CHAPTER 5

RESULTS AND DISCUSSION

5.1 INTRODUCTION

The study and investigations on twist extruded samples of AA6061-T6, AA6082-T6 and AA7075-T6 alloys, processed by twist extrusion were carried out with experimental investigation, finite element analysis and optimization. The outputs of the analysis have been validated.

The investigations on the metallurgical aspects of the twist extruded samples were carried out, to evaluate the changes in the microstructures, such as grain distribution and grain size. The studies on the mechanical properties have been carried out to assess the changes in strength and micro hardness, due to the deformation associated with twist extrusion. Finite Element analysis was carried out to determine the effective stress and effective strain. The results of the FEM analysis were compared with those of the experimental work.

The optimization of process parameters, such as the extrusion load, temperature and number of passes was carried out and the corresponding responses were measured, and the predicted values were validated experimentally. Empirical relationships in the form of multiple regression equations, correlating the dependent parameters with the independent parameters were developed using RSM.
5.2 EFFECT OF TWIST EXTRUSION ON MECHANICAL PROPERTIES OF AA6061-T6 ALLOY

5.2.1 Hardness of AA6061-T6 Specimens before and after Twist Extrusion

The various mechanical properties, like hardness and tensile strength were analyzed in order to find the variation in the properties. Specimens processed by one, two and three twist extrusion passes were studied. In order to minimize the possibilities of error, a minimum of five micro hardness readings were taken from each sample along the longitudinal and transverse directions respectively and the results are averaged. The averaged values are presented in Table 5.1. The effect of the number of passes of twist extrusion on the hardness of AA6061-T6 alloy is shown in Figure 5.1.

Table 5.1 Experimental Hardness and Tensile strength of AA6061-T6 alloy

<table>
<thead>
<tr>
<th>S.No</th>
<th>Condition of the Sample</th>
<th>Temperature</th>
<th>No. of passes</th>
<th>Hardness [Hv@0.5]</th>
<th>Tensile Strength [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Before Extrusion</td>
<td>-</td>
<td>-</td>
<td>84</td>
<td>243</td>
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<tr>
<td>2</td>
<td></td>
<td>350°C</td>
<td>Pass I</td>
<td>89</td>
<td>248</td>
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<tr>
<td>3</td>
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<td>Pass II</td>
<td>91</td>
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<td>Pass III</td>
<td>95</td>
<td>255</td>
</tr>
<tr>
<td>5</td>
<td>After Extrusion</td>
<td>350°C</td>
<td>Pass I</td>
<td>96</td>
<td>261</td>
</tr>
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<td>6</td>
<td></td>
<td></td>
<td>Pass II</td>
<td>98</td>
<td>293</td>
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<tr>
<td>7</td>
<td></td>
<td></td>
<td>Pass III</td>
<td>99</td>
<td>296</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>425°C</td>
<td>Pass I</td>
<td>106</td>
<td>299</td>
</tr>
<tr>
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<td>Pass II</td>
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<td>10</td>
<td></td>
<td></td>
<td>Pass III</td>
<td>110</td>
<td>312</td>
</tr>
</tbody>
</table>
The average Vickers microhardness of the as-received work piece is 84 Hv. From the observations, there is no anisotropy of the hardness in the parent metal at all the five readings. After the first twist extrusion pass, by moving from the head of the billet (which enters in to the die) to the end of the billet (which leaves the die), the magnitude of hardness increases and the average value obtained is 89 Hv. This hardness value increases from 89 Hv to 106 Hv at higher temperatures. The second twist extrusion pass improves the hardness in the range of 91 Hv to 107 Hv at various temperatures. The same trend was observed in the three twist extrusion passes. The hardness increases at the higher temperature, and with more number of passes. This is due to the fact that the imposed strain is less at the centre of the specimen, which increases the hardness of the alloy even after three TE passes than single TE pass (Beygelzimer et al 2009; Orlov and Beygelzimer 2009). The results are compared with the reports of twist extrusion conducted for 99.99% Aluminum (Orlov et al 2008).

Figure 5.1 Effect of the number of passes on the hardness of AA6061-T6 alloy
5.2.2 Tensile Properties of AA6061-T6 Specimens before and after Twist Extrusion

Table 5.1 shows the results of the tensile test conducted at different temperatures and number of passes. The effect of the number of twist extrusion passes on the tensile strength of AA6061-T6 alloy is shown in Figure 5.2. It was observed that the first pass of twist extrusion conducted at 350°C increases the tensile strength from 243 MPa to 248 MPa, and the tensile strength increases to 255 MPa on performing further TE passes at the same temperature. The increasing trend of tensile strength is noticed for further TE passes conducted at 425°C and 500°C. The tensile strength increases by 12% on first pass of twist extrusion conducted at temperatures 350°C to 500°C, whereas the tensile strength increased to 16% and 18% on the second and third twist extrusion passes respectively. The reason for the above behaviour is due to the grain refinement which is observed from Figure 5.5 (e-f). This agrees well with the results of the twist extrusion conducted for Ti-6Al-4V alloy at higher temperatures (Akbari Mousavi et al 2010). It was also observed that the percentage increase in tensile strength after second and third passes is less compared to the first and second pass of twist extrusion. The internal stresses which are more intensive in peripheral regions of the first twist extrusion pass oppose the new external stresses produced during the second and further extrusion passes at higher temperatures (Syed Ali et al 2011). This may be the reason for the variation in percentage of the tensile strength.

The tensile properties have been evaluated for the samples from the 0th to the 3rd pass of Twist Extruded materials. Two samples from each pass were tested. The results showed reproducible data for both the samples. All the tests were carried out at room temperature. The results of the tensile tests
are shown in Figure 5.3 depicting true stress-strain diagrams of AA6061-T6 alloy.

**Figure 5.2** Effect of the number of passes on the Tensile Strength of AA6061-T6 alloy

**Figure 5.3** Stress-Strain curve of the AA6061-T6 alloy before and after the twist extrusion
The major increase in strength is observed after the first pass of TE. A relative increase of 10 to 15% in strength was observed after three TE passes. The characteristic nature of this plot shows that the ultimate tensile strength (UTS) and yield strength increase after three TE passes. As the grain size decreases, the strain hardening rate decreases, leading to a plunging tensile test curve. The necking starts soon after yielding. This behaviour is also observed in the present tensile tests.

5.3 MICROSTRUCTURE ANALYSIS ON TWIST EXTRUSION OF AA6061-T6 ALLOY

Figures 5.4 and 5.5 display the optical and SEM microstructures of AA6061 specimen in the initial state, before as well as after TE with one, two and three passes at a temperature of 500°C. The microstructures of the specimen before extrusion show equiaxed coarse grains with an average grain size of 36 μm. The dislocation density inside the grains is low, and the grains contain the deformation twins as seen in Figures 5.4 (a-b). The coarse grain in the initial microstructure is the reason for the reduced hardness in the sample before extrusion.

The numbers of twins that are found in the specimen before extrusion decreases substantially after one TE pass as seen in Figures 5.5 (a-b) and after three TE passes they disappear. This may be due to the fact that, instead of twinning, dislocation slip becomes the main operative mechanism of plastic deformation in the TE process, at the stage of formation of the ultrafine grain structure, as reported by (Stolyarov et al 2005).
Figure 5.4 Microstructure of AA6061-T6 before extrusion (a) OM (b) SEM

Figure 5.5 OM and SEM Microstructure of AA6061-T6 (a-b) One TE pass at 500°C (c-d) Two TE passes at 500°C and (e-f) Three TE passes at 500°C
It is also observed that the grains start to elongate in the direction of the twist after one TE pass, and high angle grain boundaries tend to originate as seen in Figures 5.5 (a-b). These high angle grain boundaries refines to form a fine grain of equiaxed microstructure less than 25 μm at two TE passes at a temperature of 500°C, as shown in Figures 5.5 (c-d).

This had effected in marginal hardness enhancement in the matrix. The hardness increased with further twist extrusion passes. Figures 5.5 (e-f) illustrate that performing the third TE pass produces finer grains of average size 20 μm, which is the reason for the enhanced strength and hardness.

5.4 SIMULATION RESULTS ON TWIST EXTRUSION OF AA6061-T6 ALLOY

The von Mises stress contours of the sample during 15 steps of the deformation, are shown in Figure 5.6. The plunger and the other assembly features have been removed for better clarification. It is apparent that the maximum stress occurs in the corners, because these regions are in contact with the die interior surfaces (Seyed Ali et al 2011). Also, the heat transfer was higher at the die edges, since the specimen was hot extruded. When the heated billet is inserted into the die, the temperature of the billet will be transferred to the dies interior surfaces. Hence a sudden cooling of the specimen takes place. To avoid this, the die is maintained at the required temperature.
Figure 5.6  Von Mises Stress contours of AA6061-T6 sample during 15 steps of the deformation, arranged from right to left
Figures 5.7 (a-d) show the enlarged view of the von Mises stress contours of four different stages of (3), (6), (10) and (13) selected from Figure 5.6, respectively. Figure 5.7 (a) shows stage 3 of the deformed billet during the first twist extrusion pass, in which it was found that the maximum stress is 116 MPa. The maximum stress values for stages 6, 10 and 13 during the first twist extrusion pass were found to be 139, 141 and 158 respectively as shown in Figure 5.7 (b-d). It was found that the stress increase noticed in the above cases is not the same on further twist extrusion passes at different temperatures, which is evident from Figures 5.8-5.10.

![Step-3](image1.png)  ![Step-6](image2.png)

![Step-10](image3.png)  ![Step-13](image4.png)

**Figure 5.7**  Von Mises stress contours taken from Figure 6 in the (a) 3rd (b) 6th (c) 10th and (d) 13th steps
Figures 5.8 to 5.10 depict the variations of the von Mises stress versus time for the temperatures 350°C, 425°C and 500°C respectively. The billet experiences more stress at the beginning of the twist extrusion process, and the magnitude of the stress goes on decreasing when the billet reaches the end, as shown in Figure 5.8. The same trend is noticed for the simulation conducted at temperatures 400°C and 450°C, and at different passes, as shown in Figures 5.9 and 5.10. It is also observed that there is a sudden jump at the stress at 0.08 sec. The reason is due to the change in the billet direction from one plane to another inside the twist die. When the billet comes out of the die the magnitude of stress decreases which is evident from the figures 5.8 to 5.10.

**Figure 5.8  Stress variation against time at various TE passes at temperature of 350°C**
Figure 5.9 Stress variation against time at various TE passes at temperature of 425°C

Figure 5.10 Stress variation against time at various TE passes at temperature of 500°C
This is because the peripheral regions of the specimen are subjected to more internal stress due to the friction between the die and the specimen’s exterior surface. The study shows that the amount of stress induced in the specimen is not only different from the head to the end of the specimen, but also the magnitude of the stress is also changed along the extrusion direction.

According to the volume constancy principle the volume of the metal should remain the same after extrusion. To confirm this, simulation is carried out to check the volume reduction of the specimen against time, for various twist extrusion passes at 500°C. It was observed that there is a negligible amount of (less than 1%) reduction in the volume of the billet from the beginning to the end of one, two and three extrusion passes, as shown in Figure 5.11. The formation of the scale during a high temperature TE process, and the friction between the die and the material interface may be the reason for this behavior.

![Graph showing volume reduction over time](image)

**Figure 5.11** Reduction of the billet volume during the TE of AA6061-T6 alloy
Figure 5.12 illustrates the variations of normal plastic strain in the direction normal to the billet at various times during the deformation process at 500°C. As shown in Figure 5.12, after the first pass, the billet experiences more strain at the head compared to the end of billet (Akbari Mousavi et al 2010; Seyed Ali et al 2011). The magnitude of the strain at the end of the second pass increases compared to the first pass. The reason may be the effects of work-hardening during deformation, and the primary distortion of the crystal lattice after the first twist extrusion pass. On an average, the billet undergoes more strain in the first two passes compared to the third pass. It is clear, that the heterogeneity in strain distribution is decreased, by increasing the number of passes.

![Graph showing plastic strain against time at 500°C](image)

**Figure 5.12 Plastic Strain against time at temperature of 500°C**

Figure 5.13 shows the variation of normal plastic strain with time for various elements in the specimen. Two corner elements and one center element were taken for the simulation. It was found that the effective strain obtained at the center of the sample is less compared to the corner, and the magnitude of the effective strain values lies between those predicted in the
corners. The reason is that the corner regions which are in contact with the
die, are subjected to larger strain compared to the center where the mode of
deformation is found to be pure shear. The results are supported by the
experimental results reported by Akbari Mousavi et al (2010) and

![Graph showing plastic strain over time](image)

**Fig. 5.13 Plastic strain of the specimen for various elements**

### 5.5 OPTIMIZATION RESULTS ON TWIST EXTRUSION OF
AA6061-T6 ALLOY

The necessity of using optimized process parameters for the
effective forming of materials by various forming processes, is rapidly
growing throughout the world. It is essential to have complete control over
the relevant process parameters, to maximize the strength on which the
quality of a formed component is based. Therefore, it is very important to
select and control the forming process parameters for obtaining the maximum
strength. In order to achieve this, various prediction methods can be used, to
define the desired output variables by developing mathematical models, to
specify the relationship between the input parameters and output variables. Nowadays, response surface methodology (RSM) is used widely for analyzing problems in which several independent variables influence a dependent variable or response, and the goal is to optimize the response (Cochran and Cox, 1962 and Manonmani et al., 2005). In this investigation, an attempt was made to optimize the twist extrusion process parameters, to attain the maximum tensile strength and hardness properties, using response surface methodology.

RSM was used as an optimization tool to search the optimum values of the process variables. The empirical relationships developed in the previous chapter were framed using the coded values. The optimization was done on the coded values, which were then converted to actual values. The Design Expert statistical software package was used to optimize the process variables. In practical applications of RSM, it is necessary to develop a fitting model for the response surface, and it is typically driven by some unknown physical mechanism. For prediction, the response surface method (RSM) is more practical, economical and relatively easy to use (Gunaraj and Murugan, 1999). RSM consists of the experimental strategy for exploring the space of the process independent variables, empirical statistical modelling to develop an appropriate relationship between the yield and the process variables, and the optimization methods for finding the levels or values of the process variables that produce the desirable values of the responses (Balasubramanian et al., 2008). The empirical relationships (Equations 4.4 and 4.5) developed in the previous chapter were used in the RSM to predict the optimum values of the process variables from which the optimum responses are estimated. The optimum values obtained for the AA6061-T6 alloy are listed in Table 5.2.
Table 5.2 Optimized Twist Extrusion process parameters for the AA6061-T6 alloy

<table>
<thead>
<tr>
<th>S. No</th>
<th>Parameters</th>
<th>Optimized Values</th>
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<tbody>
<tr>
<td>1</td>
<td>Load (A), kN</td>
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</tr>
<tr>
<td>2</td>
<td>Temperature (B), °C</td>
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<td>3</td>
<td>Number of passes (C)</td>
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</tr>
<tr>
<td>4</td>
<td>Tensile Strength(TS), MPa</td>
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</tr>
<tr>
<td>5</td>
<td>Hardness (H), Hv@0.5</td>
<td>110.54</td>
</tr>
</tbody>
</table>

5.5.1 Normal Probability Plots

The normal probability plot of the residuals for responses (tensile strength and hardness) of AA6061-T6 alloy, is shown in Figures 5.14 (a-b), reveals that the residuals fall in a straight line, which means that the errors are distributed normally (Tung-Hsu Hou et al 2007). All the above considerations indicate an excellent adequacy of the regression model.

(a) Tensile Strength

Figure 5.14(a-b) (Continued)
Figure 5.14(a-b) Normal probability plots for responses of the AA6061-T6 alloy

5.5.2 Analysis of the Response Graphs and Contour Plots for the Response Tensile Strength

Response surfaces were developed for all the empirical relationships, taking two parameters in the ‘X’ and ‘Y’ axes and the response in ‘Z’ axis. The response surfaces clearly indicate the optimal response point (Kannan and Murugan, 2006). The contour plots show distinctive circular mound shapes indicative of possible independence factors with response to the display of the region of optimal factor settings. By generating contour plots using software for the response surface analysis, the optimum is located with reasonable accuracy by characterizing the shape of the surface. If a contour pattern of a circular contour occurs, it tends to suggest the independence of the factor effects, while elliptical contours may indicate factor interactions (Montgomery 2001).

The effect of the load and temperature on the output response of tensile strength for AA6061-T6 alloy is shown in Figure 5.15 (a-b). From the
response and contour plots it is observed, that for a load of 1000 kN and 350°C the average tensile strength is about 249 MPa.

(a) Contour plot of Tensile Strength for 1000 kN load and temperature of 500 °C

(b) Response plot of Load and Temperature on Tensile Strength

**Figure 5.15(a-b) Effect of Load and Temperature on Tensile Strength of AA6061-T6 alloy**
If the temperature is increased above 450°C, for the same load, the average tensile strength is about 302 MPa. At the same temperature level, by increasing the load from 1000 kN to 1200 kN, the average tensile strength predicted is 302.4 MPa.

The effect of load and number of passes on the response of tensile strength for AA6061-T6 alloy is shown in Figure 5.16 (a-b). For a load of 1000 kN and single twist extrusion pass the average tensile strength obtained is about 289.956. Similarly by increasing the number of twist extrusion passes from one to three, the tensile strength increases from 289.95 MPa to 300.23 MPa. At the same time, if the load is increased from 1000 kN to 1200 kN by keeping the number of passes constant, the tensile strength increases from 289.95 to 291.73 MPa, which is very less compared to the results obtained by increasing the number of passes.

![Contour plot of Tensile Strength for 1000 kN load and 3 TE passes](image)

(a) Contour plot of Tensile Strength for 1000 kN load and 3 TE passes

**Figure 5.16(a-b) (Continued)**
Figure 5.16(a-b) Effect of Load and Number of passes on Tensile Strength of AA6061-T6 alloy

The effect of temperature and number of passes on the response of tensile strength is shown in Figure 5.17 (a-b). It is found, that as the temperature increases from 350°C to 500°C for one TE pass, the tensile strength increased from 248.71 MPa to 298.81 MPa. At the same increasing temperature levels, the tensile strength was found to be increased from 255.74 MPa to 308.69 MPa after three TE passes. From this it is evident, that among the three parameters, the load has less influence on the tensile strength when compared to the other two parameters, the temperature and number of passes.
(a) Contour plot of Tensile Strength for temperature of 500 °C and 3 TE passes

(b) Response plot of Temperature and Number of passes on Tensile Strength

Figure 5.17(a-b) Effect of Temperature and Number of passes on Tensile Strength of AA6061-T6 alloy
5.5.3 Analysis of the Response Graphs and Contour Plots for the Response Hardness

The effect of the load and temperature on the output response hardness is shown in Figure 5.18 (a-b). From the response and contour plots it is observed, that for a load of 1000 kN and the temperature of 350°C, the average hardness is about 91.48 Hv. If the temperature is increased to 500°C, for the same load, the average hardness is about 106.13 Hv. At the same temperature level, by increasing the load from 1000kN to 1200kN, the average hardness is 106.59 Hv.

(a) Contour plot of Hardness for 1000 kN load and 500 °C

Figure 5.18 (a-b) (Continued)
Figure 5.18(a-b) Effect of Load and Temperature on Hardness of AA6061-T6 alloy

The effect of the load and number of passes on the output response hardness is shown in Figure 5.19 (a-b). It is observed that for a load of 1000 kN and single twist extrusion pass the average hardness is about 96.04 Hv. Similarly, by increasing the number of twist extrusion passes from one to three, the hardness increases from 96 Hv to 101 Hv. At the same time, if the load is increased from 1000kN to 1200kN by keeping the number of passes constant, the hardness increases from 96.04 Hv to 96.47 Hv which is very less compared to the results obtained by increasing the number of passes.
(a) Contour plot of Hardness for 1000 kN load and 3 TE passes

(b) Response plot of Load and Number of passes on Hardness

Figure 5.19(a-b) Effect of Load and Number of passes on Hardness of AA6061-T6 alloy
The effect of temperature and number of passes on Hardness is shown in Figure 5.20 (a-b). It is observed that as the temperature increases from 350°C to 500°C for one TE pass the hardness increased from 89.3 Hv to 106 Hv. Further increasing the temperature levels, the hardness was found to be increased from 95.4 Hv to 110 Hv after three TE passes. From this it is evident, that among the three parameters, the load has lesser influence on hardness, when compared to the other two parameters, such as the temperature and number of passes.

(a) Contour plot of Hardness for the temperature of 500 °C and 3 TE passes

Figure 5.20(a-b) (Continued)
Figure 5.20(a-b) Effect of temperature and number of passes on the hardness of AA6061-T6 alloy

5.5.4 Confirmation Experiment

The empirical models developed for the tensile strength and hardness have been validated with the experimental results, and the results were correlated with the confirmation test. These fitted models were found to be significant at 95 % confidence level. In addition to the statistical validation, the developed models have also been validated by conducting the confirmation experiments. The confirmation experiments were performed with the process parameters of 1000 kN load, 500°C temperature and three twist extrusion passes. The plan for the confirmation experiment and the values of the responses obtained by the confirmation experiments
and predicted through the optimization approach, are given in Tables 5.3 and 5.4. It was observed that the average error between the experimental and predicted values at the optimal combination of input parameters for tensile strength and hardness lies within 0.473% and 0.79% respectively which confirms that the fitted models were found to be significant.

**Table 5.3**  Results of confirmation experiments for the Tensile Strength of AA6061-T6 alloy at a Load of 1000 kN, Temperature of 500 °C and three twist extrusion passes

<table>
<thead>
<tr>
<th>Tensile Strength (MPa)</th>
<th>Variation (%)</th>
<th>$r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental Value</td>
<td>Predicted Value</td>
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</tr>
<tr>
<td>311.5</td>
<td>312.34</td>
<td>0.26</td>
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<tr>
<td>309</td>
<td>312.34</td>
<td>1.06</td>
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<tr>
<td>312</td>
<td>312.34</td>
<td>0.1</td>
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</tbody>
</table>

$0.99$

**Table 5.4**  Results of confirmation experiments for the Hardness of AA6061-T6 alloy at a Load of 1000 kN, Temperature of 500 °C and three twist extrusion passes

<table>
<thead>
<tr>
<th>Hardness (Hv)</th>
<th>Variation (%)</th>
<th>$r^2$</th>
</tr>
</thead>
<tbody>
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<td>Experimental Value</td>
<td>Predicted Value</td>
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</tr>
<tr>
<td>110</td>
<td>110.536</td>
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</tr>
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<tr>
<td>108.56</td>
<td>110.536</td>
<td>1.78</td>
</tr>
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</table>

$0.97$
5.6 EFFECT OF TWIST EXTRUSION ON MECHANICAL PROPERTIES OF THE AA6082-T6 ALLOY

5.6.1 Hardness of AA6082-T6 Specimens before and after Twist Extrusion

Table 5.5 presents the experimental results of AA6082-T6 alloy processed at different temperatures and various number of passes. The effect of Vickers microhardness in relation to the temperature and number of passes on the twist extrusion of the AA6082-T6 alloy is shown in Figure 5.21. The hardness values of the as received samples are homogeneous at the centre and the edge of the sample and the average hardness values obtained is 84 Hv. After one twist extrusion pass, this hardness value increases from 84 Hv to 103 Hv at higher temperatures. The second twist extrusion pass improves the Vickers microhardness to a range of 87 Hv to 109 Hv at various temperatures. The same trend was noticed with three twist extrusion passes, in which the hardness value increased to 112 Hv. It was observed that the hardness increases at high temperature with more number of passes. It is observed that there is non-homogeneity in the hardness values of the twist extruded samples, which is less at the centre compared to the edge of the sample, but there is a reasonable increase in the average hardness value of 112 Hv as compared to 75 Hv of the as received sample. Moreover it is observed that the average hardness values obtained after first and second twist extrusion passes at 425°C remains the same inspite of increase in number of passes. The distribution of the precipitates during precipitation hardening can be expected to exhibit different behaviours during plastic deformation (Ehab et al 2013). As the TE experiments were carried out at higher temperatures, the material undergoes recrystallization and grain growth. As the twist extruded material is slowly cooled in ambient air the second phase particles are precipitated, leading to an increase in hardness. Moreover, the large strain which is created at a higher number of passes results in grain refinement. This is agreed well
with the results reported earlier (Akbari Mousavi et al 2012 and Latypov et al 2012).

**Table 5.5 Experimental Hardness and Tensile strength of AA6082-T6**

<table>
<thead>
<tr>
<th>S.No</th>
<th>Specimens</th>
<th>Temperature</th>
<th>No. of passes</th>
<th>Hardness [Hv 0.5]</th>
<th>Tensile Strength [MPa]</th>
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<tbody>
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<td>1</td>
<td>Parent Material</td>
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<td>272</td>
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<td>276</td>
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<td>279</td>
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<td>Pass I</td>
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<tr>
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<td>Pass II</td>
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<td>325</td>
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<td></td>
<td>Pass III</td>
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<td>328</td>
</tr>
</tbody>
</table>

**Figure 5.21** Effect of Number of passes on Hardness of AA6082-T6 alloy
5.6.2 Tensile Properties AA6082-T6 Specimens before and after Twist Extrusion

Figure 5.22 illustrates the effect of the tensile strength in relation to the temperature and number of passes. It is observed that the tensile strength increases with an increase in temperature and number of passes. The reason for this behaviour is due to the homogeneity of the deformed billet. This is expected to be improved with a higher number of passes due to the transfer of the shear to the adjacent material via work hardening (Butra et al 2007). Moreover a higher temperature and more number of passes lead to grain refinement of the alloy AA6082, which is evident from Figures 5.25 (a-f). This may be the reason for the increase in the tensile strength, which agreed well with the already reported results of TE experiments (Valiev et al 2009).

![Graph showing tensile strength vs temperature and number of passes for AA6082-T6](image)

**Figure 5.22** Effect of the Number of passes on the Tensile Strength of AA6082-T6
Figure 5.23  Stress-Strain curve of AA6082-T6 before and after twist extrusion

The yield strength and tensile strength of the AA6082-T6 twist extruded material, before and after extrusion, are shown in Figure 5.23. The parent metal before extrusion shows lower yield strength and tensile strength when compared to the material after one, two and three twist extrusion passes. The material processed by more number of passes yielded superior tensile properties.

5.7  MICROSTRUCTURAL ANALYSIS ON TWIST EXTRUSION OF AA6082-T6 ALLOY

The SPD performed consecutively on the materials with low recovery rates, results in a decrease of grain size, and also leads to homogeneous microstructures (Cepeda et al 2011). Since, AA6082-T6 is a precipitation hardenable alloy, fine particles may be precipitated in the AA6082-T6 alloy during TE conducted at high temperature. The research
results of Zendehdel et al (2012) proved that precipitates can appreciably contribute to microstructural refinement. To obtain a homogeneous ultra-fine microstructure, it is essential to perform more than one pass of TE. As a result of this, TE experiments were conducted on AA6082-T6 alloy at different temperatures and several numbers of passes. The microstructural analyses were carried out to study the grain refinement after every pass at different temperatures. Figure 5.24 shows the SEM microstructure of the AA6082-T6 specimen in the as-received condition. The structure shows the coarse grains with equiaxed structures, with an average grain size of 38 μm.

To study the effect of temperature and number of passes on grain refinement, the microstructure of the specimens processed at one, two and three TE passes at the temperatures of 350°C, 425°C and 500°C were taken. The results of the microstructures of one and three TE passes processed at 350°C and 500°C are presented in Figure 5.25 (e-f).

![Figure 5.24 SEM Microstructure of AA6082-T6 before extrusion](image)

The SEM microstructure of the specimen after one TE pass at 350°C is shown in Figure 5.25 (a). The microstructure indicates that the billet undergoes very high strain, and the grains are oriented in the direction of the twist.
The grains in the outside edge are mostly elongated, and the flow of the material is created due to temperature and the geometry of the twist extrusion die. It is also observed, that high angle grain boundaries originate after one TE pass. Some deformation twins were also observed due to severe plastic deformation. The high angle grain boundaries, which are found after the first pass of TE at 350°C, recover to form fine equiaxed grains with an average grain size of 30 μm after three extrusion passes, which is observed in Figure 5.25 (b). The microstructure becomes finer with a clear vortex flow of
the billet material at the temperature of 425°C [Fig. 5.25 (c)]. The microstructure appears to be homogeneous, with more number of grains after three extrusion passes at the temperature of 425°C, with an average grain size of 28 μm, as illustrated in Figure 5.25 (d). The same trend was noticed in the microstructures of the specimen shown in Figures 5.25 (e and f) where the specimen is processed at the temperature of 500°C. The average grain size reduced from 28 μm to 22 μm. Thus smaller grains cause an increase in strength and hardness. The reason might be inhomogeneous distribution of grain size caused by formation of dislocation density converting them into smaller grains (Zendehel and Hassani 2012).

5.8 SIMULATION RESULTS ON TWIST EXTRUSION OF AA6082-T6 ALLOY

The stress contours of the sample during various steps of the deformation were carried out and the results of the effective stress for two different steps are shown in Figure 5.26 (a-b).

![Figure 5.26(a-b) Effective stress contours of various steps during simulation](image)

The plunger and the other assembly features have been removed for better clarity. The die was maintained at the required temperature to
compensate the heat loss from the specimen to the die. Figure 5.26 (a) shows the stress contours of the deformed billet during the 77\textsuperscript{th} step of the first twist extrusion pass at 350 °C, in which the maximum stress is found to be 149 MPa, whereas the maximum stress during the 97\textsuperscript{th} step (Figure 5.26(b)) for the same temperature and one twist extrusion pass is found to be 180 MPa. The reason for this behaviour is that the billet experiences more stress at the beginning of the twist extrusion process, and the magnitude of stress goes on decreasing when the billet reaches the end (Akbari Mousavi et al 2008). The coarse grained structure which is shown in Figure 5.25 (a), may also be the reason for the increase in the stress values, which agrees well with the simulation results on pure Aluminum (Seyed Ali et al 2011; Shahab et al 2012). The increase in the stress values observed in the single TE pass conducted at 350 °C, disappeared with the simulation conducted at a higher temperature and higher number of passes. The reason may be the grain refinement attained at a higher temperature and higher number of passes, which is evident from Figure 5.25(d and f).

Figure 5.27 (a and b) shows the effective strain contours of the deformed billet during the 77\textsuperscript{th} step and 97\textsuperscript{th} step of the simulation conducted for the first twist extrusion pass at 350 °C.

![Figure 5.27(a-b) Effective strain contours of various steps during simulation](image-url)
The maximum strain is found to be 6.39, whereas the maximum strain during the 97th step for the same temperature and extrusion pass is found to be 6.64. This reason may be due to the effects of strain hardening during deformation, and the primary distortion of the crystal lattice after the first twist extrusion pass (Seyed Ali et al. 2011). The specimen undergoes large strain at the 97th step compared to the 77th step. Moreover, form the simulation conducted at a higher temperature and more number of passes, it was found that the magnitude of the strain values decreases. It is clear, that the heterogeneity in strain distribution decreased by increasing the number of passes, which agreed well with the already reported results (Seyed Ali et al. 2011; Shahab et al. 2012 and Ranjbar Bahadori et al. 2011). The experimental and simulation results show that the hardness and tensile strength of the AA6082 T6 alloy specimen processed by twist extrusion, increases with higher temperatures and more number of passes.

Figures 5.28 to 5.30 show the variations of the von Mises stress versus time for the temperatures of 350°C, 425°C and 500°C respectively for the AA6082-T6 alloy. The stress contours are higher at the beginning of the twist extrusion process, and reach the peak and then decrease when the billet reaches the end, as shown in Figure 5.28. The same trend is noticed for the simulation conducted at temperatures of 450°C and 500°C and at different passes as shown in Figures 5.29 and 5.30. The reason for this behaviour is due to the higher magnitude of stress which is imposed during the entry of the billet into the die and during the change in the billet direction from one plane to another inside the twist die. When the billet comes out of the die the magnitude of stress decreases which is evident from the figures 5.28 to 5.30.
Figure 5.28  Stress variation against time at various TE passes at the temperature of 350°C

Figure 5.29  Stress variation against time at various TE passes at the temperature of 425°C
Figure 5.30 Stress variation against time at various TE passes at the temperature of 500°C

As presented earlier in the section 5.4, according to the volume constancy principle, the volume of the metal should remain the same after extrusion. After performing the simulation to check the volume constancy, it is noticed from the Figure 5.31, that the volume reduction from the beginning to the end of simulation for all three passes lies in a straight line, which means that the volume constancy is maintained during the process.

Figure 5.32 shows the variations of normal plastic strain at various times during the twist deformation at 500°C. The behaviour of this alloy is also similar to that of AA6061-T6 alloy. It is observed that the work piece experiences more strain at the head compared to the end. The magnitudes of strain at the end of the second pass increases, compared to the first pass. This variation in strain decreases by increasing the number of passes, which is observed from Figure 5.32, in which the strain remains constant towards the end of deformation.
Figure 5.31 Reduction of billet volume during TE of AA6061-T6 alloy

Figure 5.32 Plastic strain against time at the temperature of 500°C
5.9  OPTIMIZATION RESULTS ON TWIST EXTRUSION OF AA6082-T6 ALLOY

The empirical relationships (Equations 4.6 – 4.7) developed in the previous chapter were used in RSM, to predict the optimum value for the process variables from which the optimum responses are estimated. The optimum values obtained for the AA6082-T6 alloy, are listed in Table 5.6.

Table 5.6  Optimized Twist Extrusion process parameters for the AA6082-T6 alloy

<table>
<thead>
<tr>
<th>S. No</th>
<th>Parameters</th>
<th>Optimized Values</th>
</tr>
</thead>
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<tr>
<td>1</td>
<td>Load (A), kN</td>
<td>1200</td>
</tr>
<tr>
<td>2</td>
<td>Temperature (B), °C</td>
<td>500</td>
</tr>
<tr>
<td>3</td>
<td>Number of passes (C)</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>Tensile Strength(TS), MPa</td>
<td>328.027</td>
</tr>
<tr>
<td>5</td>
<td>Hardness (H), Hv@0.5</td>
<td>112.529</td>
</tr>
</tbody>
</table>

5.9.1  Normal Probability Plots

The normal probability plot of the residuals for responses (tensile strength and hardness) of the AA6082-T6 alloy, is shown in Figures 5.33 (a and b). From the figures it is found that the residuals fall in a straight line, which means that the errors are distributed normally (Tung-Hsu Hou et al 2007). All the above considerations indicate an excellent adequacy of the regression model.
Figure 5.33(a-b) Normal probability plots for responses of the AA6082-T6 alloy

5.9.2 Analysis of the Response Graphs and Contour Plots for the Response Tensile Strength

The effect of the load and temperature on the output response tensile strength for AA6082-T6 alloy is shown in Figure 5.34 (a-b).
(a) Contour plot of Tensile Strength for 1200 kN load and 500 °C

(b) Response plot of Load and Temperature on Tensile Strength

**Figure 5.34(a-b) Effect of Load and Temperature on Tensile Strength of AA6082-T6 alloy**

From the response and contour plots it is observed that for a load of 1000 kN and at the temperature of 350°C the average tensile strength is about 275.87 MPa. If the temperature is increased above 450°C, for the same load, the average tensile strength is about 310.47 MPa. At the same temperature level, by increasing the load from 1000kN to 1200kN, the average tensile strength predicted is 312.68 MPa.
The effect of load and number of passes on the tensile strength for the alloy AA6082-T6 is shown in Figure 5.35 (a and b).

(a) Contour plot of Tensile Strength for 1200 kN load and 3 TE passes

(b) Response plot of Load and Number of passes on Tensile Strength

Figure 5.35(a-b) Effect of Load and Number of Passes on Tensile Strength of AA6082-T6 alloy
It is observed that for a load of 1000 kN and one pass of twist extrusion the tensile strength is 268.814 MPa. Similarly, by increasing the number of twist extrusion passes from one to three, the tensile strength increases from 268.81 MPa to 279.93 MPa. At the same time, if the load is increased from 1000 kN to 1200 kN by keeping the number of passes constant, a small variation in tensile strength is observed, which is relatively very less compared to the results obtained by increasing the number of passes.

The effect of the temperature and number of passes on the tensile strength is shown in Figure 5.36 (a and b). It is found that as the temperature increases from 350 °C to 500 °C, the tensile strength increased from 268.62 MPa to 278.03 MPa for one TE pass. At the same increasing temperature levels the tensile strength was found to be increased from 268.62 MPa to 327.02 MPa after three TE passes. From these results it is evident that among the three parameters, the parameter load has less influence on the tensile strength, when compared to the other two parameters, viz, the temperature and number of passes.

(a) Contour plots of Tensile Strength for 500 °C and 3 TE passes

Figure 5.36(a-b) (Continued)
(b) Response plot of Temperature and Number of passes on Tensile Strength

Figure 5.36(a-b) Effect of Temperature and Number of Passes on Tensile Strength of the AA6082-T6 alloy

5.9.3 Analysis of the Response Graphs and Contour Plots for the Response Hardness

The effect of the load and temperature on the output response hardness, is shown in Figure 5.37 (a-b).

(a) Contour plot of Hardness for 1200 kN load and temperature of 500 °C

Figure 5.37(a-b) (Continued)
Figure 5.37(a-b) Effect of Load and Temperature on Hardness of the AA6082-T6 alloy

From the response and contour plots it is observed that for a load of 1000 kN and 350°C, the average hardness is about 87.03 Hv. If the temperature is increased to 500 °C, for the same load the average hardness is about 103.38 Hv. At the same temperature level, by increasing the load from 1000kN to 1200kN, the average hardness increases from 103.38 Hv to 106.01 Hv.

The effect of load and number of passes on hardness of AA6082-T6 alloy is shown in Figure 5.38 (a and b). From the contour and response plots it is observed that for a load of 1000 kN and one twist extrusion pass the hardness is 87.74 Hv. Similarly, by increasing the number of twist extrusion passes from one to three, the hardness increased from 87.74 Hv to 90.2 Hv. At the same time, if the load is increased from 1000kN to 1200kN by keeping the number of passes constant, the hardness increases from 90.2 Hv to 92.56 Hv.
(a) Contour plot of Hardness for 1200 kN load and 3 TE passes

(b) Response plot of Load and Number of passes on Hardness

Figure 5.38(a-b) Effect of Load and Number of Passes on Hardness of the AA6082-T6 alloy
Figure 5.39 (a and b) depicts the effect of temperature and number of passes on the response hardness. It is observed that as the temperature increases from 350°C to 500°C for one TE pass, the hardness increased from 84.25 Hv to 86.37 Hv. At the same increasing temperature levels the hardness was found to be increased from 86.37 Hv to 110.31 Hv after three TE passes. From these results obtained through the response surfaces and contour plots, it is found that among the three input parameters, the contribution of the input parameter load is less on the output response hardness, when compared to the other two input parameters, the temperature and number of passes.

(a) Contour plots of Hardness for temperature 500 °C and 3 TE passes

Figure 5.39(a-b) (Continued)
Figure 5.39(a-b) Effect of Temperature and Number of Passes on Hardness of AA6082-T6 alloy

5.9.4 Confirmation Experiment

The optimum values of the input parameters (Load, Temperature and No. of passes) and the experimental validations of the developed models are shown in Table 5.5. These fitted models were found to be significant at 95% confidence level. After selecting the optimal level of the process parameters, the last step is to predict and verify the performance of the responses using the optimal level of forming parameters. For doing this a confirmation experiment is carried out. A successful confirmation experiment is defined as one, where the average of the samples falls within the predicted range (Sooriyamoorthy et al 2010). When the average of the results from the confirmation experiments falls within the range, it proves that the significant factors as well as their levels are selected properly, and lie within the range. Three confirmation twist extrusion experiments were conducted, based on the
optimal input parameters such as load (1200 kN), temperature (500°C) and number of passes (3) for maximizing the tensile strength and hardness. The plan for the confirmation experiment, and the values of the responses obtained by the confirmation experiments, and predicted through the optimization approach, are given in Tables 5.7 and 5.8. It was observed that the average percentage of variation of the tensile strength and hardness lie within 5 percentage (0.229% and 2.07% respectively) which confirms that the developed theoretical model is significant.

Table 5.7 Results of the confirmation experiments for Tensile Strength of AA6082-T6 alloy at a Load of 1200 kN, Temperature of 500 °C and three twist extrusion passes

<table>
<thead>
<tr>
<th>S.No</th>
<th>Experimental Value</th>
<th>Predicted Value</th>
<th>Variation (%)</th>
<th>r²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>326.00</td>
<td>328.027</td>
<td>0.617</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>328.00</td>
<td>328.027</td>
<td>0.008</td>
<td></td>
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<tr>
<td>3</td>
<td>327.82</td>
<td>328.027</td>
<td>0.063</td>
<td>0.99</td>
</tr>
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</table>

Table 5.8 Results of the confirmation experiments for Hardness of AA6082-T6 alloy at a Load of 1200 kN, Temperature of 500 °C and three twist extrusion passes

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Experimental Value</th>
<th>Predicted Value</th>
<th>Variation (%)</th>
<th>r²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>110.0</td>
<td>112.529</td>
<td>2.247</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>111.6</td>
<td>112.529</td>
<td>0.83</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>109.0</td>
<td>112.529</td>
<td>3.14</td>
<td>0.99</td>
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</table>
5.10 EFFECT OF TWIST EXTRUSION ON MECHANICAL PROPERTIES OF THE AA7075-T6 ALLOY

5.10.1 Hardness of AA7075-T6 Specimens before and after Twist Extrusion

Figure 5.40 shows the variation in the hardness of the AA7075-T6 alloy, processed with increasing temperature and increasing number of passes. Specimens processed by one, two and three twist extrusion passes were studied. In order to minimize the possibilities of error, a minimum of five micro hardness readings were taken from each sample, and the results were averaged. The averaged values are presented in Table 5.9.

<table>
<thead>
<tr>
<th>S.No</th>
<th>Specimens</th>
<th>Temperature</th>
<th>No. of passes</th>
<th>Hardness [Hv 0.5]</th>
<th>Tensile Strength [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Parent Material</td>
<td>-</td>
<td>-</td>
<td>110</td>
<td>304</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>350°C</td>
<td>Pass I</td>
<td>113</td>
<td>286</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td>Pass II</td>
<td>118</td>
<td>286</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td>Pass III</td>
<td>117</td>
<td>297</td>
</tr>
<tr>
<td>5</td>
<td>Twist Extruded</td>
<td>425°C</td>
<td>Pass I</td>
<td>116</td>
<td>304</td>
</tr>
<tr>
<td>6</td>
<td>Material</td>
<td></td>
<td>Pass II</td>
<td>118</td>
<td>315</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td></td>
<td>Pass III</td>
<td>126</td>
<td>322</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>500°C</td>
<td>Pass I</td>
<td>138</td>
<td>319</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td></td>
<td>Pass II</td>
<td>140</td>
<td>326</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td></td>
<td>Pass III</td>
<td>141</td>
<td>342</td>
</tr>
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</table>

It is observed that that the hardness increases with increasing temperature and more number of passes. This is due to the fact that the imposed strain is less at the centre of the specimen, which increases the hardness of the alloy even after three TE passes than after one TE pass (Dmitry Orlov et al 2009). The same trend is noticed with the reports of TE
conducted for 99.99% Al. (Orlov et al. 2008), but different results are reported when the hardness was tested at the edge of the sample, where large strain is created. It was reported that the hardness is lower for 4 passes than for one pass when it is tested at the edge of the sample.

![Graph showing hardness vs temperature for different passes](image)

**Figure 5.40 Effect of the Number of passes on the Hardness of the AA7075-T6 alloy**

### 5.10.2 Tensile Properties of AA7075-T6 Specimens before and after Twist Extrusion

Table 5.9 lists the results of the mechanical properties of the as received and twist extruded AA7075-T6 samples, in various conditions of temperature and extrusion passes. Figure 5.41 shows the variation of the tensile strength of the alloy, processed with increasing temperature and increasing number of passes. It can be noted that the tensile strength increases with more number of passes, and on increasing the temperature from 350°C to 500°C. The reason for this behaviour is, with the increasing twist extrusion passes, the homogeneity of the deformed billet was expected to improve, because of the generally higher level of deformation and through the transfer
of shear to the adjacent material via work hardening as reported by Berta et al (2007).

Figure 5.41 Effect of the Number of passes on the Tensile Strength of the AA7075-T6 alloy

Figure 5.42 Stress-Strain curve of AA7075-T6 before and after twist extrusion
The yield strength and tensile strength of the AA7075-T6 twist extruded material, before and after extrusion, are shown in Figure 5.42. The parent metal before extrusion shows lower yield strength and tensile strength when compared to the material after one, two and three twist extrusion passes. The material processed by more number of passes yielded superior tensile properties.

5.11 MICROSTRUCTURAL ANALYSIS ON TWIST EXTRUSION OF AA7075-T6 ALLOY

The SEM micrographs shown in Figures 5.43 and Figure 5.44 (a-f) depict the microstructure of AA7075-T6 before TE, and the microstructure after one and three TE passes. It appears that grains have a similar size, irrespective of the TE passes. But when the comparison is made between the samples of one TE pass and three TE passes, there are fewer dislocations of grains. The grain boundaries are well defined with more number of passes and at higher temperatures. It is observed that the dislocation density in the grains is low and the grains contain deformation twins after one pass extrusion. These twins are found to have disappeared at higher temperatures and more extrusion passes. Moreover, it was observed that the grains starts to elongate in the direction of the twist and high angle grain boundaries are observed. Some pin hole defects tend to originate. The increase in temperature and number of passes decreases the average grain size from 38 to 20µm.

![Figure 5.43 SEM Microstructure of AA7075-T6 Parent Metal](image)
Figure 5.44 SEM microstructures of AA7075-T6 TE samples after (a) 1 pass 350°C (b) 3 passes 350°C (c) 1 pass 425°C (d) 3 passes 425°C (e) 1 pass 500°C and (f) 3 passes 500°C
5.12 SIMULATION RESULTS ON TWIST EXTRUSION OF AA7075-T6 ALLOY

The von Mises stress contours of the sample during 20 steps of the deformation of AA7075-T6 after one TE pass are shown in Figure 5.45. The plunger and the other assembly features have been removed for better clarification. Figures 5.46 (a-d) shows the enlarged view of the von Mises stress contours of four different stages during simulation, taken in order.

Figure 5.45 Von Mises Stress contours of AA7075-T6 sample during 20 steps of the deformation, arranged from right to left
Figure 5.46 (a) shows stage 2 of the deformed billet during the first twist extrusion pass, in which it was found that the maximum stress is 116 MPa. The maximum stress values for stages 7, 14 and 18 during the first twist extrusion pass were found to be 139, 156 and 202 respectively, as shown in Figure 5.46 (b-d). The reason for this behaviour is that the billet experiences more stress at the beginning of the twist extrusion process, and the magnitude of stress goes on decreasing when the billet reaches the end (Akbari Mousavi et al 2008).

![Stage-2](image1)

![Stage-7](image2)

![Stage-14](image3)

![Stage-18](image4)

Figure 5.46 Von Mises stress contours of the various steps during simulation
Figures 5.47 to 5.49 show the variations of the von Mises stress versus time for the temperatures 350°C, 425°C and 500°C respectively, for the AA7075-T6 alloy. The magnitude of stress is high at the beginning of the twist extrusion process, and then decreases when the billet reaches the end as shown in Figure 5.47. The same trend is noticed for the simulation conducted at temperatures of 450°C and 500°C, and at different passes as shown in Figures 5.48 and 5.49. This is because, the peripheral regions of the specimen are subjected to more internal stress due to the friction between the die and specimen’s exterior surface during the entry of the billet and change of plane inside the die during twist extrusion. The study shows that the amount of stress induced in the specimen is not only different from the head to end of the specimen, but also the magnitude of the stress is changed along the extrusion direction. This is agreed well with the results of the twist extrusion experiments and simulation, conducted by Latypov et al 2012.

Figure 5.47 Stress variations against time at various TE passes at constant temperature of 350°C
Figure 5.48 Stress variations against time at various TE passes at constant temperature of 425°C

Figure 5.49 Stress variations against time at various TE passes at constant temperature of 500°C

The volume of the sample remains almost the same after every twist extrusion pass, as shown in Figure 5.50. From the Figure 5.51 it is observed, that the magnitude of strain increases initially and then decreases
until it reaches the end for the first two passes. This variation in the magnitude of strain reduced on performing a higher number of passes.

Figure 5.50 Reduction of the billet volume during TE of AA7075-T6 alloy

Figure 5.51 Plastic strain against time at temperature of 500°C
5.13 OPTIMIZATION RESULTS ON TWIST EXTRUSION OF AA7075-T6 ALLOY

The optimum values of tensile strength and hardness obtained for the input parameters (Load, Temperature, and Number of passes) for the AA7075-T6 alloy are listed in Table 5.10.

Table 5.10 Optimized Twist Extrusion process parameters for the AA7075-T6 alloy

<table>
<thead>
<tr>
<th>S. No</th>
<th>Parameters</th>
<th>Optimized Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Load (A), kN</td>
<td>1200</td>
</tr>
<tr>
<td>2</td>
<td>Temperature (B), °C</td>
<td>500</td>
</tr>
<tr>
<td>3</td>
<td>Number of passes (C)</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>Tensile Strength(TS), MPa</td>
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<tr>
<td>5</td>
<td>Hardness (H), Hv@0.5</td>
<td>142.35</td>
</tr>
</tbody>
</table>

5.13.1 Normal Probability Plots

The normal probability plot of the residuals for the responses (tensile strength and hardness) of AA7075-T6 alloy, is shown in Figures 5.52 (a-b). From the figures it is found, that the residuals falling in a straight line, which means that the errors are distributed normally. This indicates an excellent adequacy of the regression model.
Figure 5.52 Normal probability plots for responses of the AA7075-T6 alloy
5.13.2 Analysis of the Response Graphs and Contour Plots for the Response Tensile Strength

The effect of the load and temperature on the output response Tensile Strength for AA7075-T6 alloy is shown in Figure 5.53 (a and b). From the response and contour plots it is observed, that for a load of 1000 kN and at temperature of 350°C the average tensile strength is about 279.39 MPa. If the temperature is increased above 450°C, for the same load the average tensile strength is about 324.211 MPa. At the same temperature level, by increasing the load from 1000kN to 1200kN, the average predicted tensile strength is 324.773 MPa.

(a) Contour plot of Tensile Strength for 1200 kN load and 500 °C

Figure 5.53(a-b) (Continued)
(b) Response plot of Load and Temperature on Tensile Strength

**Figure 5.53(a-b) Effect of Load and Temperature on Tensile Strength of AA7075-T6 alloy**

Figure 5.54 (a and b) shows the contour and surface plot on the effect of load and number of passes on the tensile strength of AA7075-T6 alloy. It is found that by increasing the number of twist extrusion passes from one to three, the tensile strength increases from 315.32 MPa to 335.57 MPa [Figure 5.45 (c-d)]. At the same time, if the load is increased from 1000 kN to 1200 kN by keeping the number of passes constant, a small variation in tensile strength is observed, which is relatively less compared to the results obtained by increasing the number of passes.
(a) Contour plot of Tensile Strength for 1200 kN load and 3 TE passes

(b) Response plot of Load and Number of passes on Tensile Strength

Figure 5.54(a-b) Effect of Load and Number of Passes on Tensile Strength of AA7075-T6 alloy

From Figure 5.55 (a-b) it is found that as the temperature increases from 350°C to 500°C for one TE pass, the tensile strength increased from
269.05 MPa to 294.55 MPa. At the same increasing temperature levels, the tensile strength was found to be increased from 294.55 MPa to 377.8 MPa after three TE passes. From the contour and response plots it is observed that even after conducting the experiments, by changing the input parameter such as load, there is little change on the output response. These results reveal that among the three parameters, the load has lesser influence on tensile strength, when compared to the other two parameters, the temperature and number of passes.

(a) Contour plot of Tensile Strength for 500 °C and 3 TE passes

Figure 5.55(a-f) (Continued)
(b) Response plot of Temperature and Number of passes on Tensile Strength

**Figure 5.55(a-f) Effect of Temperature and Number of Passes on Tensile Strength of the AA7075-T6 alloy**

5.13.3 Analysis of the Response Graphs and Contour Plots for the Response Hardness

The effect of the input process parameters load and temperature on the output response hardness, is shown in Figure 5.56 (a-b). From the response and contour plots it is observed, that for a load of 1000 kN and 350°C, the average hardness is about 112.929 Hv [Figure 5.46 (a-b)]. If the temperature is increased to 500 °C, for the same load, the average hardness is about 129.456 Hv. At the same temperature level, by increasing the load from 1000kN to 1200kN, the average hardness is 128.655 Hv.
(a) Contour plot of Hardness for 1200 kN load and 500 °C

(b) Response plot of Load and Temperature on Hardness

Figure 5.56(a-b) Effect of Load and Temperature on Hardness of AA7075-T6 alloy
The effect of Load and Number of Passes on Hardness of AA7075-T6 alloy is shown in Figure 5.57 (a and b). It is observed that, by increasing the number of twist extrusion passes from one to three, the average hardness increases from 130.374 Hv to 132.73 Hv [Figure 5.46 (c-d)]. At the same time, if the load is increased from 1000kN to 1200kN and by keeping the number of passes constant, the hardness increases from 130.374 Hv to 133.393 Hv.

(a) Contour plot of Hardness for 1200 kN load and 3 TE passes

(b) Response plot of Load and Number of passes on Hardness

Figure 5.57(a-b) Effect of Load and Number of Passes on Hardness of AA7075-T6 alloy
From Figure 5.58 (a and b) it is found, that as the temperature increases from 350°C to 500°C for one TE pass, the hardness increased from 115.80 Hv to 118.229 Hv. At the same increasing temperature levels, the hardness was found to be increased from 115.80 Hv to 142.611 Hv after three TE passes. From the results obtained through the response surfaces and contour plots, it is found that among the three input parameters, the contribution of the input parameter load is lesser on the output response hardness, when compared to the other two input parameters, the temperature and number of passes. From the above results it is found, that for higher temperature and more number of passes, the material yielded superior tensile strength and hardness properties.

(a) Contour plot of Hardness for 500 °C and 3 TE passes

Figure 5.58(a-b) (Continued)
(b) Response plot of Temperature and Number of passes on Hardness

**Figure 5.58(a-b) Effect of Temperature and Number of Passes on Hardness of the AA7075-T6 alloy**

### 5.13.4 Confirmation Experiment

The optimum values of the input parameters (Load, Temperature and No. of passes) and the experimental validations of the developed models are shown in Table 5.10. These fitted models were found to be significant at 95% confidence level. After selecting the optimal level of the process parameters, the last step is to predict and verify the performance of the responses using the optimal level of forming parameters. For doing this, a confirmation experiment is carried out. Three confirmation twist extrusion experiments were conducted based on the optimal input parameters such as load (1200kN), Temperature (500°C) and Number of passes (3), for maximizing tensile strength and hardness. The plan for the confirmation experiment and the values of responses obtained by the confirmation experiments and predicted through the optimization approach, are given in
Tables 5.11 and 5.12. It was observed that the average percentage of variation of the tensile strength and hardness lie within 5 percentage (0.38% and 1.04% respectively) which confirms that the developed theoretical model is significant.

Table 5.11 Results of the confirmation experiments for Tensile Strength of AA7075-T6 alloy at a Load of 1200 kN, Temperature of 500°C and three twist extrusion passes

<table>
<thead>
<tr>
<th>S. No</th>
<th>Experimental Value</th>
<th>Predicted Value</th>
<th>Variation (%)</th>
<th>r²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>342</td>
<td>339.587</td>
<td>0.705</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>339</td>
<td>339.587</td>
<td>0.172</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>340.5</td>
<td>339.587</td>
<td>0.268</td>
<td>0.99</td>
</tr>
</tbody>
</table>

Table 5.12 Results of the confirmation experiments for Hardness of AA7075-T6 alloy at a Load of 1200 kN, Temperature of 500°C and three twist extrusion passes

<table>
<thead>
<tr>
<th>S. No</th>
<th>Experimental Value</th>
<th>Predicted Value</th>
<th>Variation (%)</th>
<th>r²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>141</td>
<td>142.351</td>
<td>0.95</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>139.6</td>
<td>142.351</td>
<td>1.932</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>142</td>
<td>142.351</td>
<td>0.246</td>
<td>0.96</td>
</tr>
</tbody>
</table>

5.14 EVALUATION OF THE CORROSION TEST RESULTS

5.14.1 Salt spray Test Results for AA6061-T6, AA6082-T6 and AA7075-T6 Alloys

The samples of AA6061-T6, AA6082-T6 and AA7075-T6, before and after twist extrusion, were subjected to salt spray tests. The samples were placed in the salt spray apparatus which contains 5% neutral sodium chloride
solution for 120 hours. The results indicated that there is a sign of corrosion in the form of white scales, on the specimens AA6061-T6, AA6082-T6 and AA7075-T6 before twist extrusion. It was also found that there is very little sign of corrosion for the Twist Extruded samples of AA6061-T6, AA6082-T6 and AA7075-T6 alloys. To find out the amount of corrosion resistance of the above mentioned alloys, the samples were subjected to electrochemical tests.

5.14.2 Tafel Polarization Test Results for AA6061-T6, AA6082-T6 and AA7075-T6 Alloys

Tafel polarization tests were performed to find the corrosion resistance of the material, before and after extrusion. $I_{\text{cor}}$ is the corrosion current density derived by extrapolating the anodic and cathodic tafel lines at $E_{\text{cor}}$, in the absence of an inhibitor. The corrosion potential of the $E_{\text{cor}}$ and $i_{\text{cor}}$ values obtained, are shown in Table 5.13.

Table 5.13 Corrosion potential and current density of twist extruded AA6061-T6, AA6082-T6 and AA7075-T6 alloy in 3.5% NaCl

<table>
<thead>
<tr>
<th>S.No</th>
<th>Material</th>
<th>E (mV)</th>
<th>$I_{\text{cor}}$ (µA/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AA 6082-T6</td>
<td>-800.04</td>
<td>0.76</td>
</tr>
<tr>
<td>2</td>
<td>AA 7075-T6</td>
<td>-768.48</td>
<td>0.80</td>
</tr>
<tr>
<td>3</td>
<td>AA 6061-T6</td>
<td>-720.67</td>
<td>0.88</td>
</tr>
</tbody>
</table>

Figure 5.59 shows the effect of TE on corrosion potential and exchange current density of the Twist Extruded materials of AA 6061-T6, AA6082-T6 and AA7075-T6. It was found that the potential of AA6061-T6 (−720.67 mV) is higher compared to AA7075-T6 (−768.48). The potential of AA6082-T6 (−800.04) is less compared to the other two alloys. $I_{\text{cor}}$ gives the direct measure of the corrosion rate. The $I_{\text{cor}}$ value of the TE of AA 6061-T6 was found to be 0.88µA/cm² and it is 0.80µA/cm² and 0.76µA/cm² for the TE
of AA 7075-T6 and AA6082-T6 alloy respectively. From this it is found, that the corrosion resistance of the twist extruded AA6061-T6 alloy is superior to those of AA 7075-T6 and AA6082-T6 alloys.

**Figure 5.59** Effect of TE on corrosion potential and exchange current density of the AA 6061-T6, AA 7075-T6 and AA 6082-T6 alloys

### 5.14.3 Micro-structural Studies on Corrosion

The SEM microstructures of the twist extruded samples of AA6061-T6, AA6082-T6 and AA7075-T6 before and after corrosion, are shown in Figure 5.60 (a-f). The samples were etched using Keller’s reagent, to reveal the microstructures. From the microstructural observations it is found, that the material having secondary precipitates is attacked less (compared to precipitate-free zones) and seen as black spots, as shown in Figures 5.60 (a), 5.60 (c) and 5.60 (e). The reason for this behaviour is that corrosion usually occurs in the Aluminum matrix near Cu or Fe containing inter metallic particles, which are cathodic to the FSW Aluminum alloy
matrix, as mentioned by Brunner et al (2012). The presence of white boundary precipitates as seen in Figures 5.60 (b), 5.60 (d) and 5.60 (f) is the reason for the less chemical attacks in the twist extruded samples of AA6061-T6, AA6082-T6 and AA7075-T6.

Figure 5.60  Corrosion surface morphologies of the specimens before and after corrosion (a - b) AA6061-T6, (c - d) AA6082-T6 and (e-f) AA7075-T6
5.15 SUMMARY

This chapter details the analysis of the Twist Extrusion process of AA6061-T6, AA6082-T6 and AA7075-T6 Aluminum alloys. The effects of the twist extrusion parameters, such as load, temperature and number of passes with respect to different responses, such as tensile strength and hardness are discussed. The microstructural behaviour of the materials, before and after twist extrusion, are discussed with the help of optical and SEM micrographs. The overall results that have been obtained through the experiments, optimization methods for finding the optimal values and the finite element simulation results and corrosion studies, provide adequate information regarding the twist extrusion of Aluminum alloys.