4	12.4	24	60	286.2	10.353	13.004	299	115	2.60
5	12.4	24	80	292.2	10.61	12.444	299	100	2.99
6	12.4	24	100	303.2	10.821	10.094	299	90	3.32
7	12.4	25	60	294	9.777	9.777	299	75	3.99
8	12.4	25	80	306	9.9832	8.232	299	60	4.98
9	12.4	25	100	316	10.543	7.543	299	50	5.98
10	13	23	60	314.25	10.951	14.312	299	45	6.64
11	13	23	80	320.25	11.894	13.112	299	30	9.97
12	13	23	100	324.25	12.636	12.032	299	25	11.96
13	13	24	60	327.2	9.091	11.999	299	10	29.90
14	13	24	80	337.2	9.612	10.245	336	150	2.24
15	13	24	100	342.2	10.412	9.561	336	140	2.40
16	13	25	60	335	8.297	16.963	336	130	2.58
17	13	25	80	345	8.921	15.093	336	115	2.92
18	13	25	100	350	9.301	14.693	336	100	3.36
19	13.6	23	60	342.68	7.456	15.456	336	90	3.73
20	13.6	23	80	357.68	7.6412	14.412	336	75	4.48
21	13.6	23	100	364.68	8.123	13.123	336	60	5.60
22	13.6	24	60	346.4	8.895	18.256	336	50	6.72
23	13.6	24	80	356.4	9.312	17.026	336	45	7.47
24	13.6	24	100	368.2	10.099	16.055	336	30	11.20
25	13.6	25	60	355.2	6.245	16.145	336	25	13.44
26	13.6	25	80	365.2	6.68	15.745	336	10	33.60
27	13.6	25	100	378.2	7.2353	13.004	336	8	42.00

finishes, hardness requirements, and in-work-piece performance metrics. Its primary objective is to enhance the quality and dependability of products [22]. S/N ratios should be determined with forethought and consideration, as well as prior experience and skill in the field. Lower values for the S/N ratio indicate higher quality, whereas higher values indicate more depth of investigation [23]. Finding the roughness-reducing and noise-resilient parameters was the focus of this research.

3.1.1. The influence of regulating factors on the plasma power

Taguchi's approach was used in the optimization process. A loss function is described as a measurement tool that determines how much a quality characteristic deviates from an ideal value [24]. The impact of S/N analysis calculates the ratio for each process parameter level. A higher S/N ratio improves quality regardless of category [25]. The process parameters with the greatest S/N ratio are best to predict the best parametric combination [26]. Parameter settings that reduce roughness and provide the greatest S/N ratios are detailed in TABLE 2.

Fig. 4 shows the mean effect values of plasma power, the mean effect values of plasma power on remelting of surfaces refer to the average or typical effect that changing the plasma power has on the process of remelting the surface of a material. This involves heating and melting the surface coating involving a tiny layer of material to create a new surface with improved properties.

TABLE 2

Matrix to derive S/N ratios

Level	Current in (Amp)	Voltage in (v)	Travel speed in (mm/min)
1	295.9	321.0	320.7
2	332.8	328.8	329.8
3	359.4	338.3	337.7
Delta	63.5	17.2	17.0
Rank	1	2	3

Regression Equation:

$$\text{Plasma Power (W)} = -599.369 + 52.9111\ \text{Current (A)} + 8.62278\ \text{Voltage (v)} + 0.424444\ \text{Travel Speed (mm/min)} \quad R-Sq(adj) = 97.26\%\ R-Sq = 97.58\% \tag{2}$$

The results in TABLE 3 indicate that the current has the highest level of statistical significance (85.94), followed by voltage (6.30), while travel speed (6.10) is less statistically significant with respect to plasma power. It is evident from the data that an expansion in current advances to an enhance in plasma power.

It can also be inferred from the above data that an increase in current can impact the remelting process and result in increased plasma power. This is due to the temperature of the surface layer being raised, which makes melting and mixing of the material more feasible. Additionally, the increased plasma power leads to greater energy in the plasma, resulting in more effective heating and melting of the surface layer. Similarly, an increase in voltage can also increase plasma power. However,

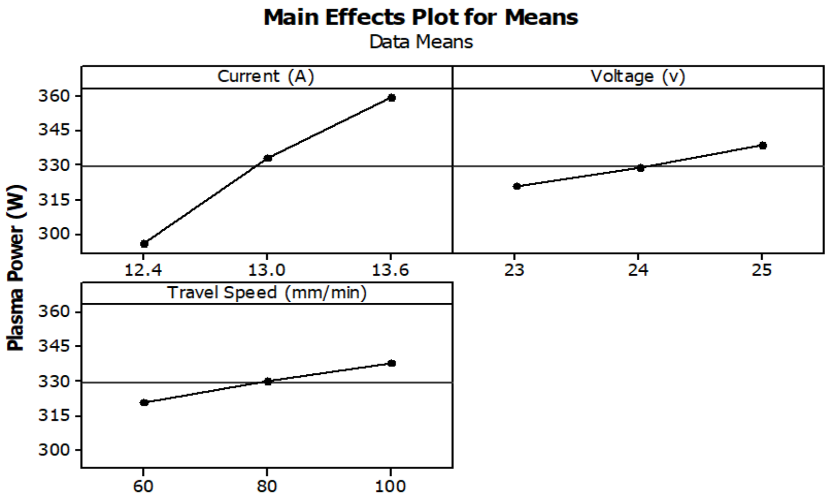


Fig. 4. Mean effect values of Plasma power

TABLE 3

Process parameters for optimal levels of plasma power

Source	Seq SS	DF	Adj MS	Adj SS	F	P	%contribution
Current (A)	18301.0	2	9150.5	18301.0	523.24	0.000	85.94
Voltage (v)	1342.8	2	671.4	1342.8	38.39	0.000	6.30
Travel Speed (mm/min)	1299.4	2	649.7	1299.4	37.15	0.000	6.10
Error	349.8	20	17.5	349.8			1.64
Total	21293.0	26					100 %

the effect of travel speed is opposite, an increase in travel rate causes reduction in the impact of plasma power on the surface, as clearly shown in Fig. 4.

Without conducting more experiments, new data may be predicted using regression equations (3) that characterise the statistical connection between one or more predictors and the response variable. The same procedure is followed for the influence of regulating variables on Ra and the influence of regulating variables on microhardness also.

Regression equations for Surface roughness is as follows.

The regression equations (4) that characterise the statistical connection between one or more predictors and the response variable.

$$\text{Surface Roughness (microns)} = 65.2094 - 2.51895 \text{ Current (A)} - 1.02904 \text{ Voltage (v)} + 0.0240786 \text{ Travel Speed (mm/min)} \; R - Sq(adj) = 97.43\%, \; R - Sq = 98.64\% \quad (3)$$

Regression Equation for Microhardness is as follows.

$$\text{Microhardness (HVN)} = -36.5142 + 4.09102 \text{ Current (A)} + 0.0446111 \text{ Voltage (v)} - 0.0586583 \text{ Travel Speed (mm/min)} \; S = 1.89876 \; R - Sq = 94.94\% \; R - Sq(adj) = 96.43\% \quad (4)$$

3.1.2. Effect of parameters on plasma power

The plasma power was measured for various parametric combinations, and the results were analysed the purpose was to assess the effect of every single parameter on the output of plasma power. As shown in Fig. 5, increase in current generally increases the plasma power, while increasing the voltage also had a positive effect on the plasma power output. However, the effect of travel speed was more complex, as there was an optimal travel speed for each combination of current and voltage that maximized the plasma power output. If the travel speed was too high or too low, the plasma power output decreased. The ANOVA findings in respect to plasma power are shown in the TABLE 3. The current has the most statistical significance, as can be shown the importance of current (67%) on plasma power, followed by voltage (17.39%) and transit speed (17%).

Fig. 5. Includes 3D surface plots that show how plasma power is influenced by the interaction between current and voltage (a), current and travel speed (b), and voltage and travel speed (c). The same procedure is followed for the impact of process parameters on surface roughness and microhardness.

In one of the experiments, the optimal values for current, voltage, and travel speed for maximizing microhardness were found to be 18 A, 17 V, and 60 mm/s, respectively. In another experiment, the optimal values were 22 A, 15 V, and 40 mm/s, respectively. The results suggest that carefully controlling these process parameters can help maximize microhardness and enhance the mechanical properties of additive manufactured components.

Plasma beam remelting uses a plasma beam to melt and resolidify a metal surface. This process involves heating the surface to a very high temperature using the plasma beam, which causes the surface to melt and then rapidly cool and solidify. When the plasma beam is directed onto the surface, it can have different effects depending on the intensity and duration of the beam. If the plasma beam is too weak, it may have no

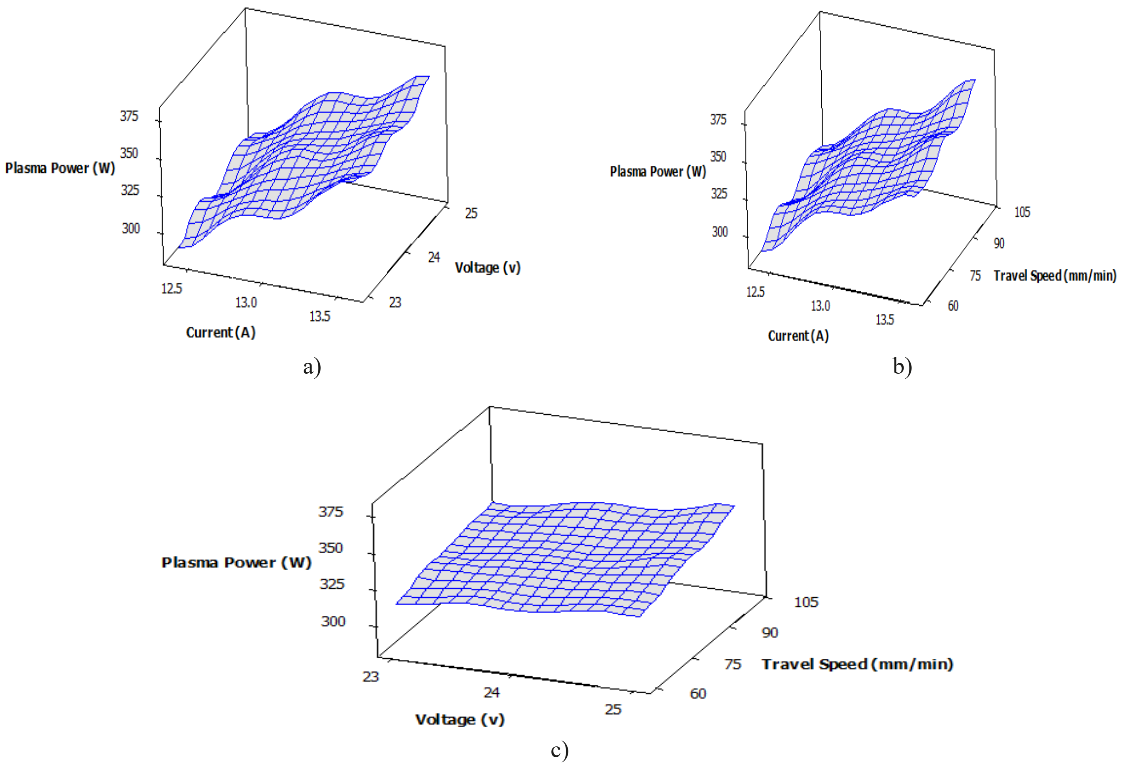
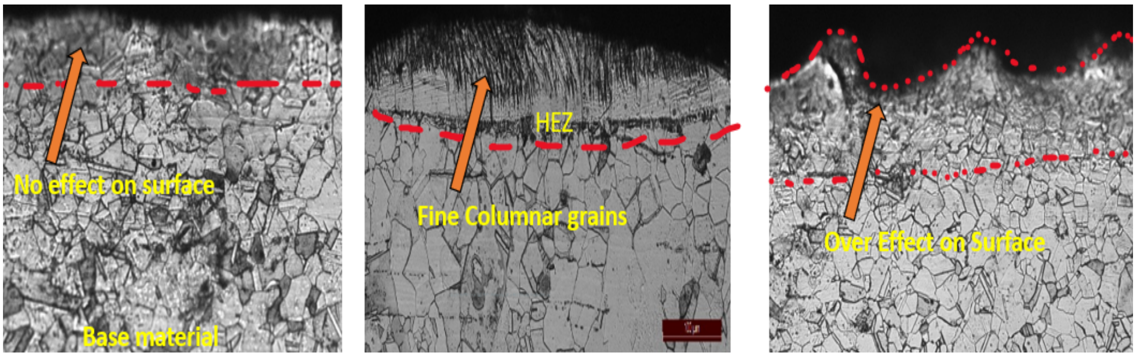


Fig. 5. Mean cause values of Plasma power



a) b) c)

Fig. 6. The images obtained using a scanning electron microscope (SEM) depict the exterior of the models prior and after undergoing plasma beam polish treatment a) No effect on surface b) proper plasma beam remelting c) Additional effect on surface

effect on the surface as shown in Fig. 5(a). On the other hand, if the plasma beam is too intense or applied for too long, it can overheat the surface, causing damage or deformation it shown in Fig. 5(c).

Fig. 5(b) shows optimum plasma beam remelting that can reduce surface roughness, resulting in a smoother and more uniform surface. This is because the rapid heating and cooling of the surface causes the material to solidify quickly, which can help to eliminate surface irregularities and imperfections [27].

The study found that the optimal surface geomorphology was accomplished while using a power range between 298-335 W and a speed of travel range of 51-91 mm per min. This resulted in a significant reduction in Ra from an initial value of 13.8521 ± 0.3 μm to 5.452 ± 0.05 μm, which was a decrease of about 55 to 60%. The SEM microscope showed that plasma beam remelting affected the surface depth, ranging from 20 to 101 μm. Furthermore, the PBR treatment improved the uniformity of the microstructure near the upper surface.

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4. Conclusion

- During plasma beam remelting, the input parameters such as the travel speed, voltage and current have a considerable influence on surface irregularity and microhardness.
- By utilizing a plasma source power range between 298-335W and a speed of travel range of 51-91 mm per min, a considerable reduction in surface irregularity was found. The surface irregularity from an initial value of 13.8521 ± 0.3 μm to 5.452 ± 0.05 μm, was decreased to about 55-60%. The SEM micrographs showed that plasma beam remelting affected the surface depth, ranging from 20 to 101 μm.
- The hardness of the material was observed to increase significantly after undergoing the PBR treatment from an initial value of 167.98 ± 3.2 HV to 294.61 ± 4.1 HV, indicating an improvement of approximately 74.95%.

In summary, plasma beam polishing is a micro-level polishing process that can enhance the surface properties of the samples without affecting their original geometry. Therefore, plasma beam remelting is a potentially effective technique for improving surface properties.

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