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Study of the effect of process factors on the wear rate and surface integrity in incremental point forming of the AA6061 aluminum alloy

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ABSTRACT

Incremental point forming is a contemporary method employed in sheet metal forming to achieve great flexibility in fabrication of intricate forms, eliminating the requirement for a specific mold. According to its exceptional mechanical characteristics and low weight, this method is particularly employed in the production of aluminium alloys. The essential aim of this research was to examine the deformation mechanisms and discuss the mechanical properties of aluminum during the incremental forming process. The aim was to examine how various process parameters influence the surface properties, hardness, and wear resistance of the workpieces using aluminum alloy type AA6061. The parameters under investigation were increment step down size, feed rate, and spindle rotational speed. Furthermore, the impact of these factors on the forming process was investigated using several methodologies, including the Taguchi method for parameter optimization and surface analysis. The findings of this study demonstrated that spindle rotation speed exerted a substantial influence on both surface roughness and hardness, accounting for 63.41% for hardness and 52.19% for roughness. In terms of wear rate, the step size had the most significant impact, accounting for 48.53%.

Keywords: wear resistance, microhardness, surface roughness, ANOVA, Taguchi design.

INTRODUCTION

Incremental sheet forming (ISF) creates components by subjecting them to a succession of tiny incremental deformations. Eliminating the requirement for a punch and die, ISF – an active manufacturing method that is both versatile and cost-effective – is well-suited to low-volume production. Among the many varieties of incremental sheet-forming technologies, SPIF stands out as the most basic process variant. One new technique that has shown promise for low-volume manufacturing is SPIF [1]. A concise summary of current ISF techniques for lightweight materials was supplied by Gohil et al. [2], their goal in writing this paper was to help researchers stay on track with the latest advancements in the Single Point Incremental Forming (SPIF) technology of lightweight metallic materials and to offer motivation for the upcoming endeavors in this area. This article [3] proposed a different method to evaluate the potential environmental effect of new technologies. By taking into account environmental implications during a product lifespan, presuming cost-effectiveness, and eliminating idealistic application scenarios that disrupt the long-established trends in human behavior, the approach makes up for the flaws of previous studies with an emphasis on ISF and new end-use goods, such as driverless vehicles. An investigation was carried out to analyze the microstructure of aluminum alloy sheets type AA-6061 during the SPIF process by Barnwal [4], in order to gain insights into their deformation characteristics. The analysis revealed that the metal exhibited the greatest resistance to deformation in the ID direction, leading to little misorientation, grain elongation, and texture development. A laboratory-scale test setup was developed for inducing plastic deformation in AA6061 sheet metal [5]. This was achieved by utilizing the response surface methodology and the Box-Behnken design technique. The most favorable factors for the SPIF product were identified as (4 mm, 0.2 mm and 782 mm/min) for tool diameter, step size and feed rate, respectively. The fracture occurred under the conditions of plane strain deformation, resulting in enhanced hardness as a result of grain refinement and texture evolution. Hussain et al. [6] examined the impact of forming factors on the microstructure and mechanical characteristics of the AA6061 alloy. The researchers discovered that ISF parameter processing affects the ultimate strength and microstructure behavior of alloys. The increasing wall angle enhances ultimate strength by about 10%, while slight changes in feed rate and spindle speed have insignificant effects. Elongation leads to increased material strength and decreased ductility, whereas grain and second-phase particles undergo elongation. The study [7] used ISF tests on aluminum alloy sheet metals, categorizing them into three samples based on deformation extent. They analyzed the microstructures using EBSD, an X-ray microscope, SEM, and TEM. The results revealed significant grain fragmentation, elongation, grain size reduction, grain misorientation, and increased void volume. The ISF division of grains into smaller sub-grains caused dislocations and grain fragmentation. Scalable applications of the incremental forming technique allow for the formation of a wide variety of materials, not limited to metals. As an example, sheets of various aluminum alloys have been utilized in numerous experiments. Additionally, titanium plates were utilized in study [8]. This study investigated the changes in the texture and microstructure of titanium sheets that were hot-rolled and subjected to incremental sheet formation. The phenomenon observed involves the division of basal poles and the formation of twin structures inside the damaged microstructure. The pyramid walls are experiencing a state of deformation characterized by compression in one direction and shear in the other. The wall areas exhibit observable rolling texture components. Slip activity graphs demonstrate that prismatic slip is the primary factor influencing the development of texture. The occurrence of twinning is diverse and relies on multiple characteristics. Also, an investigation was carried out on titanium sheet metal by [9] using SPIF and frustum cups at different spindle speeds. The results indicated that there were only minor changes in grain size as the spindle speed rose, and there was an increase in dislocation density. They achieved a maximum tensile strength of around 550 MPa. Shrivastava et al. [10] investigated the property and mechanism of sheet deformation, forming behavior in the SPIF. The evaluation of process deformation characteristics allows for the identification of dominant shearing during the early phases of forming, as well as the development of dominant P texture components during the middle stages of forming. The study also elucidated the cause of common failure under biaxial strain mode. The increased malleability in SPIF is due to the reduction of Cube texture as well as formation of P and Brass textures. Murugesan et al. [11] determined the most effective forming parameters using the Taguchi design in order to manufacture formed items of superior quality. The parameters comprised the forming tool radius, spindle rotational speed, step size, and the feed rate. The findings indicated that decreasing the step size with increasing the feed rate led to a decrease in surface roughness. Najm et al. [12] declared the impact of four process factors on the hardness of a sheet manufactured utilizing a cone shape with a thickness of 0.6 mm (AA1100). The study looked at different types of grease and found that using coolant oil increases hardness, whereas using grease results in a decrease. The characteristics of grease can have an impact on hardness measurements. Dabwan et al. [13] performed a study on how process parameters affect sheet roughness and accuracy of a truncated cone form. Manipulating these parameters can enhance the smoothness of the surface and minimize mistakes in circularity, waviness, and side wall angle. Reducing sheet thickness, increasing tool diameter, and decreasing spindle speed result in improved precision of profiles and higher quality of surfaces. Kumar et al. [14] examined the effect of seven input variables on the aluminum sheets roughness using incremental forming method. The sheet thickness is the primary factor influencing the surface roughness followed by spindle rotational speed. Additional factors, such as the size of the tool, the distance between each step, the type of lubricant used, and the rate at which the material is fed, have a moderate influence. The article [15] showed the examination of how SPIF process factors affect stiffened rib roughness in Alclad aluminum alloy panels. This study employed 7075-T6 and 2024-T3 Alclad alloy sheets with various step size and spindle speed. The study indicated that incremental vertical step size increased surface roughness. Coman et al. [16] investigated the thinning ratio of Al 3003 material, and surface roughness that occur during incremental forming. The investigation revealed that the tool coated with titanium nitride (TiN) produces the most favorable roughness outcomes. The study for Habeeb et al. [17] survey the utilization of SPIF process for producing truncated pyramids, with a particular emphasis on the effect of specific factors on sheet roughness. The study employed a complete factorial design and ANOVA to examine the data, which demonstrated that the most favorable average roughness value was attainted with 60° wall angle, 2 mm sheet thickness and 0.2 mm increment step depth. Tayebi et al. [18] investigated the SPIF technique for Al 1050/Mg-AZ31B, a popular material in automotive and aerospace. Five simulation approaches were used, with the FLDcrt method showing superior accuracy in predicting failure. The study also found an optimal tool diameter condition. Mughir and Jaleel [19] studied how process variables affect the geometric precision of pyramid shapes formed with a CNC milling machine. The findings indicated that while geometric accuracy increases with wall angle, it decreases along with tool diameter and step size. There were two different kinds of defects identified: springback and sheet bending problems. A 55° wall angle, 0.2 mm step size, and 8 mm tool diameters produced the best geometric precision. The present study aimed to analyze the effect of forming process variables, such as step size, feed rate, and spindle speed, on the wear rate, hardness, and microstructure of aluminum, in addition to the effect of these variables on the surface properties. In previous studies, surface and microstructure changes have not been sufficiently highlighted, so this research aimed to study the effect of these factors on the forming of the AA6061 aluminum alloy. A set of experimental methods, including the "Taguchi" method for parameter optimization and surface analysis, were used to evaluate how these variables affect the final working properties.

MATERIAL AND PROCESS

The single-point incremental forming process was used on aluminum alloys, namely Al6061, with a thickness of 1.5 mm. This process was performed using a CNC machine. The chemical composition of the alloy was calculated through XRF examination, as presented in Table 1, which shows the elements and their percentages; in turn, Table 2 shows the mechanical properties of the AA6061 alloy. SPIF was used to form a conical shape from the AA6061 alloy with a 100 mm diameter and 45 mm depth. The fixture consists of a cube-shaped frame with a mounting plate that have 140 mm circular hole in the center. The dimensions of the sheets used were 200 × 200 × 1.5 mm. A distance of about 26 mm was left between the edge of clamping plate and the inner diameter of the formed shape to avoid bending. The fixture was located on the CNC machine, as shown in Figure 1. A tool with 15 mm diameter has hemispherical head made of high-hardness steel was used. A helical tool path was used to form a truncated cone shape (Figure 2). There are several variables that are controlled in the incremental forming process and they are chosen based on the outputs. Therefore, based on previous studies, feed rate, step size, and spindle speed were used as process variables with three levels for each variable. Taguchi was used to design the practical aspect, as shown in Table 3. Higher spindle rotation speed means improved surface finish and reduced friction and thus fewer defects, so it has a significant effect on the alloy microstructure. As for the feed rate, it directly affects the internal deformation of the crystals, as does the step depth, in addition to its effect on strains and delamination, as well as the possibility of cracks.

To achieve a smooth surface and prevent tool wear as well as blank sheet, proper lubrication is necessary. Thus, by employing KIXX ATF multi liquid lubrication, AA6061 was created.

Table 2. Mechanical properties of AA6061

Yield strength (Mpa)	Ultimate strength (Mpa)	Elongation (%)
298	315	12

Table 1. Chemical composition of the AA6061 alloy (wt%)

Mg	Si	Fe	Cu	Cr	Zn	Ti	Mn	Al
0.8	0.63	0.52	0.23	0.2	0.103	0.05	0.043	97.424

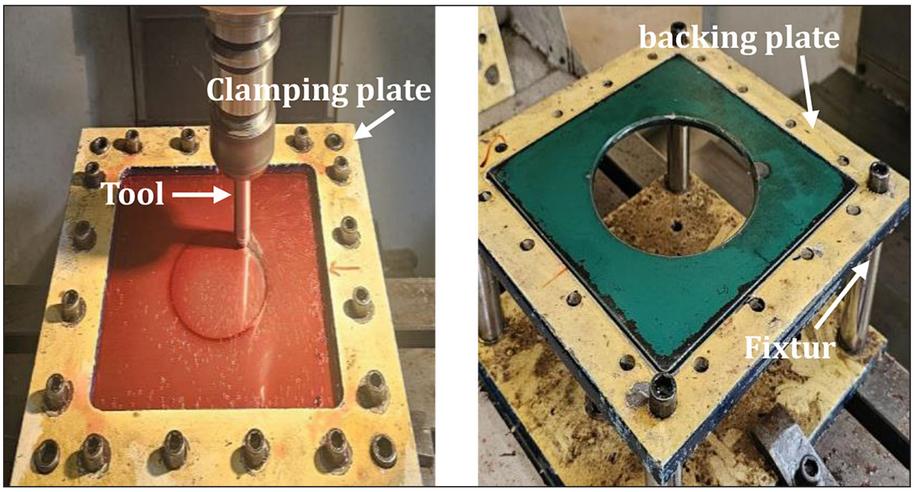

Figure 1. Fixture component

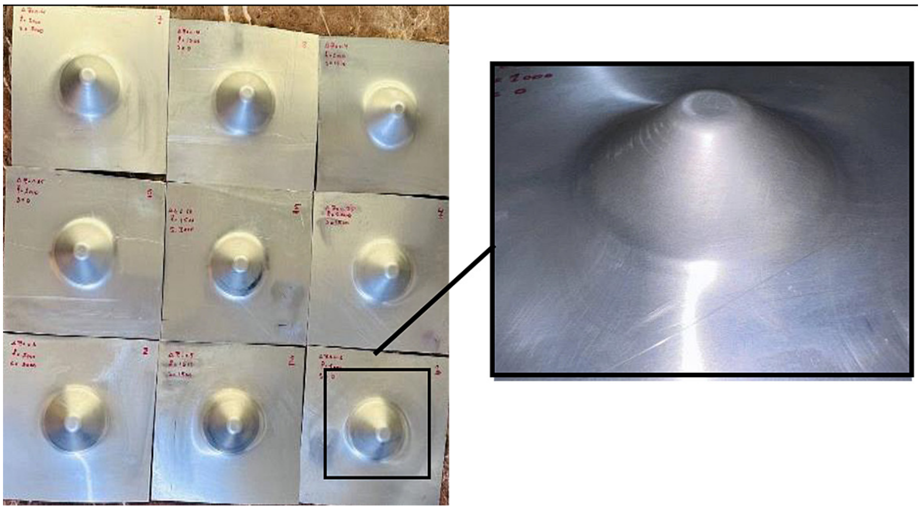

Figure 2. Cone shape after forming

EXPERIMENTAL WORK

Wear test

Aluminum alloy 6061 is commonly used in numerous applications, encompassing the aerospace and marine sectors, engineering structures, as well as automobiles and bicycles. Therefore, it is exposed to many harsh conditions, whether mechanical or chemical. In order to determine the extent of the resistance to frictional wear characterizing this alloy, conduct a pin-on-disc wear test was conducted under specific conditions that were chosen based on the hypothesis of the application in which the alloy will be used. An example of this is in small aircraft parts, such as axles or parts that connect the parts of the small aircraft together. The operating conditions were taken as close as expected to the real conditions, and they were as follows: the load 10 N, the speed was taken as a constant value, which is 300 rpm, while the time was one hour.

Table 3. Taguchi design

Step size (mm)	Feed rate (mm/min)	Spindle speed (rpm)
0.30	1000	0
0.30	1500	1500
0.30	2000	3000
0.35	1000	1500
0.35	1500	3000
0.35	2000	0
0.40	1000	3000
0.40	1500	0
0.40	2000	1500

Microhardness test

The hardness of each specimen was assessed in three specific areas, see Figure 3a. Figure (3b) displays a shaped component that has been cut to the necessary shape and size in order to prepare test samples and establish three hardness measurement zones. The hardness was conducted thrice at distinct locations within each specified zone. The hardness level was determined by calculating the average hardness amount of the specified zone. The mean value was calculated for each three zones. The part to be used for hardness inspection was fixed with regular putty and then polished. A force of 100 N was applied for a duration of 10 seconds using a Vickers device that has a diamond pyramid indenter.

Microstructure test

A microscopic examination was conducted to reveal the microscopic structure at 10X magnification of the alloy using a special demonstration solution for aluminum alloy which is 12 mL HCl, 6 mL HNO_3, 1 mL HF (48%), 1 mL H_2O [21] to determine the effect of the process parameters on the microscopic structure.

Roughness test

Therefore, so as to study the effect of the various factors that were used during the incremental shaping process on the surface roughness of the specimens, five readings were taken from several areas of one specimen to obtain more accurate readings.

RESULTS AND DISCUSSION

Wear rate

This section will specifically address the percentage contribution and p-value of the elements utilized in the analysis of variance Tables 4 and 5. The contribution is a percentage that quantifies the level of impact. The contribution of the step size to the wear rate is considerable, as seen by the 48.53% contribution and the P-value (0.039) being below 0.05. This indicates that step size

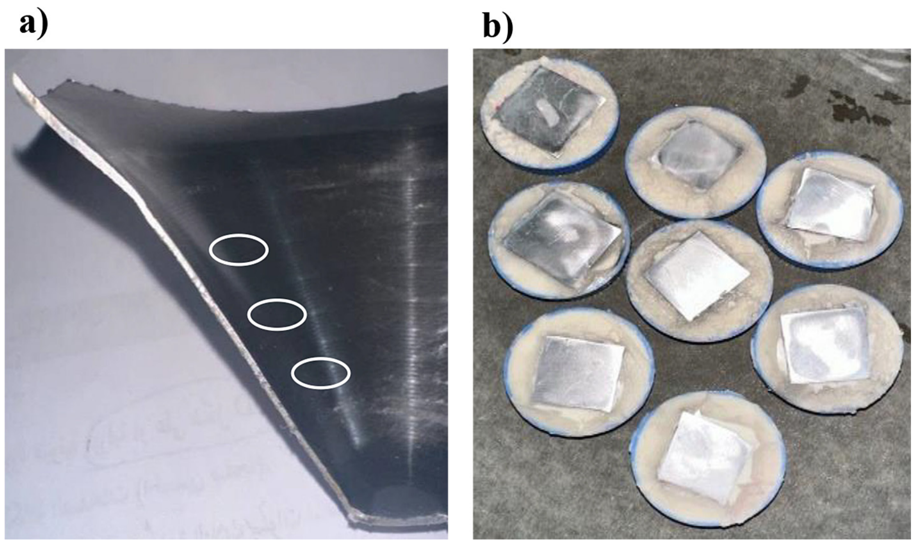

Figure 3. (a) specimen area, (b) specimens after cut

Table 4. Analysis of variance for wear rate

Source	DF	Contribution	Adj SS	Adj MS	P-Value
Step size	2	48.53%	0.000247	0.000123	0.039
Feed rate	2	5.70%	0.000029	0.000015	0.259
Spindle speed	2	43.78%	0.000223	0.000111	0.044
Error	2	1.99%	0.000010	0.000005	
Total	8	100.00%			

Table 5. Response table for means for wear rate

Level	Step size	Feed rate	Spindle speed
1	0.01200	0.02060	0.01390
2	0.02467	0.01643	0.01717
3	0.02010	0.01973	0.02570
Delta	0.01267	0.00417	0.01180
Rank	1	3	2

was statistically significant on the wear rate. The impact of the feed rate on the wear rate is minimal, having a mere 5.7% influence. The P-value of 0.259 means its lacks to statistical significance. Although a higher feed rate can lead to surface deformation, it is not the primary determinant of increased wear. Ultimately, the spindle speed ranks second in terms of impact, accounting for 43.78% and demonstrating statistical significance (P-value = 0.044). These fluctuations in temperature can result in surface fragility and higher rates of wear. Practical analysis of the results reveals that the samples with larger step size and faster spindle speed (such as samples 7, 9, and 5) exhibit greater wear rates due to the concurrent effects of increased mechanical and thermal deformation. The samples characterized by a smaller step size and lower spindle speed, namely samples 1 and 2, exhibited significantly reduced wear rates. This can be attributed to the reduced deformation caused by the forming process, which therefore decreases the surface stress and consequently the wear rate. vulnerability to wear when subjected to friction loads.

As the step size increases, the material experiences more significant mechanical deformation at each succeeding step. This further distortion amplifies the concentrated pressures on the surface of the specimen, leading to a greater occurrence of mechanical damage, including microcracks and surface tears. The presence of these defects amplifies the surface area subjected to friction during the wear test, so leading to a higher observed wear rate. The feed rate directly impacts the velocity at which the tool moves across the material surface, as shown in Figure 4. An increase in the feed rate

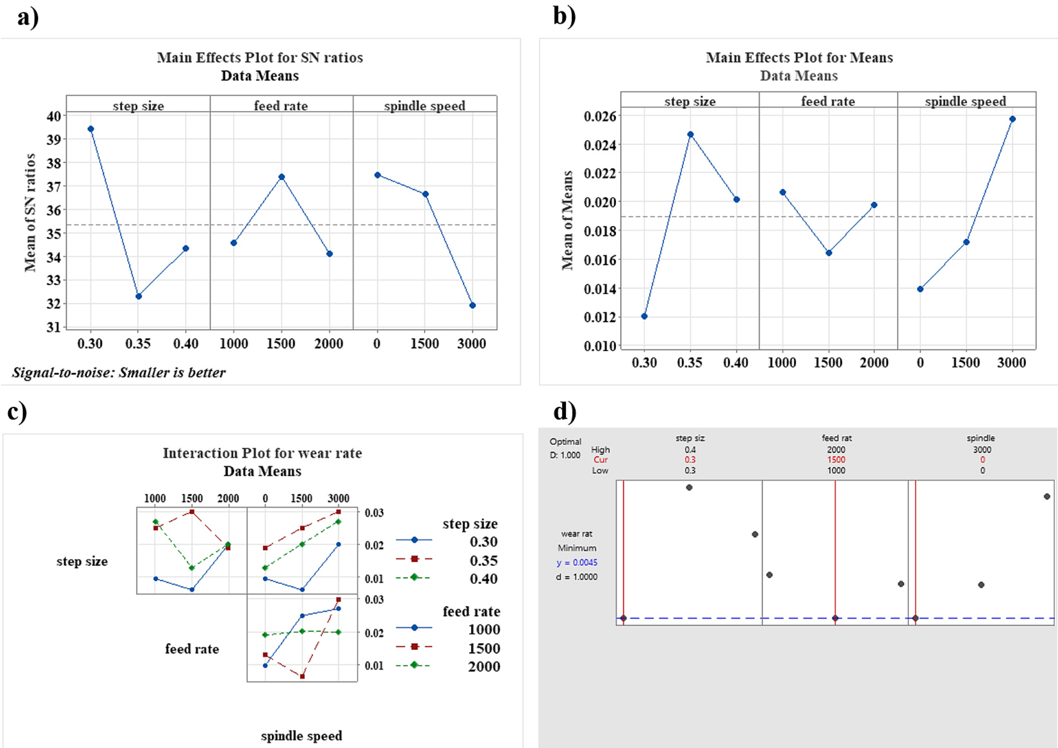

Figure 4. Main effects for wear rate for (a) SN ratio, (b) means, (c) interaction plot, (d) response optimization for wear rate

causes a corresponding increase in the instantaneous mechanical load on the material, potentially resulting in excessive surface deformation. Increased spindle speed leads to a proportional rise in the heat produced by friction between the tool and the material. At high temperatures, the microstructure of the material undergoes greater alterations, including surface softening and the development of oxides or scales, which renders the surface more prone to wear. These heat fluctuations result in surface fragility and heightened. The analysis of variance revealed that the optimal input values for wear rate, namely (0.3 mm, 1500 mm/min and 0 rpm) for step size, feed rate and spindle rotation speed respectively, as shown in Figure 4 (d).

Microhardness

Referring to Table 6: A P-value of 0.018 is observed for the step size. Hence, the P-value being below 0.05 suggests that the step size exerts a substantial effect on the outcomes. Statistically significant, the step size manifests a distinct impact on both hardness. Furthermore, the p-value for the feed rate is 0.233. Therefore, the results show that the feed rate does not have a statistically significant impact, as it reported by [13], as the P-value exceeds 0.05. No robust statistical evidence exists to support the notion that feed rate has a substantial impact on hardness. The P-value for spindle speed is less than 0.001. Among all the variables considered, spindle speed has the lowest probability value, which is less than 0.001. This indicates that spindle speed has a highly significant effect on the outcomes [12]. High velocity significantly impacts hardness. Referring to Tables 6 and 7, step size contribution percentage = 33.86% Thus, the step size accounts for around 34% of the overall impact on hardness. Size of the step is a crucial determinant of surface quality and mechanical characteristics. The contribution of the feed rate to the total influence on hardness values is minimal, as it amounts to a mere 2.12%. This observation validates that the impact of the feed rate is very relatively insignificant in relation to the other variables. The contribution of spindle speed is 63.41%. Indeed, the spindle speed emerges as the predominant determinant in this experiment, accounting for 63.41% of the overall impact on hardness.

Practically, the pace at which the tool is fed typically impacts the duration of tool contact with sheet, thereby influencing the output of heat throughout the cutting operation. An increase in spindle speed leads to a higher friction rate between the tool and the material, resulting in the generation of substantial heat and grain recrystallization [12, 13]. The variation in step size during hardness testing impacts the residual stress levels in the material. The observation of higher hardness values with increasing step size can be attributed to the fact that larger steps induce greater mechanical stress, thereby leading to increased hardening occurring from material deformation. At elevated spindle speeds, there is a rise in vibration and friction, resulting in surface modifications such as distortions or undulations. For interaction effect, it is clear from Figure 5, that the way spindle speed and step size work together is

Table 6. Analysis of variance for hardness

Source	DF	Contribution	Adj SS	Adj MS	P-Value
Step size	2	33.86%	732.36	366.182	0.018
Feed rate	2	2.12%	45.91	22.954	0.223
Spindle speed	2	63.41%	1371.60	685.802	0.010
Error	2	0.61%	13.19	6.596	
Total	8	100.00%			

Table 7. Response table for means for HV hardness

Level	step size	feed rate	Spindle speed
1	156.3	169.1	170.6
2	156.3	157.5	157.0
3	175.4	161.4	160.4
Delta	19.2	11.7	13.7
Rank	1	3	2

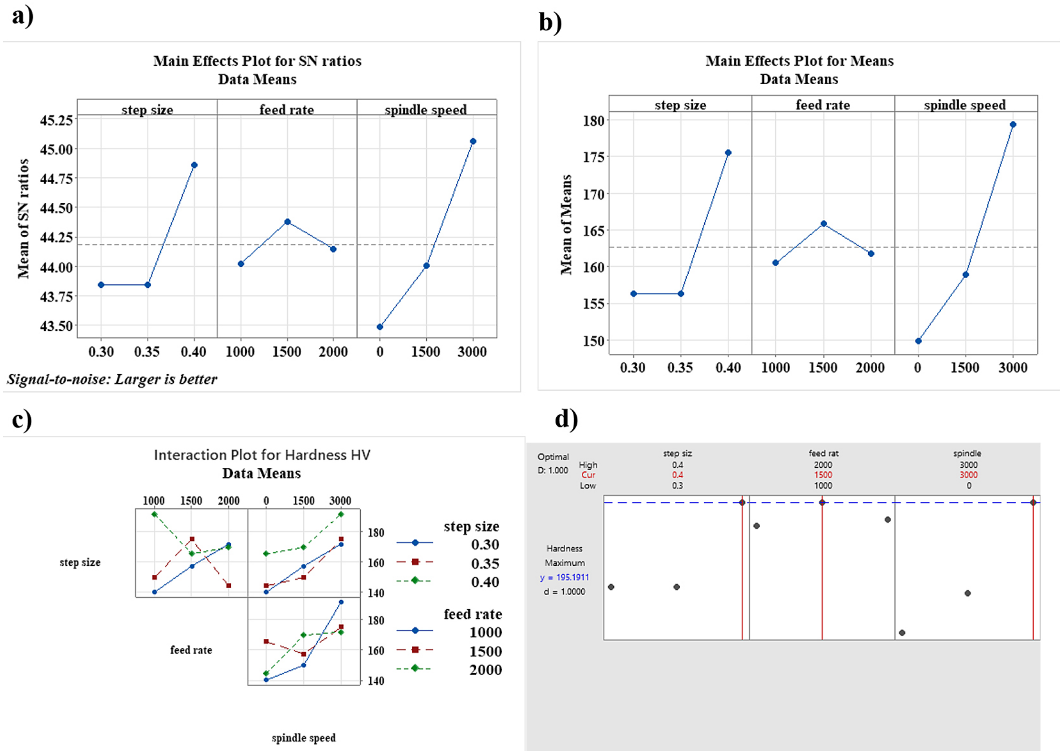

Figure 5. Main effects for hardness for (a) SN ratio, (b) means, (c) interaction plot, (d) response optimization for hardness

very important. The analysis of variance revealed that the optimal input values, namely 0.4 for the step size, 1500 for the feed rate, and 3000 for the spindle rotation speed, as shown in Figure 5 (d).

Microstructure test

The objective of microscopic investigation is to discern the alterations that transpire within the crystal structure of the metal. The factors of step size, feed speed, and spindle rotation speed have a substantial impact on heat generation and friction, resulting in particle deformation, recrystallization, and granular development. Basic concepts of friction, heat production, and plastic deformation can be used to explain the wear mechanisms and microstructural alterations that have been observed. Increased frictional forces from higher feed rates and spindle speeds cause localized heat generation, which, according to thermodynamic principles, encourages recrystallization and grain development. On the other hand, reduced heat is produced by slower feed rates or by not rotating the spindle, which limits deformation and recrystallization. These occurrences are consistent with material science concepts, which state that dislocation motion and grain boundary migration are two methods by which heat and mechanical energy propel microstructural evolution. In general, the step size of a tool affects the distortions in the crystal structure, while the feed speed of the tool impacts the distribution and crystallization of the crystals because of heat generated by the friction induced by the tool rotation. Trials 1–3 utilized a constant step size of 0.3, leading to minimal deformations, as depicted in Figure 6. In the initial trial, the feed speed was slow and the tool did not rotate. Consequently, insufficient heat was generated to induce deformations. As a result, the resulting structure is microscopic and cohesive, with grains evenly distributed due to the absence of deformation and heat. The step sizes in trials 4–6 exhibit a modest increase compared to the prior samples, resulting in a higher degree of deformation. Trial 4 yielded an intermediate microstructure characterized by a dispersion of grains ranging from fine to large. The microstructure in Trial 5 was noticeably affected by the heat, leading to the formation of larger granules. Trial 6: Eliminating spindle speed decreases the generation of heat due to friction, but a high feed rate enhances deformation. Consequently, this combination results in a microstructure that exhibits pronounced deformations with a moderate grain size, but without a substantial

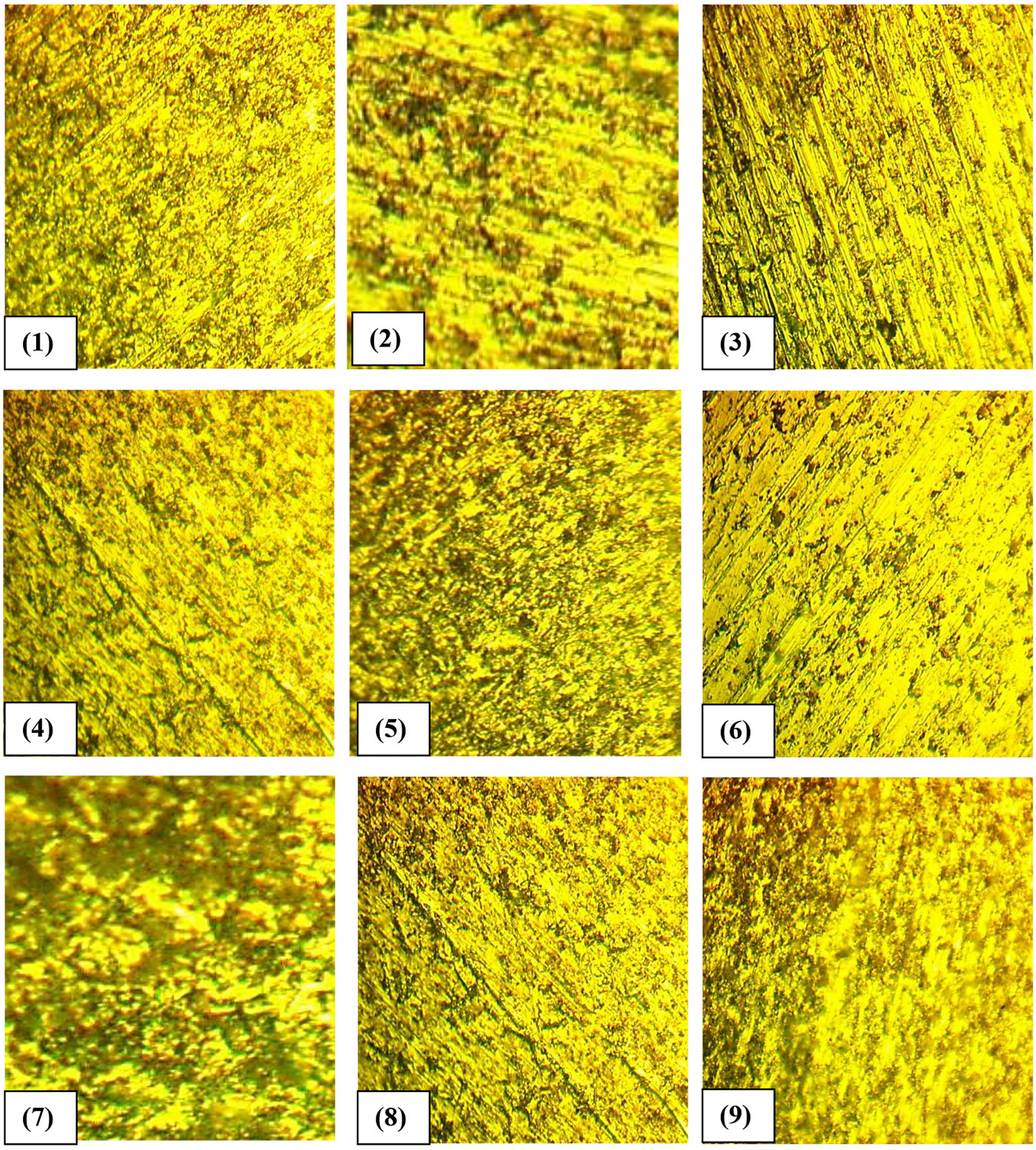

Figure 6. Macrostructure for specimens after incremental forming

influence of heat, as illustrated in Figure 7 the same result was recorded by [6]. Regarding attempts 7 and 9, the outcome was a coarse, granular microstructure with incomplete recrystallization caused by elevated temperature and deformation, as depicted in Figure 6. In regard to the eighth attempt, the lack of spindle speed causes a decrease in temperature, resulting in a microstructure that exhibits a harmonious combination of deformation and temperature, with grains of medium size. See specimens after incremental forming.

Surface roughness

Scaling up the step size leads to a rise in surface roughness, since the removal of more material in each step produces a less homogeneous surface. This phenomenon can be elucidated by the increased mechanical strain that arises from the application of larger loads at each stage of cutting. By increasing the feed rate, one may observe a marginal rise in surface roughness, as it allows for more precise manipulation of variables such as spindle speed and step size. One possible explanation for this phenomenon is that the roughness caused by the feed rate is counteracted by other more significant variables. Furthermore, the speed of the spindle has a direct effect on the heat produced during the forming process. As the spindle velocity rises, the resistance between the tool and the material intensifies, producing substantial thermal energy. The thermal energy has a direct impact on the microstructure of the material, causing the surface to become softer and, in certain instances, the grains to recrystallize. This phenomenon accounts for the observed reduction in hardness at extremely high speeds. An increase in step size (0.40) results in a notable rise in roughness, as anticipated due to the exacerbation of surface ripples through larger steps, Figure 8 clarified the impact of factors on surface roughness. The spindle speed considerably influences the level of roughness. As previously stated, although high speeds might enhance surface smoothness, they can also result in scaling caused by thermal deformation. The analysis of variance, shown in Tables 8 and 9, reveals that spindle speed has the greatest influence, accounting for 52.19% of the total. This indicates that it is the primary determinant of roughness. The step size

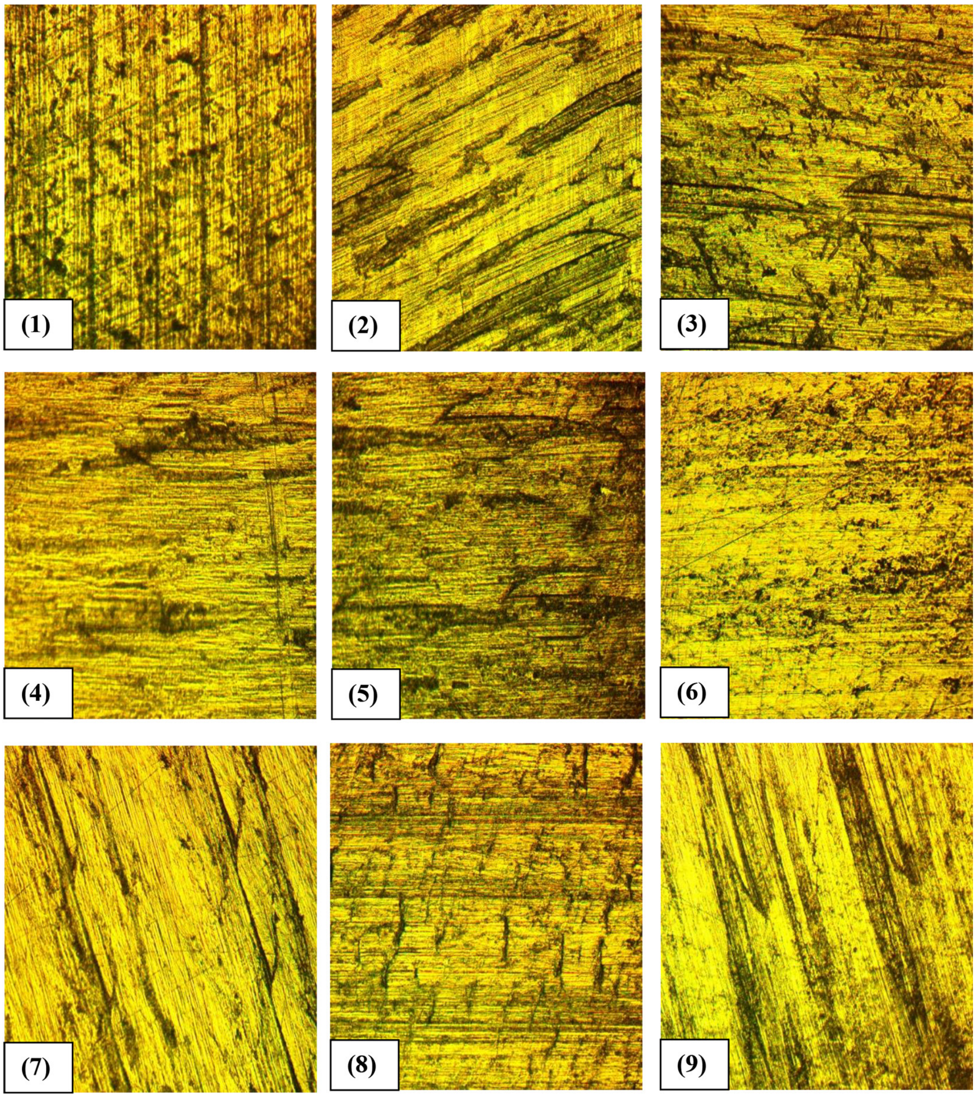

Figure 7. Tool track after forming process

Table 8. Analysis of variance

Source	DF	Contribution	Adj SS	Adj MS	P-Value
Step size	2	36.54%	0.058478	0.029239	0.009
Feed rate	2	10.95%	0.017527	0.008763	0.028
Spindle speed	2	52.19%	0.083528	0.041764	0.006
Error	2	0.32%	0.000514	0.000257	
Total	8	100.00%			

Table 9. Response table for means

Level	Step size	Feed rate	Spindle speed
1	0.2750	0.3687	0.2437
2	0.3937	0.4387	0.4460
3	0.4710	0.3323	0.4500
Delta	0.1960	0.1063	0.2063
Rank	2	3	1

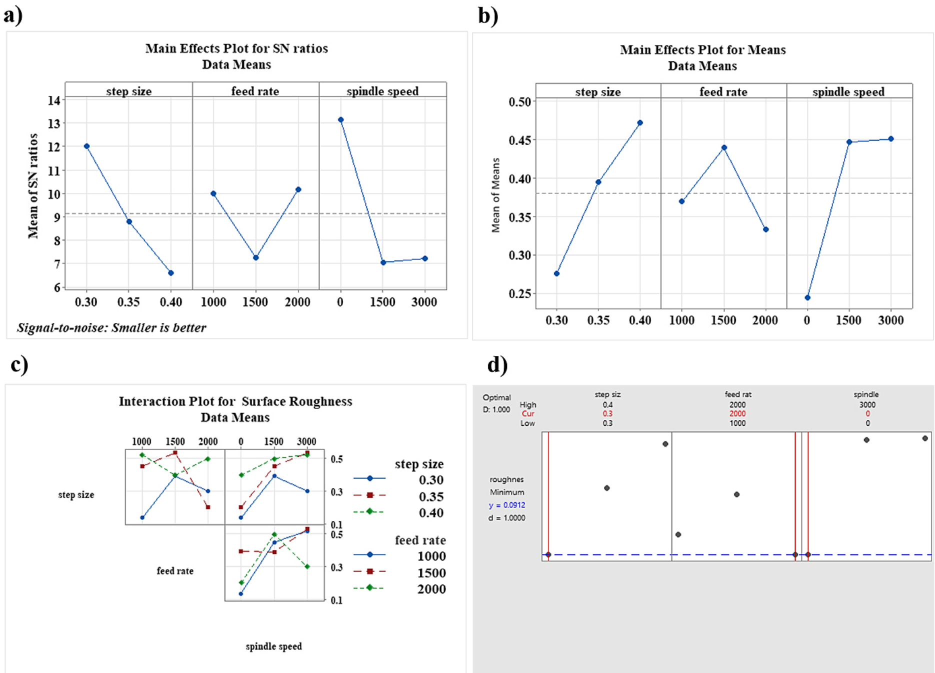

Figure 8. Main effects for roughness for (a) SN ratio, (b) means, (c) interaction plot for roughness

also had a highly significant impact of 36.54%. By comparison, the impact of feed rate was far less significant, estimated at 10.95%. The analysis of variance revealed that the optimal input values for roughness, which is (0.3 mm, 2000 mm/min 0 rpm) for step size, feed rate and spindle speed in sequence, as shown in Figure 8(d).

CONCLUSIONS

Spindle speed is the most influential factor, which it has P-value as 0.01 for hardness and 0.006 for surface roughness, and has great importance in controlling hardness and roughness. Step size comes second in importance and has a significant effect on mechanical properties. Feed rate has a very small and insignificant effect in the scope of the experiment. A larger step size results in more significant mechanical deformation, thereby inducing heightened stress and surface damage. The distribution of stress is influenced by the feed rate, although its impact is comparatively less substantial than that of step size and spindle speed. An elevated spindle speed raises the temperature produced by friction, resulting in surface induced physical and chemical alterations that contribute to heightened wear.

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