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Effect of Strontium Modifier on Machinability Characteristics of Heat Treated A357 Alloy Using Statistical Techniques

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Abstract

The current study sought to determine the influence of strontium addition on the microstructure and machinability of the A357 alloy. Furthermore, the influence of cutting parameters and aging temperatures on the machining performance of the modified alloy was investigated using a statistical technique. The machinability characteristics were investigated by milling experiments with a carbide tool. Experimental trials were carried out using Taguchi's L27 orthogonal array. Process parameters studied were strontium (Sr) percentage, aging temperature, cutting speed, and feed rate. Cutting force, surface roughness, and tool wear were investigated as responses. The microstructure of the specimens revealed that the addition of Sr to the A357 alloy helped to achieve refined grain structure. Furthermore, increasing the Sr concentration from 4 to 8% resulted in the enhanced refined microstructure. ANOVA analysis of responses revealed that Sr%, aging temperature, and feed rate have a significant effect on all the responses considered. However, cutting speed has exhibited the least influence. Further, the increase in Sr% resulted in an increase in cutting force and tool wear. Whereas, a decrease in surface roughness was observed due to increased Sr%. Whereas the increase of aging temperature, cutting temperature, and feed rate has resulted in the increase of response values. The aging temperature has shown significant influence on the variation of cutting force and surface roughness..

Keywords: *Heat Treatment, Machining Force, Milling, Strontium Modified A357 Alloy, Surface Roughness*

1.0 Introduction

Aluminum (Al) and its alloys are widely spread in engineering applications owing to their combined properties, such as low density and ability to enhance mechanical properties. Also, they are highly attractive materials for automotive and aerospace sectors due to their specific strength and economical[1]. Further enhanced characteristics of Al alloys are possible with the manipulation of their microstructure through different techniques such as heat treatment, addition of modifiers, *etc*[2]. The modifier addition during casting has attracted material scientists and engineers greatly more than other possible techniques[3]. Since it causes fundamental changes in microstructure homogenously and helps to uniform properties with reduced defects[4]. In addition, the effect of extrinsic factors such as temperature and cooling rate has less influence on the resultant properties. Furthermore, based on the obtained properties, they can be directed for component production in several

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applications. Baskaran *et al.*[5] have employed copper (Cu) as a microstructure modifier for the A356 Al alloy. The refined microstructure with better mechanical properties of the resultant alloy was noticed due to precipitation of intermetallic compound. Besides, many chemical modifiers are used in Al-Si alloys as eutectic modifiers. Commonly used modifiers are scandium (Sc), strontium (Sr), calcium (Ca), sodium (Na), and antimony. The Sc doping in Al-Si-Mg alloy is capable of multi-refinement phenomena such as grain refinement, secondary dendrite arm spacing, eutectic silicon (Si) manipulation, and harmless disposal of intermetallic phase[6]. Moustafa and Mosleh[7] have employed titanium and boron (Ti-B) as modifiers in the Al 5052 alloy. The Ti-B addition helped to achieve grain-refined microstructure and improved corrosion resistance of the alloy. Ali developed models correlating hardness with tensile strength of Al-Si alloys with different modifiers[8]. Lipinski and Szabracki have modified the mechanical properties and microstructure of hypoeutectic Al-Si alloy with the addition of Na[9]. Yang *et al.* investigated the wear behavior of Sb and Sr-modified A357 Al alloy and found that modified alloys possess better wear resistance compared to unmodified alloys[10]. Thus, available research has proved that modifiers are beneficial in improving the desired properties of Al alloys. Besides, optimal content of modifiers in the parent alloy is necessary. The percentage inclusion over the threshold limit may result in deterioration of mechanical properties[11]. Furthermore, machining of modifiers with added Al alloys is inevitable for their utilization in the production of components. With the evolution of modifiers added to Al alloys, research direction is concentrated on their machining characteristics study. Ficici and Keser studied the effect of casting modifiers on machinability performance, such as surface roughness and chip formation, in the turning of Al-Si alloy[12]. Prema *et al.* reported that grain refiner-added LM-6 Al alloy exhibited better surface roughness characteristics during drilling operation compared to unmodified alloy[13]. The significant challenge during machining of Al alloys is the tendency of Built-Up-Edge (BUE) formation during machining. Whereas, cutting force slightly increases with the increase in the machining parameters during the machining of Al alloys[14]. The addition of bismuth to the Al-Si-Cu alloy has helped to reduce the cutting force during its machining[15]. The addition of elements like bismuth to Al alloys forms a compound during the pulling and shearing mechanism of machining. Compounds formed act like a lubricant and help to reduce surface roughness through the diminished chances of BUE formation. Also, they help to decrease the cutting forces during machining[16,17]. In addition to workpiece material properties, selection of appropriate machining conditions is also important to achieve better machinability performance[18]. Thus, much literature has investigated the modeling and optimization of parameters for machining Al alloys using statistical techniques[19-21]. The literature survey revealed that investigations were carried out through the addition of modifiers and grain refiners to various types of Al alloys, such as A356, Al-Si-Mg, hypoeutectic Al-Si, hypereutectic Al-Si alloys, *etc.*, with the objective of improving their mechanical properties and refinement of microstructure. However, the similar investigation on A357 alloy is limited. Further, the improvement in mechanical properties such as tensile strength and hardness also increases the challenge of machining. A limited number of studies have reported on the machinability characteristics of grain refiners and microstructure-modified Al alloys. Furthermore, studies on the effect of strontium addition on the microstructure and machinability properties of A357 aluminum alloy are lacking. Hence, the current study aims to investigate the machinability characteristics of A357 alloy modified with the addition of Sr. The study was carried out with the help of Taguchi's design of experiment to capture the experimental data. Also, the effect of strontium on the machinability performance of A357 is determined substantially through a statistical approach.

2.0 Materials and Methodology

2.1 Material and Specimen Preparation

In the current study, A357 alloy is used as the base alloy. Composition of A357 aluminum is comprised of 6.5 to 7.5% silicon, 0.04 to 0.07% beryllium, 0.2% iron, 0.2% copper, 0.4 to 0.7% magnesium, 0.04 to 0.2% titanium, 0.1% zinc and 0.1% manganese. This alloy is typically heat treated to improve its strength characteristics. It was modified with the addition of strontium (Sr) modified A357 alloy.

Initially, measured quantity of A357 billet (charge) were melted in the crucible of an electric furnace. The charge was heated till 750°C to obtain molten mixture in

the crucible. Modifier Sr components of specific quantity, which were preheated about 250 °C is introduced to crucible. It was stirred with the help of mechanical stirrer at a speed of 250 rpm for 10 minutes to achieve homogenous mixture of alloy. Later, the metling temperature of 750°C was maintained for 20 minutes to facilitate the diffusion of Sr in Al alloy. The de-oxidizer and gasifiers were utilized for the elimination of oxygen, subsequently to prevent porosity in the cast. Die-releasing agent was sprayed on to the pre-heated dies to prepared for casting. Later, the homogenous mixture was transferred to die cavity of rectangular shape with dimension of 10mm × 100mm × 100mm. Consequently, it was allowed to cool under ambient conditions to room temperature with approximately 0.2°C/s of average cooling rateto yield desired cast specimens. The specimens of A357 alloy with 4%, 6% and 8% Sr were casted. Based on the improved properties due to addition of Sr at different percentage reported in the available literatures, the interval of Sr % variation was considred[10,12]. The present research studied with variation of Sr about 2% in each step, and its effect on the microstructure and machinability properties of A357 alloy.

2.2 Experimentation

The machining study was employed using carbide end mill cutter of 8 mm diameter for milling operation. Milling operation was done on the ACE® make winner vertical milling machine with Fanuc control system. Milling machine specifications are maximum speed of 5000 rpm with maximum bed size of 800mm × 400mm. The setup of tool and workpiece on the machine during experimentation is shown in the Figure 1. The Medilab make of 3000N electric mill tool dynamometer was used in the study for capturing cutting forces. It possesses great sensitivity and good operating temperature range. The dynamometer was connected to the milling machine and data acquisition software in the computer through amplifier and transducers. The dynamometer was connected to charged amplifiers and personal computer through an analogue to digital converter card. Data acquisition software was used to obtain and record the force data. The cutting forces and their amplitudes were measured with an accuracy of ± 0.012 N, ± 0.010 N and ± 0.020 N, for the cutting (tangential) force (Fc), thrust (radial) force (Ft) and feed (axial) force (Ff) respectively.

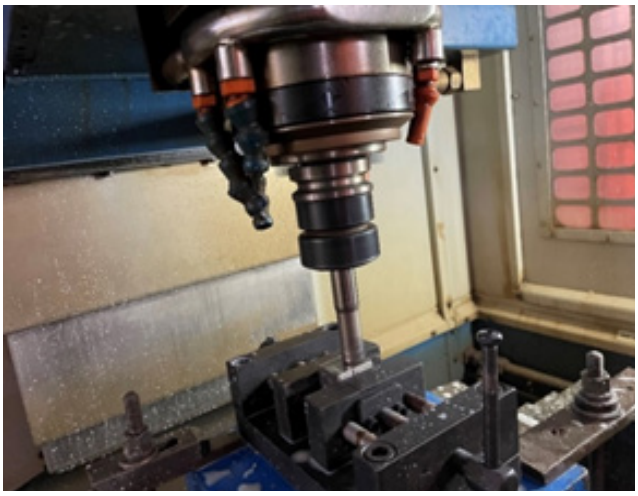


Figure 1. Illustrates the machine set up with work piece and tool.

The talysurf surface roughness tester (model: Surftest SJ-201) was used to measure the surface roughness values (Ra) of machined samples. The irregularities detected by the vertical displacement of stylus. Thus, stylus traverse movement detects the surface irregularities present over the distance equal to sampling length. It was measured with a cutoff length of 0.8 mm over five sampling lengths. They were distributed circumferentially at an angle of 120°. The average of three trials of surface roughness values was considered for the investigation. Calibration of instrument was performed before the actual measurement with the help of standard block provided by the supplier.

2.3 Plan of Experiments

The milling experimentation was conducted utilizing Taguchi's design of experiments. It enables users to analyze the effect of process parameters on responses with the minimum number of experiment trials. Taguchi's L27 orthogonal array was used to plan the experimentation. It has 13 columns which facilitate to analyze effect of 13 process parameters, each at 3 levels. In the present study, 4 parameters, each at 3 levels were considered. The considered parameters and their levels for experimental trials are illustrated in Table 1. The machining parameter levels were fixed based on the trial and error method of fixing the boundary values of parameters of study. Whereas ageing hours and temperature values were considered based on the reported research elsewhere[5,10]. Each experimental trails were repeated 3 times and

Table 1. Parameters and their levels

Sl. No.	Factors	Level 1	Level 2	Level 3
1	Sr, Wt. %	4	6	8
2	Aging Temp. (hrs)	6	8	10
3	Spindle Speed (rpm)	1000	1500	2000
4	Feed rate (mm/min)	0.1	0.15	0.2

average values were considered for the analysis to eliminate the error.

3.0 Results and Discussions

3.1 Microstructure

The microstructure of Al-Si eutectic alloy A357 modified through 4%, 6%, and 8% strontium (Sr) addition is shown as Figure 2 (a), (b), and (c), respectively. The eutectic solid solution of the Al-Si alloy typically consists of 12.6% Si, approximately. The microstructure of an eutectic alloy is generally comprised of coarser grains with needles or plates like Si structures embedded in the white matrix phase of Al. With the objective of modifying microstructure and refining grains, Sr is added to the eutectic alloy. Thereby, it was anticipated to reduce the formation of intermetallic compounds of the <0xC9><0x85>-phase with the primary composition of Fe-based compounds. Since they are detrimental for yielding good mechanical properties of alloys. The available literature has proven that Sr addition helps to achieve better mechanical properties of eutectic Al-Si alloy. Thus, in the present study, Sr was added to the based Al-Si eutectic alloy in the range of 4-8%. Figure 2(a) suggests that 4% Sr addition has resulted in the broken rod-like structure dispersed in the matrix phase. Perhaps the <0x7D>structure occurring in the alloy is comprised of Al4Sr due to the lean composition of Sr in the base

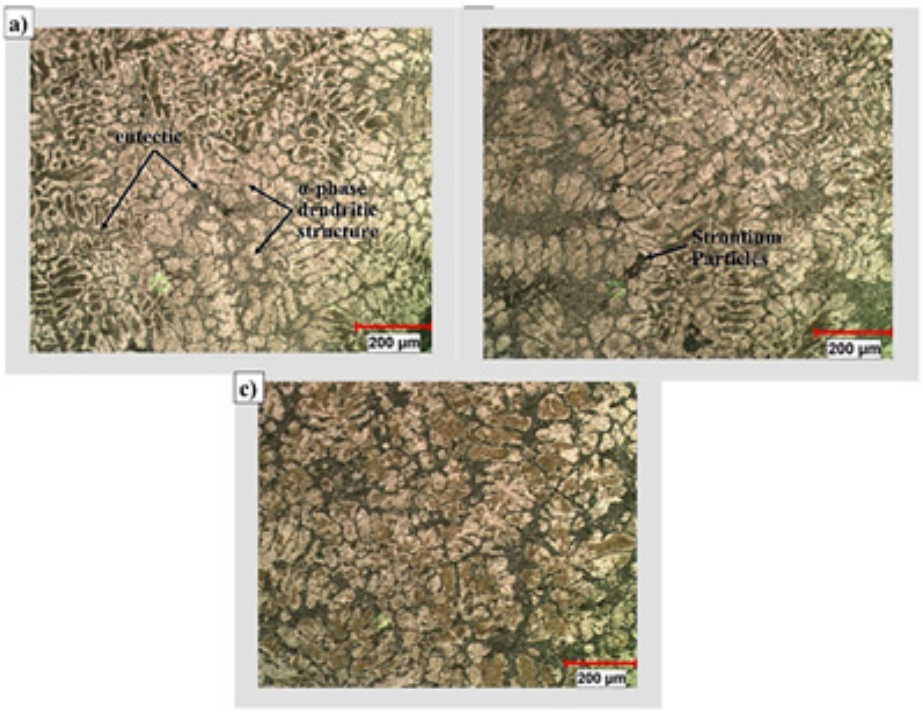


Figure 2. Microstructure of **(a)** A357 with 4% Sr **(b)** A357 with 6% Sr **(c)** A357 with 8% Sr.

alloy[22]. The increase in Sr content to 6% Figure 2(b) and 8% (Figure 2(c) has led to the further dissolution of Sr in the parent eutectic alloy with the modified eutectic point. In addition, the occurrence of proliferated rod-like fine grain structure was noticed. It can be described with the help of restricted growth theory, which explains that Sr addition has possibly been adsorbed by the eutectic composition. Thereby Si adhesion to Al atoms to form eutectic solid solution composition was hindered, resulting in twinning. Hence, formation and growth of fine rod-like structures were promoted in the Sr-added Al-Si eutectic alloy[23]. The resulted finer grain structure is lucrative and aids in

Table 2. Experimental results with L27 orthogonal array

Sl. No.	Sr (wt. %)	Aging Temp. (Deg.C)	Spindle Speed (rpm)	f (mm/min)	Fm (N)	Ra (µm)	VB_{max} (mm)
1	4	6	1000	0.1	12.5 8	1.8	0.02
2	4	6	1500	0.15	30.6 7	2.1	0.03
3	4	6	2000	0.2	45.6 7	2.7	0.03
4	4	8	1000	0.15	36.0 0	3	0.03
5	4	8	1500	0.2	46.6 7	3.9	0.04
6	4	8	2000	0.1	35.5 0	4.2	0.02
7	4	10	1000	0.2	51.6 7	5.4	0.04
8	4	10	1500	0.1	32.1 7	6	0.03
9	4	10	2000	0.15	56.6 7	6.9	0.03
10	6	6	1000	0.15	15.0 0	1.5	0.04
11	6	6	1500	0.2	32.5 0	1.8	0.05
12	6	6	2000	0.1	20.1 7	1.95	0.03
13	6	8	1000	0.2	37.5 0	2.1	0.04
14	6	8	1500	0.1	22.0 8	2.4	0.03
15	6	8	2000	0.15	40.5 0	3.3	0.04
16	6	10	1000	0.1	29.0 0	3.9	0.03
17	6	10	1500	0.15	43.3 3	4.5	0.04
18	6	10	2000	0.2	57.00	4.8	0.0 5
19	8	6	1000	0.2	24.17	1.2	0.0 6
20	8	6	1500	0.1	17.08	1.35	0.0 4
21	8	6	2000	0.15	32.50	1.65	0.0 5
22	8	8	1000	0.1	21.67	1.5	0.0 4
23	8	8	1500	0.15	36.67	1.8	0.0 5
24	8	8	2000	0.2	49.17	2.4	0.0 6
25	8	10	1000	0.15	34.17	3.3	0.0 6
26	8	10	1500	0.2	53.33	4.2	0.0 8
27	8	10	2000	0.1	43.33	3.9	0.0 5

achieving enhanced mechanical properties of the alloy. The improved mechanical properties due to refinement of grain structure owing to the addition of Sr content to Al-based alloys are reported elsewhere[24,25]. In addition, modified microstructure resulted in the change of alloy hardness, owing to the presence of higher concentration of Sr. The determined Vicker's hardness values of studied alloys with 4%, 6% and 8% Sr are correspondingly 56 VHN, 64 VHN and 72 VHN.

3.2 Machinability

The experimentation was conducted as per the Taguchi's L27 orthogonal array. During the experimentation plan, the weight percentage of Sr., aging temperature, cutting speed, and feed rate were respectively assigned to columns 1, 2, 5, and 9 of the orthogonal array as per the standard procedure followed for the L27 array. Further, the interaction effect of % of Sr with other experimental parameters was studied by assigning to other columns as suggested by Taguchi's experimentation plan for the L27 array[26]. Parameter-level combination for each trial was followed as the design of the experimentation plan, which is illustrated in Table 2. Each row of indicates the combination of parameter levels employed for the corresponding experimental trial. The resultant values of responses, *viz.*, cutting force, surface roughness, and tool wear, for each trial were captured three times, and the average value of each was considered for the analysis. Experimental results were analyzed through Analysis of Variance (ANOVA) and regression analysis methodologies. The ANOVA helps to understand the significance of each parameter and their effect on the response variation. While the regression analysis and modeling approach aids in building correlation between process parameters and responses. In addition, it also helps to establish a prediction model for the prediction of the corresponding response.

3.2 ANOVA Analysis

In the present study, ANOVA analysis was studied with a 95% confidence interval. Thus, the p-value of the parameter with <0.05 was considered statistically significant. The significance of the effect of each parameter was studied as a function of % of contribution. ANOVA results for cutting force are summarized in Table 3. It shows that the p-values of individual parameters, *viz.*, Sr%, aging temperature, and feed rate, were >0.05, whereas the p-value of cutting speed was >0.05. Furthermore, the interaction of % strontium with aging temperature, speed, and feed rate is less than 0.05. Hence, process parameters excluding cutting speed have a significant effect on the cutting force induced during the machining of the alloy

Table 3. Analysis of variance for cutting force

Source	DF	Adj SS	Adj MS	F	P
Sr (%)	2	517.68	258.84	12.37	0.007
Ageing Time (hr.)	2	2543.59	1271.80	60.78	0.000
Cutting Speed (m/min.)	2	17.51	8.76	0.42	0.676
Feed Rate (mm/min.)	2	2086.61	1043.31	49.86	0.000
Sr (%)*Ageing Time (hr.)	4	327.51	81.88	3.91	0.067
Sr (%)*Cutting Speed (m/min.)	4	177.93	44.48	2.13	0.195
Sr (%)*Feed Rate (mm/min.)	4	149.74	37.44	1.79	0.250
Residual Error	6	125.54	20.92		
Total	26				

Table 4. Analysis of variance for surface roughness

Source	DF	Seq SS	Adj MS	F	P
Sr (%)	2	10.1617	5.0808	415.70	0.000
Ageing Time (hr.)	2	41.0317	20.5158	1678.57	0.000
Cutting Speed (m/min.)	2	0.3906	0.1953	15.98	0.004
Feed Rate (mm/min.)	2	3.2939	1.6469	134.75	0.000
Sr (%)*Ageing Time (hr.)	4	2.0767	0.5192	42.48	0.000
Sr (%)*Cutting Speed (m/min.)	4	0.8728	0.2182	17.85	0.002
Sr (%)*Feed Rate (mm/min.)	4	0.3294	0.0824	6.74	0.021
Residual Error	6	0.0733	0.0122		
Total	26	58.2300			

Table 5. Analysis of variance for tool wear

Source	DF	Adj SS	Adj MS	F	P
Sr (%)	2	0.002985	0.001493	100.75	0.000
Ageing Time (hr.)	2	0.000230	0.000115	7.75	0.022
Cutting Speed (m/min.)	2	0.002452	0.001226	82.75	0.000
Feed Rate (mm/min.)	2	0.000185	0.000093	6.25	0.034
Sr (%)*Ageing Time (hr.)	4	0.000326	0.000081	5.50	0.033
Sr (%)*Cutting Speed (m/min.)	4	0.000037	0.000009	0.62	0.662
Sr (%)*Feed Rate (mm/min.)	4	0.000037	0.000009	0.62	0.662
Residual Error	6	0.000089	0.000015		
Total	26				

studied. Similarly, the interaction effect of strontium% with other process parameters was found statistically significant. Besides, the percentage of contribution computation illustrates that aging temperature was the most significantly contributing parameter, with the highest contribution percentage, followed by the feed rate and Sr.%. Cutting speed has influenced the least on the cutting force. ANOVA analysis of the results of surface roughness measured on the machined surface for each trial is illustrated in Table 4. Based on the p-values, it suggests that surface roughness was mainly affected by the influence of each parameter, *viz.*, Sr%, aging temperature, cutting speed, and feed rate individually. Besides, % of contribution signifies that aging temperature was the

highest influencing factor, followed by Sr% and feed rate. Cutting speed has the least influence on the surface roughness produced. Table 5 denotes the ANOVA results of tool wear determined as a function of flank wear of the cutting tool insert. The influence of individual parameters studied and the interaction of Sr% with aging temperature were considerably significantly based on the resultant p-values. The percentage of contribution column suggests that the effect of Sr% in the alloy was dominant, followed by the cutting speed and aging temperature. Whereas feed rate was the least influencing factor on tool wear.

3.3 Main Effect Plot Analysis

The main effect plots were utilized in the study to understand the effect of variation of parameters on the response values. Figure 3, 4, and 5 represent the main effect plots obtained for cutting force, surface roughness, and tool wear, respectively. Figure 3 illustrates that cutting force increases with the increase in Sr%, aging temperature, and feed rate, while decreasing with increasing cutting speed. Perhaps increasing the content of Sr and aging temperature leads to enhanced hardness of the alloy[27,28]. It conversely demands a greater amount of machining energy to overcome shear strength for causing work material shear. Hence, a higher cutting force was recorded for a higher Sr content alloy. The higher cutting force at the maximum studied level of feed rate is attributed to the increased friction at the tool-work interface zone. The phenomenon is favored by the higher strength and hardness of work material resulted due to the Sr content and increased aging temperature. Furthermore, the examination of surfaces produced for

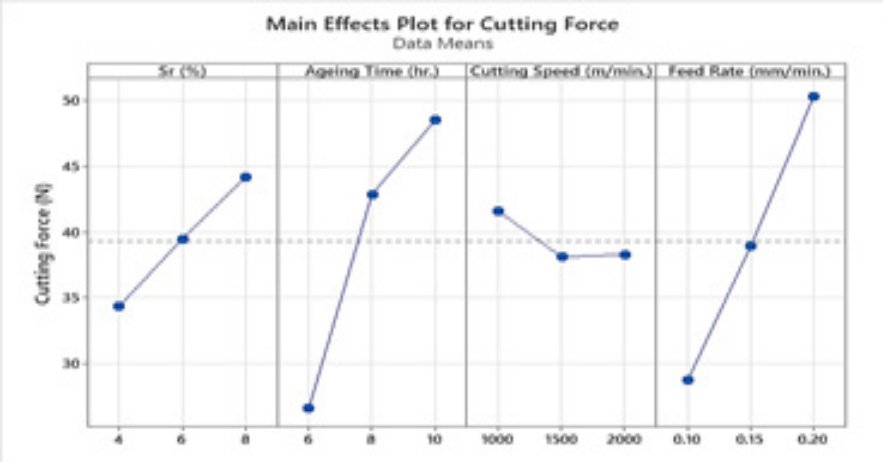


Figure 3. Main effect plot of cutting force.

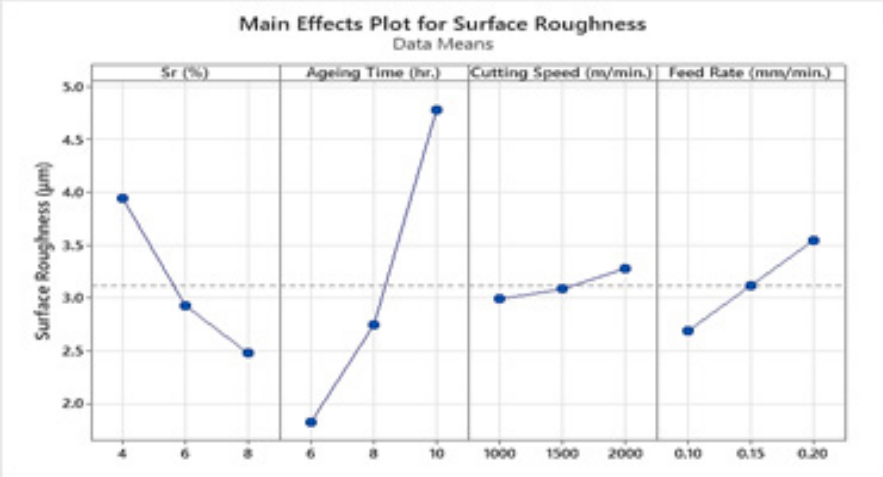


Figure 4. Main effect plot of surface roughness.

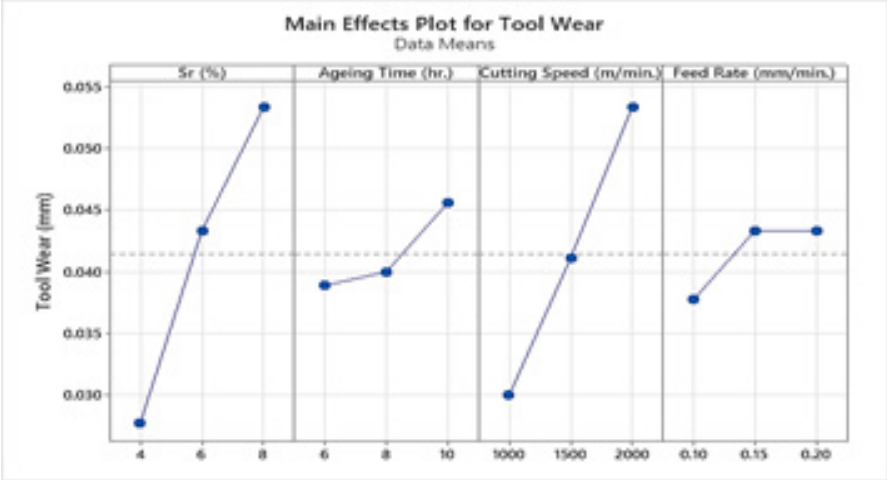


Figure 5. Main effect plot of tool wear.

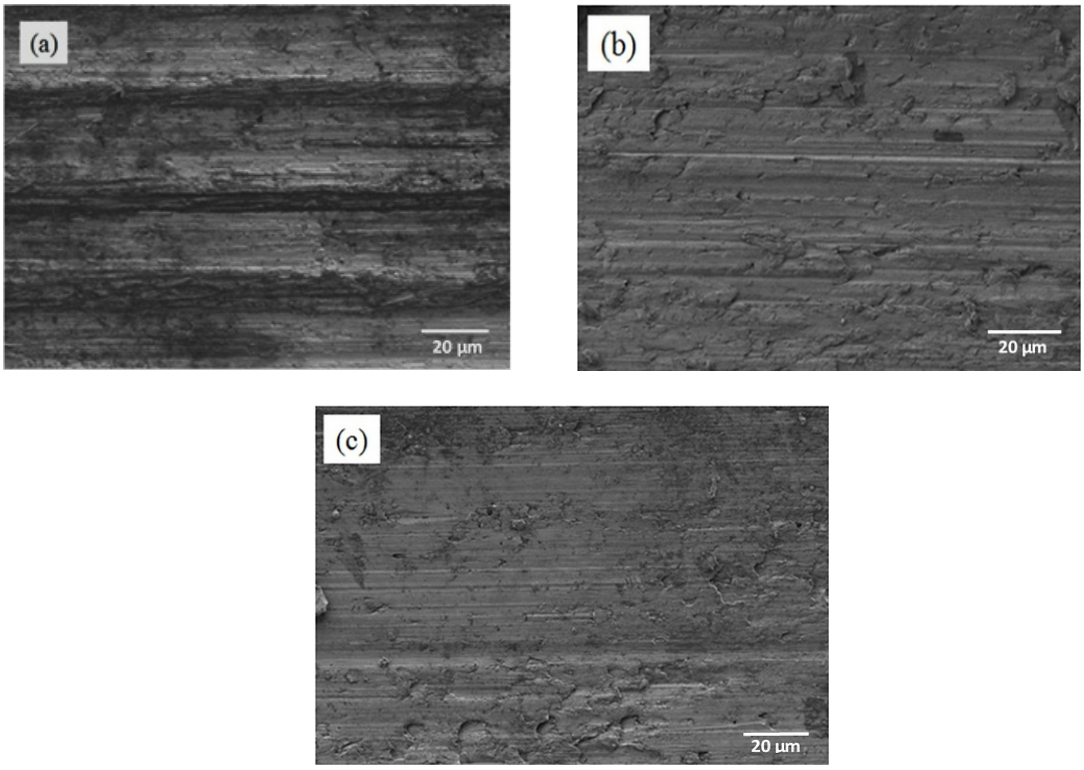


Figure 6. SEM images of machined surface at aging time of 10 hrs, spindle speed of 2000 rpm and feed rate of 0.2 mm/min **(a)** A357 with 4% Sr **(b)** A357 with 6% Sr **(c)** A357 with 8% Sr.

4%, 6%, and 8% Sr content alloys is illustrated in Figure 6. It revealed peaks and valleys on the surface owing to the plowing of the work surface from the tool tip during the cutting of 4% Sr content alloy. The ridges and surface cracks with dominant material folding are evident on the 6% Sr content alloy. The material's folding is more clearly pronounced, with intermittently produced surfaces indicating insufficient cutting energy to produce chips satisfactorily.

Figure 4 indicates that surface roughness decreases with an increase in Sr% and increases with the increase in aging temperature, feed rate, and cutting speed. The

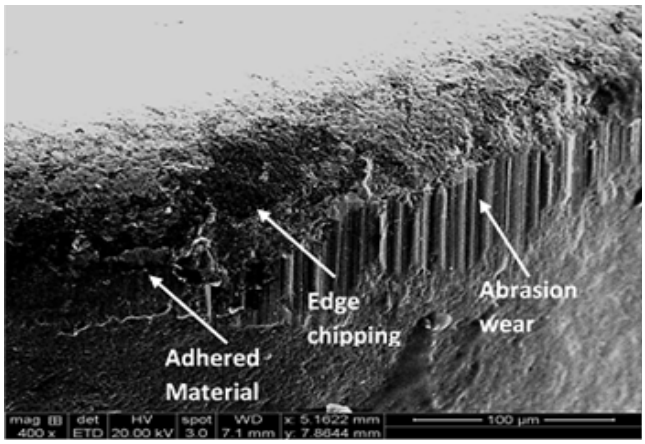


Figure 7. SEM image of tool wear at cutting condition of A357 alloy with 4% Sr, aging time of 10 hrs, spindle speed of 2000 rpm and feed rate of 0.2 mm/min.

enhanced hardness and strength due to the higher content of Sr% has probably resulted in the machining phenomenon identical to the hard machining process. Chips were separated from the workpiece volume at ease without a greater amount of built-up edge formation[29]. Whereas lower Sr content alloys possessing low hardness and strength due to minimum grain refinement tend to form built-up edge formation, hence producing poorly finished machined surfaces. The increasing surface roughness due to the increment of aging temperature is attributed to the dominant effect of cutting parameters over aging temperature. Besides improving the hardness, an increment in the values of cutting parameters has probably raised the machining temperature, resulting in thermal softening of the workpiece. It has resulted in an annealing effect on the worksurface, leading to diminishing the effect caused by aging temperature. Hence, softened worksurfaces due to higher cutting parameter levels facilitate easy removal of materials. Also, generation of temperature promoted the BUE formation[30]. Therefore, higher surface roughness was noticed at higher levels of speed, feed rate, and aging temperature.

Figure 5 illustrates the main effect plot of tool wear. It demonstrates that tool wear increases with the increase in Sr%, aging temperature, feed rate, and cutting speed. However, the variation of tool wear against change in Sr% and feed rate was significant compared to the effect of change in aging temperature and cutting speed. The refined grain structure attributed to the higher enhanced strength of the alloy with a higher Sr% has probably caused greater resistance against deformation during machining. Thus, it resulted in thermal softening of the tool surface, leading to greater tool wear. Whereas the effect of aging temperature was minimal on tool wear. As discussed earlier, the effect of variation of cutting parameters has outperformed the effect of aging temperature. The increase in cutting speed promotes the thermal softening of the tool significantly owing to elevating temperature at the tool-work interface zone[31]. Hence, a drastic rise in tool wear was noticed at higher cutting speeds. The increase in feed rate increases the tool-work interaction due to the increased volume of material being removed. In addition, cutting forces generated at a higher feed rate substantially affect the cause of rapid tool wear[32]. Therefore, greater tool wear at higher feed rate levels was recorded. In addition, Figure 7 depicts the examination of the worn tool surface employed during the cutting of 4% Sr content alloy aged for 10 hours, suggesting the adhesive tool wear mechanism occurrence on the nose of the flank face. Whereas abrasion on the rake surface is revealed. Perhaps continuous chips were formed owing to the dominance of greater value of cutting speed, causing adhesion of chips on the flank. Further, progress in chip travel has resulted in the abrasion of the rake surface due to rubbing by the plastically deformed, sharp-edged chips. Hence, it validates the dominant effect of cutting parameters over aging time at their higher levels.

3.4 Regression Modeling

Response prediction models were developed in the study to correlate process parameters with responses and to predict the responses within the range of studied parameter levels. Multiple linear regression models were established, which are presented as Equations (1)-(3). Equations 1, 2, and 3, respectively, represent the prediction models of cutting force, surface roughness, and tool wear. The coefficient of determination (R2) value of each model was considered to account for its feasibility. The R2 and R2 (adj.) values of established models are greater than 85%. Also, the difference between them is less than 20%. Thus, established models and correlation between parameters and responses are feasible and adequate. Further, the efficiency of prediction of each model was studied by comparing the experimental values with the predicted values of regression. Comparison plots are illustrated in Figure 8. They indicate the existence of closeness between

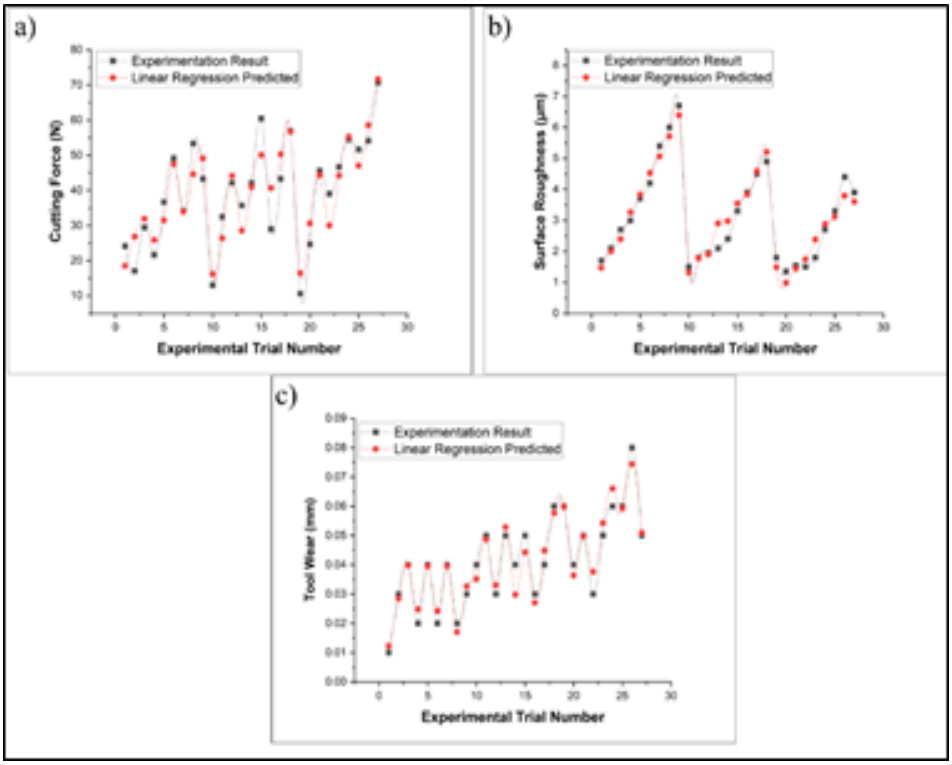


Figure 8. Comparison between experimental and predicted values of **(a)** cutting force **(b)** surface roughness **(c)** tool wear.

model predicted and experimental values for most of the experimental trials. Also, the deviation between them lies within the acceptable range. Hence, it can be concluded that the presented models can be utilized for the prediction of responses adequately, and the efficiency of the prediction is acceptable.

$$CF(N) = -2.4 - (9.53 \times Sr) + (2.09 \times AT) - (0.0041 \times CS) + (295 \times FR) + (0.841 \times Sr \times AT) + (0.0013 \times Sr \times CS) + (22.1 \times CS \times FR) + (0.00034 \times CS \times AT) - (14.4 \times FR \times AT) - (0.0646 \times FR \times CS)$$
$$R^2 = 92.10\%; R^2(Adj.) = 87.16\%;$$

…*Eq.* (1)

$$SR(\text{i m}) = -6.13 + (0.386 \times Sr) + (1.136 \times AT) - (0.00033 \times CS) + (14.5 \times FR) - (0.0936 \times Sr \times AT) + (0.000162 \times Sr \times CS) - (1.64 \times Sr \times FR) + (1.01 \times FR \times AT) - (0.00276 \times FR \times CS)$$
$$R^2 = 94.90\%; R^2(Adj.) = 91.71\%;$$

…*Eq.* (2)

$$TW(mm) = -0.0295 - (0.0005 \times Sr) - (0.00433 \times AT) + (0.000024 \times CS) + (0.287 \times FR) + (0.000778 \times Sr \times AT) - (0.0111 \times Sr \times FR)$$
$$R^2 = 93.07\%; R^2(Adj.) = 88.73\%;$$

…*Eq.* (3)

3.0 Conclusion

The investigation of microstructure and machinability of Sr modified A357 alloy in presented. In addition to cutting parameters, effect of Sr content variation and ageing temperatures on the machining performance was studied through statistical approach. Based on the carried-out study, following conclusions were drawn.

1. The microstructure analysis revealed that, Sr addition to A357 alloy has helped to achieve refined grain structure. Futhermore, increase in Sr content from 4 to 8% has enhanced the grain refinement.It has significant role in the resultant superior mechanical properties.

2. Statistical analysis of machinability characteristics of A357 alloy was carried out with Sr content %, ageing temperature, cutting speed and feed rate as process parameters. While cutting force, surface roughness and tool wear were studied as machinability characteristics.

3. ANOVA analysis of responses revealed that, Sr %, ageing temperature and feed rate has significant effect on all the responses considered. However, cutting speed has exhibited least influence.

4. The increase in Sr % resulted in the increase of cutting force and tool wear. Further, decrease of surface roughness was observed due to increased % of Sr. Whereas the increase of other parameters *viz.* ageing temperature, cutting temperature and feed rate has resulted in the higher values of responses.

5. The ageing temperature has shown significant influence on the variation of cutting force and surface roughness. However, decline effect of ageing temperature was noticed on tool wear.

6. The increment in the levels of feed rate has resulted in the increased of responses. Whereas cutting speed increment has lead to decrease of cutting force and increase of surface roughness as well as tool wear.

7. Perhaps, tool-work interface temperature, enhanced hardness of workpiece owing to modified grain structure and thermal softening of tool are the governing phenomenon for the observed results.

8. Ploughing and sufficient machining evidence was observed on low Sr content machined surface, whereas ridges with surface cracks were found on the machined surface of higher Sr content alloy.

4.0 References

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