Optimization of Process Parameters Using Taguchi Technique in Severe Surface Mechanical Treatment of AA6061

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***Abstract*—Many engineering applications demand materials with hard surface and tough core. In the present study, the enhancement of this combination of properties was achieved in aluminium alloy AA6061 by Severe Surface Mechanical Treatment (SSMT). The process parameters were optimized using Taguchi L9 orthogonal design of experiments. The size of shots, speed of revolution of shaft and duration of treatment were the parameters taken into consideration as they are directly related to the energy imparted to the surface during the process. The optimal levels were independently determined with reference to surface hardness and ultimate tensile strength of the material. The predicted optimal values of surface hardness and ultimate tensile strength were confirmed by experiments. Analysis of variance (ANOVA) showed that there is no significant difference in the contribution towards the hardness of the surface from these parameters, but in the case of ultimate tensile strength, the shot diameter was found to be more dominant than the other parameters. Results from optical microscopy and X-ray diffraction (XRD) studies were used to explain the enhancement of properties.**

Keywords-Severe Surface Mechanical Treatment, AA6061, Mechanical Properties, Optimization

I. INTRODUCTION

AA 6061 aluminium alloys find a variety of industrial applications such as aircraft fittings, hydraulic pistons, valves, automotive frames, hinge pins etc. due to their high strength-to-weight ratio, good corrosion resistance and formability. However, their hardness and wear resistance are not satisfactory in a number of potential applications which employ high pressure, sharp impacts, wear and fatigue loading. There are several approaches to make the surface of these aluminium alloys extremely hard so that they may replace steel in some of the components such as gears, cams, shafts, bearings and automotive components. Severe Surface Mechanical Treatment (SSMT) is one such technique similar to shot peening which employs mechanical peening to produce a very hard surface on the aluminium alloys. It involves the creation of a zone of residual compression (ZRC) on the surface of the aluminium alloy leading to work hardening. The complete overlapping of ZRC due to repeated peening will result in severe plastic deformation, which will eventually lead to grain fragmentation and accumulation of dislocations. Due to the variation in the energy imparted by the peening media to the surface / sub-surfaces to the interior, there will be a gradation in the grain refinement with ultrafine grains in the surface and relatively coarse grains in the interior of the component. Hence there will be a variation in the hardness of the component with peak hardness at the surface to decreasing values as one goes towards the interior.

II. SSMT PROCESS

The equipment consists of a shaft, which holds the specimen housed inside a drum containing the shots. Two DC motors drive the shaft and drum in opposite directions so that the shots get accelerated due to centripetal force and impinge on the specimen at random with high velocities. The complete details of the equipment are not revealed here due to a pending patent. A schematic diagram of the equipment is shown in Fig. 1.

The influence of the process parameters such as shot diameter (D), speed of revolution of the shaft (N) and duration of the treatment (T) were considered in this investigation as they are directly related to the energy imparted to the surface during the process. The usefulness of SSMT lies in its ability to control the energy input and creation of impacts at different angles, which leads to grain refinement with near random orientation of the grains. A careful trade-off between these process parameters could make SSMT a viable process for increasing the surface hardness and ultimate tensile strength of the material.

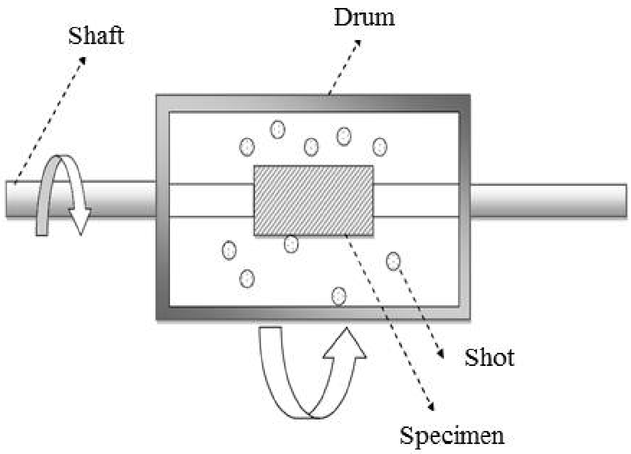

Fig. 1. Schematic Diagram of the Equipment Used for SSMT

III. TAGUCHI EXPERIMENTAL DESIGN

Taguchi experimental design [1] is widely used to optimize the process parameters in order to improve the quality characteristics of components. Classical experimental design becomes more complex with increase in the number of process parameters, as this would lead to a dramatic increase in the number of experiments to be performed.

Taguchi addresses quality in two main areas: offline and online quality control [2]. This method facilitates the use of a unique design of orthogonal arrays (OAs) to study the whole parameter space with a limited number of experiments [3]. The most important difference between a classical experimental design and a Taguchi design technique is that the former tends to focus solely on the mean of the quality characteristic while the latter reduces the variability of the quality characteristic.

The steps [4] in Taguchi experimental design are as follows:

(a) Selection of the response variable(s) to be optimized
(b) Identification of the factors (input variables) affecting response (output variables) and their respective factor levels
(c) Selection of the appropriate OA
(d) Assignment of factors and interactions to the columns of the OA
(e) Conduction of the matrix experiment
(f) Analysis of the data using S-N (signal-to-noise) ratio and ANOVA (analysis of variance)
(g) Determination of the optimal levels of process parameters
(h) Performing the confirmatory experiments.

IV. EXPERIMENTAL DETAILS

SSMT process is similar to shot peening process capable of producing the impacts at random with the velocity of the impacts ranging from 1 ms^{-1} to 20 ms^{-1}. The diameters of the shots used in SSMT range from 1-10 mm. Trial experiments were performed to identify the levels of the process parameters needed to be varied. The identified levels of performing experiments for Taguchi design are presented in Table I.

TABLE I
Process Parameters (Factors) and Their Levels

Level	A Shot Diameter (mm)	B Speed of Revolution (rpm)	C Duration of Treatment (min)
Level 1	4	500	30
Level 2	6	750	45
Level 3	8	1000	60

The usage of shots with diameter less than 4mm in SSMT process resulted in less energy input than the one required for creating severe plastic deformation (SPD). On the other hand, usage of shots with diameter greater than 8 mm resulted in the creation of large craters and hence the surface roughness. Similarly, speed of revolution of shaft less than 250 rpm did not create SPD, while in excess of 1000 rpm it resulted in surface damage. The duration of treatment less than 15 minutes was insufficient for a complete coverage of the surface to be treated. Excessive duration of treatment beyond 60 minutes caused damage to the surface. Since the property enhancement in bulk as a result of SPD could be estimated through tensile test, the ultimate tensile strength is considered as one of the response variable, in addition to surface hardness.

The degrees of freedom (DoF) for each factor are 2 (Number of levels minus one, i.e. (3-1) = 2) and therefore the total DoF will be 3 x 2 = 6. Generally the DoF of the OA should be greater than that of the whole experiment. Hence, L9 OA was chosen for the study. Nine experiments were carried out on the material by varying the process parameters at certain levels according to the chosen orthogonal array.

Hardness measurements at the surface of the specimen were taken using a microhardness (Vickers) tester (Matsuzawa, Japan), applying a load of 1 N and a dwell time of 10 s. The tensile test specimens were prepared by wire electro-discharge machining (EDM) as per ASTM - E8 standard [5] and the ultimate tensile strength was measured using an electromechanical universal testing machine (Make: Instron 3369K1550).

V. RESULTS AND DISCUSSION

A. *Signal-to-Noise Ratio*

The Taguchi method can be used to determine the experimental condition having the least variability as the optimal condition. This variability can be expressed by signal-to-noise ratio (S/N ratio, denoted by η). The experimental condition that has the maximum S/N ratio is considered as the optimal condition because the variability of the characteristics is inversely proportional to S/N ratio [6]. The experiments were conducted at random as per the principles of design of experiments. The objective function described in this investigation is maximization of hardness and ultimate tensile strength. So, the S/N ratios were calculated using the "larger the better" approach.

$$\eta(\mathrm{dB}) = -10\log_{10}\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}$$

where y_i is the i^{th} value of the response variable (surface hardness or ultimate tensile strength).

The experimental data were converted to their corresponding means and S/N ratios, as shown in Table II (for surface hardness) and Table III (for ultimate tensile strength).

TABLE II
Experimental Layout – L9 Orthogonal Array, Mean Value and S-N Ratio Value for Surface Hardness

S. No	[A] Shot Diameter (mm)	[B] Speed of Revolution (rpm)	[C] Duration of Treatment (min)	Mean Surface Hardness (H_v)	S-N Ratio for Hardness
1	4	500	30	116.4	41.31905961
2	4	750	45	114.1	41.14571289
3	4	1000	60	115.3	41.23658615
4	6	500	45	115.9	41.28166872
5	6	750	60	111.3	40.92990329
6	6	1000	30	125.4	41.96595073
7	8	500	60	119.1	41.51823523
8	8	750	30	120.6	41.62694616
9	8	1000	45	120.3	41.60531255

TABLE III
Experimental Layout – L9 Orthogonal Array, Mean Value and S-N Ratio Value for Ultimate Tensile Strength

S. No	[A] Shot Diameter (mm)	[B] Speed of Revolution (rpm)	[C] Duration of Treatment (min)	Mean Ultimate Tensile Strength (MPa)	S-N Ratio for Tensile Strength
1	4	500	30	347.4	50.81659628
2	4	750	45	345.7	50.77398759
3	4	1000	60	337.1	50.55517505
4	6	500	45	353.6	50.97024513
5	6	750	60	358.2	51.08251163
6	6	1000	30	353.1	50.95795435
7	8	500	60	311.0	49.85520778
8	8	750	30	311.6	49.87194898
9	8	1000	45	321.4	50.14091745

The average mean and S/N ratios of all levels of surface hardness are tabulated in Table IV, and those for ultimate tensile strength are shown in Table V. Applying the maximization criteria, it was found from the means and S/N ratio values that the optimal level setting for surface hardness is $A_3B_3C_1$ and that for ultimate tensile strength is $A_2B_2C_2$.

TABLE IV
Response Table for Means (Left) and Signal-to-Noise Ratios (Right) of Surface Hardness

Level	A	B	C
1	115.3	117.1	**120.8**
2	117.5	115.3	116.8
3	**120.0**	**120.3**	115.2
Delta	4.7	5.0	5.6
Rank	3	2	1

Level	A	B	C
1	41.23	41.37	**41.64**
2	41.39	41.23	41.34
3	**41.58**	**41.60**	41.23
Delta	0.35	0.37	0.41
Rank	3	2	1

TABLE V
Response Table for Means (Left) and Signal-to-Noise Ratios (Right) of Ultimate Tensile Strength

Level	A	B	C
1	343.4	337.3	337.4
2	**355.0**	**338.5**	**340.2**
3	314.7	337.2	335.4
Delta	40.3	1.3	4.8
Rank	1	3	2

Level	A	B	C
1	50.72	50.55	50.55
2	**51.00**	**50.58**	**50.63**
3	49.96	50.55	50.50
Delta	1.05	0.03	0.13
Rank	1	3	2

B. Analysis of Variance (ANOVA)

The analysis of variance (ANOVA) gives a clear picture of the extent to which a particular process parameter affects the response. Hence ANOVA was used to statistically distinguish the significant factors from insignificant ones. The ANOVA for means of surface hardness and ultimate tensile strength are shown in Table VI and Table VII.

TABLE VI
ANOVA Table for Means (Surface Hardness)

Source	DoF	SS	MS	F	% Contribution
A	2	33.6	16.8	1.75	23.84667
B	2	38.5	19.2	2.00	27.32434
C	2	49.6	24.8	2.58	35.20227
Error	2	19.2	9.6		13.62667
Total	8	140.9			

TABLE VII
ANOVA Table for Means (Ultimate Tensile Strength)

Source	DoF	SS	MS	F	% Contribution
A	2	2583.5	1291.7	24.14	94.68572
B	2	3.0	1.5	0.03	0.109951
C	2	35.0	17.5	0.33	1.28276
Error	2	107.0	53.5		3.92157
Total	8	2728.5			

The main effects for means and S/ N ratios of surface hardness and ultimate tensile strength are shown in Fig. 2 and Fig. 3. F-test was carried out for testing the significance of the process parameters. From the F-test, it was found that there is no significant difference in the contribution of the process parameters to the surface hardness of AA 6061 alloy. Also, the shot diameter was found to be statistically significant in affecting the ultimate tensile strength of the alloy, with a contribution of 95% for a confidence level of 95%, while the other parameters were insignificant at the same confidence level.

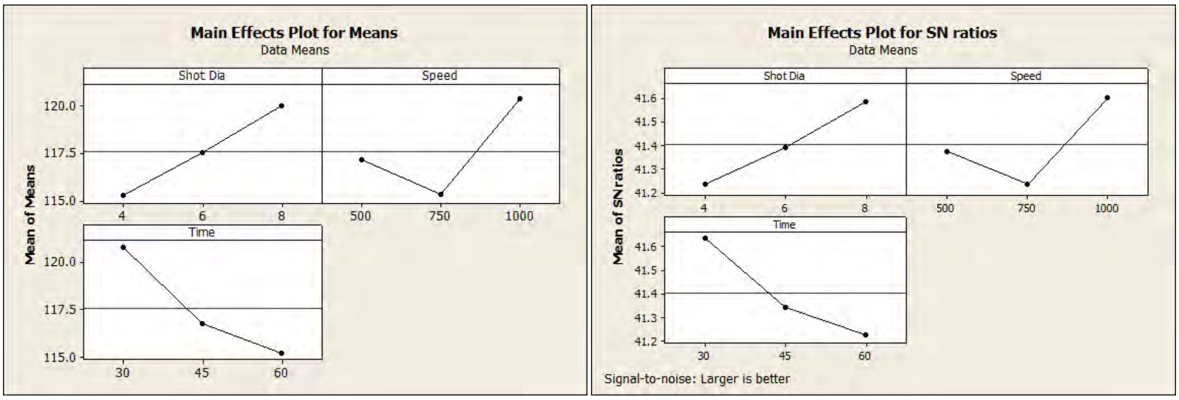

Fig. 2. Main Effects Plot for Means and S-N Ratios of Hardness

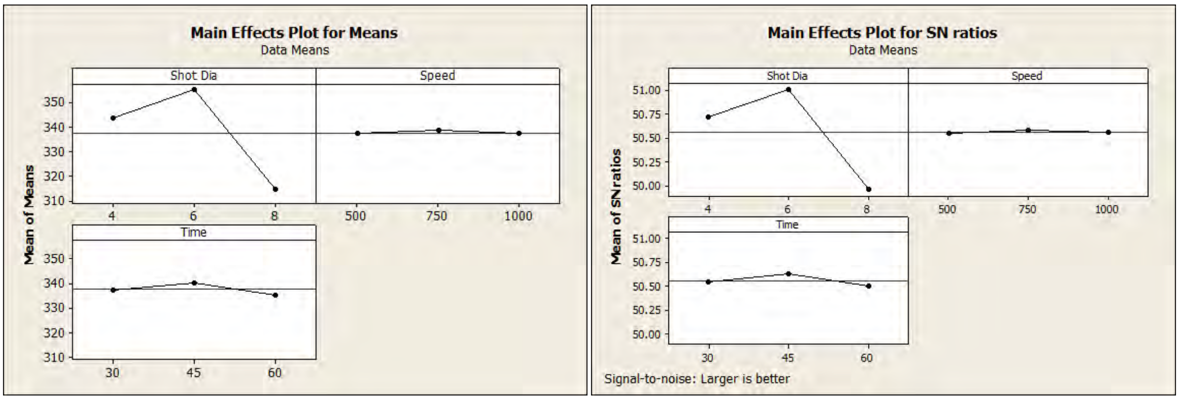

Fig. 3. Main Effects Plot for Means and S-N Ratios of Ultimate Tensile Strength

C. Predicted values

The average values of the factors at their levels are taken from Table IV for surface hardness and Table V for ultimate tensile strength. The values of surface hardness and ultimate tensile strength for the optimal level of process parameters were predicted using the formula given below:

$$\begin{aligned}\text{Surface Hardness (predicted)} &= A_3 + B_3 + C_1 - 2Y \\ &= 120 + 120.3 + 120.8 - 2(117.6) \\ &\approx 126\ H_v\end{aligned}$$

$$\begin{aligned}\text{Ultimate Tensile Strength(predicted)} &= A_2 + B_2 + C_2 - 2Y \\ &= 355 + 338.5 + 340.2 - 2(337.7) \\ &\approx 358\text{MPa}\end{aligned}$$

where A_i, B_i and C_i are the average mean values of shot diameter, speed of revolution and duration of treatment at their i^{th}levels respectively, and Y is the overall mean.

D. Confirmation Experiments

The confirmation experiments were carried out in three different samples with the process parameters set at their optimal levels. The shot diameter, speed of revolution and duration of treatment were set at 8 mm, 1000 rpm and 30 minutes respectively for confirmation of surface hardness, and at 6 mm, 750 rpm and 45 minutes respectively for confirmation of ultimate tensile strength. The average values of the surface hardness and ultimate tensile strength were found to be 122 H_v and 356 MPa respectively. These values are within ±5% of the predicted mean values.

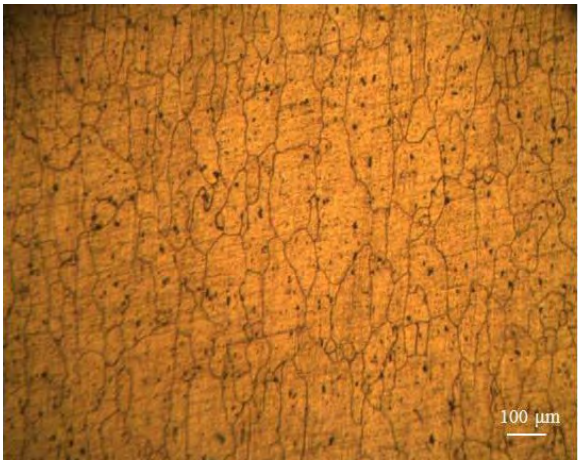

Fig. 4. Optical Microstructure of Untreated AA6061 (200x)

E. Optical Microscopy and XRD Analysis

Vickers microhardness measurement revealed an improvement in the surface hardness of the AA6061 from 104 H_v in the as-received condition (T651) to 122 H_v when treated with a process combination of 8 mm-shot diameter, 1000 rpm-speed of revolution and 30 minutes-duration of treatment. This hardness is 17% more than that of as-received condition and three times greater than that of annealed condition. An optical micrograph of AA6061 before SSMT treatment is shown in Fig. 4. It shows elongated grains typical of a rolled alloy. The Mg_2Si precipitates are visible as tiny dark spots in the microstructure, the existence of which is also confirmed by XRD as shown in Fig. 5.

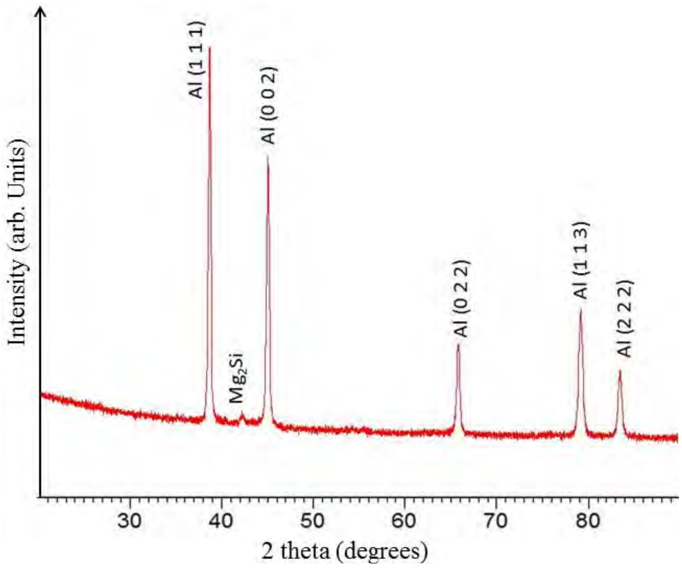

Fig. 5. XRD Pattern of AA6061 Treated by SSMT with the Process Combination of 8 mm Shots, 1000 Rpm Speed of Revolution and 30 Minutes Duration of Treatment

. The average grain size in the as-received condition was 30 microns. The sample subjected to SSMT process has undergone severe plastic deformation, leading to accumulation of dislocations and subsequently grain distortion and fragmentation. The extent of grain refinement by SSMT process was found to be so high that it was impossible to resolve the grains in the optical microscope. Since the numerous dislocation walls in the treated material get more preferentially etched than the grain boundaries, there was difficulty in exposing the grain boundaries by conventional etching techniques, which make the XRD technique a more convenient choice to find the crystallite size. The comparison of XRD patterns of AA6061 in the annealed, as-received and SSMT samples revealed a sharp peak for annealed one and peak broadening in theothers. This may be due to a combined effect of the presence of high strains and ultrafine grains. Hence crystallite size was determined from the peak broadening observed in XRD patterns, using the Scherrer formula. To eliminate the instrumental effects on peak broadening, XRD was performed on a standard silicon sample under the same experimental conditions and thus the peak broadening due to the instrument was eliminated.

The crystallite size and the equivalent lattice strain for the treated sample were 60 nm and 0.263% respectively. The property enhancement that results from SSMT can thus be attributed to the presence of ultrafine crystallites in the treated material.

VI. CONCLUSIONS

In light of the above discussion, the following conclusions are drawn:

1. The levels of the parameters of the SSMT process were optimized with respect to surface hardness and ultimate tensile strength.
2. ANOVA elucidated that all the three process parameters i.e. shot diameter, speed of revolution and duration of treatment have an almost equal contribution towards the surface hardness, while the size of shots was found to be the dominant factor contributing towards the ultimate tensile strength.
3. It was inferred from the Taguchi analysis that the combination of 8 mm-shot diameter, 1000 rpm-speed of revolution and 30 minutes-duration of treatment was the optimal setting for obtaining maximum surface hardness, the value of which was predicted as $126H_v$. It was also deduced from the Taguchi method that an optimal process setting with the usage of 6 mm shots, 750 rpm-speed of revolution and 45 minutes-duration of treatment would result in maximum ultimate tensile strength that was predicted as 358 MPa.
4. The respective confirmation experiments were carried out with the optimal settings on three different samples. The average hardness and the ultimate tensile strength were found to be 122 $H_v$and 356 MPa respectively, which were in good agreement with the predicted responses and have a deviation of less than 5%.
5. The optical microscopy and XRD analysis indicated that the hardness enhancement is a consequence of grain refinement effected by severe plastic deformation, which accompanies SSMT.

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