A study on the combined effect of aging and severe plastic deformation on the mechanical properties of AA6061 alloy

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Abstract. Severe plastic deformation (SPD) process is used to attain ultra fine grains in the material. Twist channel angular pressing (TCAP) is an effective SPD technique that is used to achieve more grain refinement in less number of passes. This work explores the combined effect of aging and TCAP on the mechanical properties of aluminium-6061 alloy. Finite element analysis (FEA) was performed to predict the load for two coefficients of friction (µ=0.2&0.5). Based on the strain to load ratio, µ=0.2 was used to perform the experiments. The samples were aged at 150ºC for 9 hours and extruded by twist channel angular pressing process. The hardness and tensile strength of the aged and un-aged samples before and after twist channel angular pressing was measured. Compared to the un-aged sample the tensile strength and hardness is increased by 34% and 23% respectively for the aged specimen after the twist channel angular pressing process.

1. Introduction

Severe plastic deformation (SPD) method is intended to refine the grains of the material by inducing the strain, which brings about the improvement of the mechanical properties [1-2]. Among the various SPD methods for bulk material, Equal channel angular pressing (ECAP) process is a widely used, as the strain path can be varied [3]. But the major drawback of the ECAP process is that a limited amount of strain is induced in single pass [4]. Another effective method of processing the bulk sample is twist extrusion (TE), in which the shear strain induced in a single passes is high, but the strain homogeneity in poor [5]. Kocich et al [6] developed a new SPD method known as Twist channel angular pressing (TCAP). This method is a combination of ECAP and TE, by which the strain induced and the strain homogeneity was improved. Aluminium-6061 alloy is used as primary material in aviation and automobile industries due to its high strength and low density. Deschamps et al [7] studied the dynamic precipitation of Al-alloy after straining the material by SPD process and he also studied the kinetics behind the precipitation of Al-7075 alloy during SPD process [8]. Vaseghi et al [9] and Roven et al [10] have concluded that by combining aging and ECAP process, grain refinement attained in the alloy is high. Kuncicka et al [11] studied the properties of aged aluminum alloy after TCAP process and stated that precipitation achieved after the TCAP has improved. Shaeri et al [12] has analyzed the
effect of pre-ECAP and post-ECAP aging process on Al-7075 alloy. From the results, the authors stated that pre-ECAP aged sample exhibit superior mechanical properties. Chandiran Sakthivel et al [13] performed experiments to study the effects of prior annealing on the mechanical properties of a Twist-Extruded AA 7075 Aluminum Alloy. It was concluded that the two major factors that influence the material tensile strength and micro-hardness are the prior-annealing temperature and the increased number of TE passes. Iqbal et al [14] optimized the TCAP die parameters and stated that channel of 110º and twist angle of 45º yields better load to strain ratio.

From the past research studies, it was observed that SPD of aged aluminum alloy results in better grain refinement and improved mechanical properties. Most of authors have worked on the ECAP of aged alloy. So, the aim of this work is to extrude the aged aluminium alloy by TCAP and to study its mechanical properties. In addition, FEA is performed in the TCAP process to identify the coefficient of friction that will yield better load to strain ratio.

2. Finite element analysis
The finite element simulation was performed using DEFORM3Dv11.0. The property of the AA6061 alloy is defined as elasto-plastic. Lagrangian incremental model, SPARSE solver and Newton-Raphson iteration method was used for the simulation. The tetrahedral mesh type and 10,000 elements were used for the simulation [6]. The simulation was performed at 20ºC, considering the room temperature. Figure 1 shows the simulation results of TCAP process performed with friction value of 0.2 and 0.5 respectively. The simulation performed with 0.5 friction factor give the maximum effective stress of 416MPa.

![Figure 1. Stress distribution (a) µ=0.2; (b) µ=0.5.](image)

The strain/load ratio was used as criterion to the select the friction factor for performing the experiments. The numerical values obtained through simulation results were shown in table.1 From the tabulated result it is observed that the coefficient of friction of 0.2 have higher strain/load ratio of 0.033. The strain induced on the material with friction of 0.5 is 2.1, which is higher than the friction of 0.2. But the load required to induce the deformation in the material with friction of 0.5 was the highest with 65 tones. So friction factor 0.2 was selected, as the required strain was induced at lesser load which reduces the cost of processing by hydraulic press and also it reduces the risk of damage to the die. From the Fig 1 it is evident that stress distribution is uniform for the friction of 0.2. So the friction of 0.2 is selected as the optimal case and the experiment was conducted with the co-efficient of friction of 0.2.
Table 1. Predicted strain to load ratio.

| S.No | Co-Efficient Of Friction | Load (Tons) | Effective Stress (Mpa) | Effective Strain | Strain/Load Ratio |
|------|--------------------------|-------------|------------------------|------------------|-------------------|
| 1    | 0.2                      | 57          | 370                    | 1.9              | 0.033             |
| 2    | 0.5                      | 65          | 416                    | 2.1              | 0.032             |

3. Experimental setup

The aluminium AA 6061 alloy used in this study has the following composition in wt% of 1.2 Mg, 0.5 Fe, 0.7 Cu, 0.15 Mn and balance Al. The sample size of 27x17 mm was cut out for the TCAP processing. The aging on the AA 6061 alloy is carried out by heated the samples to 500°C and soaked it for 5 hours in the muffle furnace. Then it is quenched in the water medium. In the next day the same samples were heated to150°C for 9 hours and then it is water quenched. The experiment was performed in the TCAP die with the channel and slope of 110° and 45° respectively [14]. Based on the FEA results the experiment is conducted with the friction co-efficient of 0.2. MoS2 spray was used as the lubricant which gives the co-efficient of friction between 0.2. To understand the combined effect of aging and SPD process, the aged and un-aged AA6061 alloy was extruded by the TCAP process. Both the sample was extruded at room temperature using a 100 tons hydraulic press (Henrison make, US). Figure 2 shows the split type TCAP die and plunger used for the experimentation [14]. The two halves of the die were aligned with each other using a Class 12.9 alloy steel bolt and nuts. In addition, four steel clamping were used to secure the die in its position during extrusion. The experimentation was carried out with the ram speed of 2mm/sec.The TCAP die is fabricated with H13 tool steel and oil quenching was performed to improve its hardness. The two half of the die are again clamped with the plates with the lead screw to increase the clamping force. The plunger used in this work has a total length of 130mm with the stem length of 80mm. This plunger design helps to transfer the load smoothly to the samples during extrusion process.

Figure 2. TCAP die with plunger.

ASTM A370 standard was used to prepare the tensile test specimen. The tensile strength was measured using GR-3 micro-tensometer (Kyowa instruments Pvt. Ltd, India). Akash VKM Vickers hardness tester was used to determine the hardness of the samples. An indentation load of 5 kg and a dwell time of 10 sec were applied during the hardness testing. Figure 3 shows the aged and un-aged extruded AA6061 aluminium alloy. The actual load observed to extrude the aged and un-aged sample
were 62 and 68 tons respectively. The difference between actual and predicted load might be due to variation in actual co-efficient of friction and material properties.

![Figure 3](image1.jpg)

**Figure 3.** Samples after extrusion (a) Un-aged sample; (b) aged sample.

4. **Results and discussion**

The tensile strength of the processed samples are listed in Table 2. The tensile strength of the initial AA6061 aluminium alloy on average is 213.9 MPa. After the aging process the tensile strength is increased by 10.1%. The aging process results in the formation of precipitate in the alloy. These precipitates will offer hindrance to the movement of the dislocation [15].

**Table 2.** Tensile test results.

| Nature of Specimen     | Specimen 1 (MPa) | Specimen 2(MPa) | Increase in % |
|------------------------|------------------|-----------------|---------------|
| Before Aging           | 213.2            | 214.6           | -             |
| After Aging            | 234.4            | 233.5           | 10.1          |
| After Extrusion(Un-Aged)| 251.4            | 250.6           | 18.2          |
| After Extrusion(Aged)  | 287.3            | 287.1           | 34            |

Figure 4 shows the variation in the tensile strength of the samples. It is evident that after the TCAP the tensile strength of sample was increased. The TCAP of the alloy will induce the strain on the material and it result in the grain refinement. The tensile test specimens after extrusion is shown in figure 5.

![Figure 4](image2.jpg)

**Figure 4.** Variation in tensile strength of samples.
According to Hall-Petch equation, strength is inversely proportional to the grain size, hence a significant increase in tensile strength was observed [16]. After the extrusion of un-aged and aged samples an increase in the strength of 18.2% and 34% was observed respectively. This is attributing to the fact that TCAP of the aged sample distribute the precipitate and also reduces the GP zone in the alloy [12].

**Table 3. Hardness test results.**

| Nature of Specimens          | Specimen 1 | Specimen 2 | Increase in % |
|------------------------------|------------|------------|---------------|
| Before Aging                 | 31.7       | 32.4       | -             |
| After Aging                  | 37.4       | 36.8       | 11.2          |
| After Extrusion(Un-Aged)     | 42.1       | 42.7       | 18            |
| After Extrusion(Aged)        | 53.4       | 52.8       | 23            |

The hardness test results of the samples was tabulated in table 3. It is observed that the hardness value is maximum for the aged extruded sample. After the aging the hardness of the aluminium is increased by 11.2%. The hardness of both aged and un-aged sample after the TCAP process is increased by 18% and 23% respectively.
Figure 6 shows the variation in hardness of the processed samples. It is clear that TCAP process increase the hardness of the alloy. The reason for this behavior is attributed to the fact that the TCAP result in formation of more number of high angle grain boundaries (HAGB) which leads to the formation of cell blocks. While applying the load, this HAGB provide high resistance to the slipping of the cell [17].

4.1 Micro-structural analysis:
Figure 7 shows the OLM image of TCAPed aged and un-aged AA6061 aluminium alloy. From the microstructure it is evident that fine grain refinement is achieved in the aged extruded sample than the un-aged extruded sample. This is clearly reflected in the mechanical properties, as the extruded aged specimen give the highest tensile strength and hardness. The fine grain refinement increases the cell block in the metal, due to this the mechanical properties is increased in the extruded samples [18,19]. During the TCAP of the aged sample, the precipitate formed aid the dislocation interaction in the material. This results in the formation of more sub-cell within the grain boundary and this lead to fine grain refinement than the un-aged sample [20,21].

5. Conclusions
The following conclusion was drawn from this study.

- The Effective stress and Effective strain value is favor for the friction co-efficient $\mu=0.5$, but the strain/load ratio is higher for the friction co-efficient $\mu=0.2$, as the load required to extrude the alloy is relatively less.
- The tensile strength is increased after the aging process and when extruded with aging sample the tensile strength is maximum i.e. 287.3 MPa.
- Compared with the unaged sample the tensile strength is increased to 34% in aged specimen after the extrusion processes.
- The hardness of the aged sample is increased by 23% after the TCAP process; relatively the hardness value favors the aged specimen.
- Aging of the sample before TCAP, results in highest percentage increase of tensile strength and hardness of the AA6061 aluminium alloy due to even distribution of precipitate and lesser GP zones.
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