Experimental and numerical analysis of orthogonal cutting of high strength aluminium alloy Al7075-T6

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Abstract. High strength Aluminum alloys are the key material class for the structural parts of aircraft, aerospace, military, and transportation industries because of their well-known performance, high strength, and light weight. In this present study, the Al7075-T6 tube was machined under orthogonal tool geometry conditions at different parametric combinations of cutting speeds and feed rates to investigate the chip morphology. Orthogonal cutting tests were performed with the high speed steel tool having a back rake angle of 8° and clearance angle of 7°, with varying cutting speeds and feed rates. The metallographic analysis was carried out on the chips obtained from experiments to find out the chip thickness and the type of serrations. Two dimensional finite element analysis was simulated by using ABAQUS/Explicit software. 2D orthogonal plane strain model was created using the Johnson-Cook elastoviscoplastic material model and chip separation criteria were given by the Johnson-Cook damage model. Orthogonal cutting simulations were carried out with the same machining conditions. The orthogonal cutting operation was predicted with numerical simulation and the predicted chip thicknesses were close to experimental chip thickness.

Keywords: Al7075-T6; orthogonal cutting; finite element analysis; Johnson-Cook damage model; numerical simulation.

1. Introduction

Al alloys have been used for the structural bodies in construction for many years due to their good-established design systems, ability to easy manufacture, and consistent inspection methods. Aluminum metals are relatively light weight materials and cheaper compared to other structural materials[1]. Some of these Al alloys may be heat treated to load comparatively high amount of stresses. Due to its exceptional properties such as excellent surface finish characteristics, excellent resistance to corrosion, easy workability, and good weldability, the Al alloys are extensively used in the aircraft and automotive industry[2]. There have been significant latest advances in Al alloys in all sectors. The aluminum 7000
series show better strength while compared to other series of Al materials and are particularly used in the manufacture of stringers, wing skins, and frames in the aircraft industry. Al 7075 alloys can be age-hardened (artificially aged tempers T6 and T7) to attain high strength and these series of aluminum alloys were highly susceptible to stress corrosion cracking in aqueous and air mediums[3]. Although various researches have carried the work in the region of metal cutting and it is still sometimes revealed as one of the least known manufacturing processes due to its complications. The nature of chips in the machining process depends on the type of material, tool geometry, cutting parameters (speed, feed rate, and depth of cut), and type of lubrication (dry, wet, and minimum quantity lubrication). Chip morphology and its formation, usually known as the effect of shear distortion in the machining zone. Different chip sizes (discontinuous or continuous) and shapes influence many characteristics such as cutting forces, temperature, and chatter constancy which affect surface finish, tool life, and efficiency of the metal cutting process. With the advent of computer technology and its widespread use, obtaining numerical solutions that are similar to approximation has become a more viable option. On the one side, this allows one to retain the problem's complexity while maintaining the preferred precision on the other. FEM is a standard numerical tool for analyzing the machining process that has evolved in recent years. It delivers close displacement and velocity field outcomes based on the assumptions made while designing the model for the orthogonal machining process[4]. Daoud et al.[5] investigated the thermomechanical behavior of the material by the JC model in orthogonal cutting of two Al alloy Al2024-T3, Al6061-T6 using FEM. The chip morphology and the experimental flow stress were matched with the FEM simulation. Paulo et al.[6] analyzed the thermal and mechanical behavior in orthogonal cutting of Aluminum 7075 with PCD and cemented carbide tools, using alagrangian FEA based machining method and projected machining forces, heat distribution, plastic strain, vonmises stresses, and was concluded that the polycrystalline diamond tool has got a superior performance during the analysis. Filice et al. [7] investigated the orthogonal cutting experiments on an AISI 1045 steel tube workpiece with the axial feeding using the uncoated carbide (0° rake angle and 4° relief angle) in a dry condition with the parameters as 100 m/min machining speed and a feed rate of 0.1 mm/rev, and the experimental results (temperature and cutting forces) were compared with the numerical results. Johnet al.[8] analyzed two FEM model formulations as lagrangian approach and eulerian approach during the orthogonal cutting of aluminum 2024-T361 and compared the stresses, strain fields, chip morphology, and cutting forces with all the cutting conditions and obtained a good agreement with lower cutting speeds for both dry conditions and wet conditions. Kara et al. [9] investigated the study of machining forces and temperature during orthogonal cutting of experimental and numerical analysis using Deform-2D on AISI 316L steel with coated and uncoated carbide inserts, and predicted the numerical machining temperatures by means of numerical forces using an artificial neural network model. Shaomin et al.[10] presented the mathematical model comprises of strain mechanism, cutting forces and kinematic response during machining of aluminium alloy to examine the burr formation. Parida et al.[11] validated experimental and numerical results of machining forces, chip analysis (flow angle, morphology), surface quality, and cutting tool wear during turning of Ti alloy with the help of DEFORM software. Asit[12] studied the influence of parameters (speeds and feed rates) during machining of Ti alloy (Ti-6Al-4V) to validate both the experimental and numerical results on the characteristics like temperature, deformation, stresses, and cutting forces. Mabroukiet al.[13] investigated the numerical analysis and experimental procedure on chip damage and fracture energy during the orthogonal machining of aluminium A2024-T351 and the authors used the numerical approach ABAQUS software to explain the fragmentation of the chip and the chip morphology. Kai et al. [14] studied the tool variation on the size effect in the orthogonal cutting process and resulted that the strain effect was dominant at all machining conditions. In this research work, a coupled thermo-mechanical finite element model was established in ABAQUS/Explicit, to assess the effect of different rotating speed of work piece (270, 443, and 650 rpm and at different feed rate 0.08, 0.12, 0.2, 0.28, and 0.32 mm per revolution) on chip morphology (chip thickness and serrations) of Al 7075-T6. As the machining was a short period process with substantial non-linear plastic strain, therefore explicit scheme was chosen in the present investigation. A 2-D cutting
experiment was carried out on the Al7075-T6 tube on the lathe machine to validate the numerical simulation data. The objective of this study was to find out the chip morphology in the Aluminum alloy (7075-T6) workpiece at different parametric conditions like machining speed and feed rate by means of experimental and numerical methods.

2. Experimental details
The orthogonal machining experiments were performed on the Aluminum alloy 7075-T6 tube with the dimensions of 34.11 mm outside diameter of the tube and 27.18 mm inner diameter of the tube. The chemical composition of the Al 7075-T6 alloy is shown in Table 1. HSS tool used in the cutting experiment was designed with 8° back rake angle and 7° clearance angle. Tube face turning was performed with the help of a conventional lathe machine and high speed steel tool. The Al alloy tube was locked on the machine tool (lathe) using the 4 jaw chuck and the HSS tool was tightened on the tool holder of the lathe machine. The orthogonal cutting experimental setup is shown in Figure 1.

Table 1. Chemical composition (wt.%) of Al 7075-T6 alloy.

| Element | Si     | Fe     | Cu     | Mn     | Mg     | Cr     | Zn     | Ti     | Al     |
|---------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Al 7075-T6 alloy (wt.%) | 0.0526 | 0.1053 | 1.3518 | 0.0189 | 2.318  | 0.2243 | 5.3536 | 0.015  | Balance |

Figure 1. Photograph showing (a) Al 7075-T6 alloy, (b) HSS tool, (c) front view of the experimental set up, and (d) top view of experimental set up of orthogonal cutting.

In the present work, speed in rpm, and feed rate in mm/rev are the parameters selected for the tube face turning operations. Machining experiments were performed at three different speeds (270, 443, and 650 rpm), and different feed rates (0.08, 0.12, 0.2, 0.28, and 0.32 mm/rev) as presented in Table 2. The tool feed rate was given in axial direction to the workpiece. Dry turning i.e. without lubrication orthogonal cutting was performed on the aluminum workpiece. Seven different cutting conditions were selected by varying cutting speeds and feed rates as shown in Table 2. After every machining condition, chips were collected from the machining zone for the study of chip morphology.
Table 2. Cutting parameter of orthogonal cutting experiment.

| Experiments | Cutting speed (rpm) | Feed rate (mm/rev) |
|-------------|---------------------|---------------------|
| 1           | 270                 | 0.08                |
| 2           | 270                 | 0.12                |
| 3           | 270                 | 0.28                |
| 4           | 443                 | 0.08                |
| 5           | 443                 | 0.12                |
| 6           | 443                 | 0.32                |
| 7           | 650                 | 0.2                 |

Figure 2. Chip mould images at different machining conditions (a) 273 rpm and 0.08 mm/rev feedrate, (b) 273 rpm and 0.12 mm/rev, (c) 273 rpm and 0.28 mm/rev, (d) 443 rpm and 0.08 mm/rev, (e) 443 rpm and 0.12 mm/rev, (f) 443 rpm and 0.32 mm/rev, and (g) 650 rpm and 0.2 mm/rev.

For the metallographic analysis of the chip, the mould preparation has been done by using the acrylic plus powder along with acrylic plus hardener solution. On the top of the plane glass, the chip samples were placed inside the circular shape of the empty mould and a small amount of grease is applied on the glass surface as well as inside the wall mould surface area in order to have easy removal of the mould after solidification. The acrylic powder was poured inside the mould above the sufficient height of the chip. After this process, the acrylic hardener solution was poured into the mould and in order to harden the setup was kept in the air for one hour. Finally, after the hardening process, the mould cases were removed and polished using grit papers of different sizes 300, 600, 1000, and 1200. The moulds are cloth polished and
examined in a microscope for further analysis to study the chip thickness and serrations. The chip moulds were as shown in figure 2.

3. Numerical simulation

In recent times, the finite element method (FEM) became the essential tool for the investigation of the machining process. In the recent advancement of FEM method a non-linear geometric boundaries, which includes free surfaces and chip-tool Interactions can be modeled easily. Therefore FEM based numerical analysis offers thorough qualitative and quantitative details into the chip formation process, which is very much essential for a detailed awareness of the effect of various process parameters. The computational models and simulation are commonly employed out to decrease the experimentation work.

| Table 3. Al 7075T6 alloy properties and HSS tool materials. |
|-------------------|-------------------|
| **Material Property** | **Values** | **Tool properties** | **Values** |
| Density (kg/m³) | 2800 | Density (kg/m³) | 7800 |
| Modulus of elasticity (GPa) | 71.7 | Conductivity (w/mk) | 21 |
| Poisson’s Ratio | 0.33 | Young modulus (GPa) | 207 |
| Specific heat (J/kg°C) | 960 | UTS (MPa) | 572 |
| Thermal conductivity (W/m°C) | 130 |
| $T_{\text{melt}}$ (°C) | 635 |
| $T_{\text{transition}}$ (°C) | 10 |
| Inelastic heat fraction | 0.9 |

In this present work, the FEM model was established in ABAQUS to model the chip formulation at the orthogonal cutting of Al 7075-T6 using HSS tool to find the effects of various parametric combinations of machining speeds and feed rates on the chips.

Metal cutting is a highly complex method in which large geometric deviations occur. The Abaqus program was preferred since it treats temperatures and deformations as nodal parameters in combined temperature-displacement measurements, leading to higher mesh aspect ratio by appropriate meshing. The finite element model was established in ABAQUS/Explicit software with Al7075-T6 as workpiece and high speed steel tool. Al7075-T6 and HSS tool dimensions, properties, and mesh were created in the modules. The work piece is fixed in x and y direction and a prescribed displacement is given to tool in negative of x directions i.e. the length of cut. To specify speed of tool predefined field is used where speed is given in m/sec. Figure 3(a) represents the workpiece in a 2D cutting model with loading conditions. The meshed aluminium work part is shown in figure 3(b). Al 7075-T6 workpiece properties and high speed steel tool properties are shown in Table 3. After the completion of the model, ABAQUS/CAE creates an input/initial data for the analysis part, which produces the required output in post-processing. Lagrangian FEM formulation method was used in this research work [15].
Figure 3. (a) 2D cutting model with loading conditions and (b) Meshed work piece

Johnson-Cook material model is an appropriate for high strain-rate variation over immense range, which is used for calculating large plastic deformation. This model defines the equivalent stress of the machined surface in view of strain, strain-rate, and temperature distribution and the flow stress[5] is given by the equation (1).

\[
\bar{\sigma} = \left( A + B \bar{\varepsilon}^n \right) \left[ 1 + C \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right] \left[ 1 - \left( \frac{T - T_{\text{room}}}{T_{\text{melt}} - T_{\text{room}}} \right)^m \right]
\]  

(1)

Where, \(\bar{\sigma}\) = equivalent stress, \(\bar{\varepsilon}\) = equivalent plastic strain, \(n\) = work-hardening exponent, \(\dot{\varepsilon}\) = plastic strain rate, \(\dot{\varepsilon}_0\) = reference strain rate, \(A\) = yield stress, \(B\) = strain hardening constant, \(C\) = strain rate sensitivity, \(m\) = thermal softening coefficient, \(T_{\text{room}}\) = ambient temperature, and \(T_{\text{melt}}\) = molten temperature.

Table 4 represents the values of various constants used in the existing simulations[16]. JC damage model is also used to define chip deformation founded by the value of equivalent plastic strain at element integration points. Damage and failure in the JC model are represented by a cumulative damage rule, which is given by equation (2).

\[
D = \sum \frac{\Delta \bar{\varepsilon}}{\bar{\varepsilon}_f}
\]

(2)

Where, \(\Delta \bar{\varepsilon}\) represents that the increase in equivalent plastic strain

\(\bar{\varepsilon}_f\) = equivalent strain corresponding to failure.

\(\bar{\varepsilon}_f\) is given by the following equation (3)

\[
\bar{\varepsilon}_f = \left[ D_1 + D_2 \exp \left( D_3 \frac{P}{\overline{\sigma}} \right) \right] \left[ 1 + D_4 \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right) \right] \left[ 1 + D_5 \left( \frac{T - T_{\text{room}}}{T_{\text{melt}} - T_{\text{room}}} \right) \right]
\]

(3)

In the above equation, the 1st term denotes the pressure-dependent, the 2nd term denotes the strain-rate influence and the 3rd term denotes the heat effect. The \(D_1\) to \(D_5\) values of damage quantities were considered
based on the literature as given in Table 5[17]. One of the most complex phenomena in the metal cutting process is the friction around the cutting tool surface and chip. In this work Coulomb’s friction concept is used to define surface to surface contact. The penalty method was used to give friction of 0.5 [13].

**Table 4.** Johnson cook model for Al7075-T6.

| A (MPa) | B (MPa) | n   | C    | M    |
|---------|---------|-----|------|------|
| 546     | 678     | 0.71| 0.024| 1.56 |

**Table 5.** Johnson cook damage model of Al7075-T6.

| D_1     | D_2    | D_3    | D_4    | D_5    |
|---------|--------|--------|--------|--------|
| -0.068  | 0.451  | -0.952 | 0.036  | 0.697  |

4. Results and discussion

4.1 Numerical analysis

Numerical analysis of the orthogonal cutting process of Al7075-T6 at different cutting conditions was carried out using ABAQUS and is shown in figure 4. From the results, it was observed that the highest von-mises stress occurs in the shear plane along the interface between chip and tool. When the stress value in the shear plane is more than the yield strength of the aluminum Al7075-T6, deformation of the chip occurs at the tool-chip interface. It was also observed that the von-mises stress values in the deformed chips increases with a rise in the feed rate. During machining of the tube at the cutting speed of 270 rpm, it was observed that the value of the maximum von-mises stresses increases when the feed rate rises from 0.08 to 0.28 mm/rev and it is greater than the ultimate tensile strength of the material. When the feed rate rises from 0.08 to 0.32 mm/rev with the 443 rpm cutting speed machining conditions, the value of the maximum von-mises stresses has been increased.

4.2 Metallographic analysis of chip

Experimental chip thickness was investigated using microscopic images of chip thickness at magnification factor 5X at all machining conditions. From the experimentation outcomes of chip morphology, it was observed that the serrated chips were generated. At a lower feedrate, these sawtooth appearance were low in the chip, but with the increment of feed rate, saw tooth appearance in the chip was also increased. This was due to the high machining forces and alternating large shear strain followed by low shear strain. The thickness of the chip was found and compared between numerical chip thickness with experimental chip thickness shown in above Figure 5 and Table 6 presents the chip thickness comparison. It was seen that 2-dimensional plain strain orthogonal cutting operation was predicted with numerical simulation and the numerically predicted chip thickness was close to the experimental chip thickness. From the experimental analysis, the lowest chip thickness was found to be 0.1662 mm at 270 rpm cutting speed and 0.08 mm/rev feed rate. As the feed rate increases the chip thickness increases from 0.1662 mm to 0.5 mm at 270 rpm cutting speed and 0.203 mm to 0.625 mm at 443 rpm.
Figure 4. Photographs showing von-mises stresses at conditions (a) 273 rpm and 0.08 mm/rev feedrate, (b) 273 rpm and 0.12 mm/rev, (c) 273 rpm and 0.28 mm/rev, (d) 443 rpm and 0.08 mm/rev, (e) 443 rpm and 0.12 mm/rev, (f) 443 rpm and 0.32 mm/rev, and (g) 650 rpm and 0.2 mm/rev.

The chip thickness was also observed to be increased with the rise of machining speed from 270 rpm to 650 rpm. The numerical analysis also resulted in a similar effect that the simulated chip thickness increases from 0.128 mm to 0.448 mm as the feed rate increases from 0.08 mm/rev to 0.28 mm/rev at 270 rpm cutting speed. And the simulated chip thickness was found to be increased from 0.134 mm to 0.4992 mm with the increase of feed rate from 0.08 mm/rev to 0.32 mm/rev at 443 rpm cutting speed. From the numerical simulation analysis, the chip thickness grows from 0.128 mm to 0.2746 mm when the cutting speed raises from 270 rpm to 650 rpm. At 0.08 mm/rev feed rate, the chip thickness was found to increase from 0.1662 to 0.203 mm, as the speed rises from 270 to 473 rpm and a similar trend was observed with 0.12 mm/rev feed rate, as the speed rises from 270 to 473 rpm, the chip thickness changes from 0.301 to 0.3602 mm.
Figure 5. Comparison of experimental and numerical results of chip morphology at different machining conditions.

Table 6. Experimental and numerical chip thickness

| SNo. | Cutting speed (rpm) | Feed rate (mm/rev) | Experimental chip thickness (mm) | Simulated chip thickness (mm) | % error Approx |
|------|---------------------|--------------------|----------------------------------|-----------------------------|----------------|
| 1    | 270                 | 0.08               | 0.1662                           | 0.128                       | 22.98          |
| 2    | 270                 | 0.12               | 0.301                            | 0.1903                      | 36.77          |
| 3    | 270                 | 0.28               | 0.5                              | 0.448                       | 10.4           |
5. Conclusions
In this study, the orthogonal machining of Al7075-T6 using high speed steel tool has been carried out at different parametric combinations using cutting speed and feed rate. FEM was used to model the predicted chip morphology using a Johnson-Cook material and Johnson-Cook damage model under a certain range of parameters in ABAQUS.

- FEM using ABAQUS provided satisfactory results compared with analytical results in terms of the main cutting speed and feed rate. Hence, the FE model and material model can be used to forecast the chip morphology analysis.
- The serrations on the free surface of the chips have been observed using the metallographic studies with all machining conditions. The saw-tooth appearance of the chip increases with the increase of feed rate. And also the serrations on the chip rises with the rise of cutting speed.
- From the experimental analysis and numerical analysis of chip morphology, it was found that the chip thickness rises with the increase of speed and feed rate.
- Finally, the chip morphology in the numerical analysis showed closeness to the experimental analysis.

References
[1] Miller W, Zhuang L, Bottema J, Wittebrood A J, De Smet P, Haszler A and Vieregge A 2000 Mater. Sci. Eng., A280 37-49
[2] Dursun T and Soutis C 2014 Mater. Des.56 862-71
[3] Li J-F, Peng Z-w, Li C-X, Jia Z-Q, Chen W-j and Zheng Z-Q 2008 Trans. Nonferrous Met. Soc. China18 755-62
[4] Bagci E 2011 Int. J. Phys. Sci. 6 1267-82
[5] Daoud M, Jomaa W, Chatelain J and Bouzid A 2015 Int. J. Adv. Manuf. Technol.77 2019-33
[6] Davim J P, Reis P, Maranhao C, Jackson M, Cabral G and Gracio J 2010 Int. J. Mater. Prod. Technol.37 46-59
[7] Filice L, Micari F, Rizzuti S and Umbrello D 2007 Int. J. Mach. Tools Manuf.47 709-14
[8] Carroll III J T and Strenkowski J S 1988 Int. J. Mech. Sci.30 899-920
[9] Kara F, Aşlantaş K and Cicek A 2016 Appl. Soft Comput.38 64-74
[10] Li S, Zhang D, Liu C and Tang H 2020 J. Manuf. Processes56 350-61
[11] Parida A, Rao P and Ghosh S 2020 J. Braz. Soc. Mech. Sci. Eng.42 1-14
[12] Parida A K 2018 Int. J. Lightweight Mater. Manuf.6 197-205
[13] Mabrouki T, Girardin F, Asad M and Rigal J-F 2008 Int. J. Mach. Tools Manuf.48 1187-97
[14] Liu K and Melkote S N 2007 Int. J. Mech. Sci.49 650-60
[15] Ceretti E, Fallböhmer P, Wu W and Altan T 1996 J. Mater. Process. Technol.59 169-80
[16] Brün I 2016 J. Mech. Sci. Technol.30 1843-50
[17] Brün N, Joshi V and Harris B 2009 AIP Conf Proc. (American Institute of Physics) pp 945-8