Chip Morphology of Stainless Steel in Oblique Cutting Process using Finite Element Modeling and Simulation

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Abstract. Finite Element Method (FEM) is a numerical modelling technique that can increase the understanding of characteristic and behavior of the machining process. In order to increase the machining efficiency, the suitable selection of cutting parameter is very important. Simulation can be used to compress a time frame and investigate quickly the change of parameter and their effects like in a real situation without producing a physical sample. In addition, simulation study also able to minimize material cost involved due to trial and error manufacturing techniques. Due to many advantages of simulation, this work conducts a study on oblique cutting process. 3D model of turning process of Stainless Steel 316L (workpiece) using tungsten carbide, WC (cutting tool) was developed by FEM software ABAQUS. Three different velocity of cutting tool which are 185, 415 and 660 (m/min) was carried out as manipulated variables. Simulation of cutting process was conducted to examine the chip morphology and their stress distribution in the workpiece. Then, chip morphology was compared with previous study and the gap between these two techniques were discussed. From the results obtained, developed model was successfully produced similar chip morphology produced by experiments and able to mimic oblique cutting process.

1. Introduction
Machining is one of the material removal technique in which excess material is removed from a raw material to get desire shape or final geometry. Traditionally, in order to understand and optimize the parameters, it involved high cost and long lead time due to many experiments needs to be done. Turning process is one of the types of machining process that are not exceptional from receiving the bad effects due to understand the operation. Turning process is the metal cutting process that the material of the work piece will be removed by the cutting tool from the surface. In general, the running process can be divided into two types which is orthogonal cutting and oblique cutting. These two types of techniques most likely depending on the position of cutting tool to work piece during turning process. Oblique model is one of the ways to simulate the cutting process with the value of angle or (k) between edge of tool and the direction of cutting speed less than 90º [1].

In previous study, chip morphology is one of the famous parameters around the world to be study. The most common issue found includes industries and educational is about cost due to many repeating and testing to get desire condition in real situation. For instance, the observation of chip formation produced either favorable or unfavorable and was compared with the International Standard Organization (ISO) chip form classification [2]. Then, the study on chip formation in machining titanium alloy that influences by cutting speed was conducted and involved very high cost. Besides that, the influences of cutting speed to chip formation are the essential of information from metallurgical aspects and total damage [3]. Other research on effect of tool grades on Titanium and Stainless steel has produce more than 1400 chips roots [4]. This effort involved high cost to focus on that segmented formation. Moreover, the research about stainless steel on the independent variables for cutting speed and depth of cut was conducted in order to optimum the condition of machining [5]. Next, the cutting speed is more dominant factor contribute to the tool life compare to the feed rate [6]. In a negative side, the cost of this previous study definitely is high due to large quantity of raw materials, man power, and others. Time consume in this experiment is too long due to get optimizing result until achieved also are
considered and take into account. Thus, Finite Element Modelling (FEM) is one of the reliable techniques to mimic the metal cutting simulation. FEM is an approximation technique of simulation that increase understanding machining process. It can perform complex geometries and wide variety output like chip formation and stress distribution. Definitely, the simulation technique is not completely mimic the real experimental due to reduce complexity and runtime. The most important is simulation can be used to compress time frame and investigate quickly the change of parameter and their effects without producing a physical sample. In this study, turning techniques operation been used between stainless steel 316L as work piece and tungsten carbide as cutting tool. A model of oblique cutting was built using Abaqus software to understand the machining process. Then, developed model will be compared with experiments conducted previously to look their gaps.

2. Finite Element Modeling and Simulation

2.1 Cutting tool model

The tool was developed as 3D deformable body and assigned material is tungsten carbide (WC). The rake angle, clearance angle and oblique angle are 45º, 0º and 20º respectively. The width of tool is 4mm. The size of mesh using approximate global size (0.0005). Figure 1 (a) shows a geometry of tool and Figure 1 (b) shows a developed took in mesh condition. Table 1 shows mechanical and thermal properties of WC.

![Figure 1](a) Cutting tool geometry and (b) cutting tool mesh condition

| Density, \( \rho \) (kg/m³) | Young’s Modulus, \( E \) (Pa) | Poisson’s Ratio, \( \nu \) | Thermal Conductivity, \( K \) (W/m.k) | Specific Heat, \( C \) (J/kg.k) | Expansion, \( \alpha \) (k⁻¹) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 15500           | 6.50E+11        | 0.21            | 50              | 203             | 5E-6 at 293K    |

2.2 Workpiece model

Work piece was developed as stainless steel as 3D deformable body. The measurement of work piece is (20x4x2) mm for (height, length and width). The model consists two partition lower and upper. Upper area for chip formation area while the lower area for the un-machined area (Figure 2 (a)). The depth of cut is 0.5mm and constant at all time. The type meshed used is C3D8R with combine element deletion to build chip formation. The mesh generated as shown in Figure 2(b). The properties materials are shown in Table 2.
Figure 2. (a) 3D model of workpiece showing partition and (b) workpiece in mesh condition

Table 2. Mechanical and thermal properties of Stainless Steel 316L

| Density, $\rho$ (kg/m$^3$) | Young’s Modulus, $E$ (Pa) | Poisson’s Ratio, $\nu$ | Thermal Conductivity, $K$ (W/m.k) | Specific Heat, $C$ (J/kg.k) | Expansion, $\alpha$ (k$^{-1}$) |
|-----------------------------|-----------------------------|------------------------|-----------------------------------|-----------------------------|-----------------------------|
| 8000                        | 1.93E+11                    | 0.27                   | 16.3                              | 500                         | ~                           |

Johnson cook (JC) model was applied in this simulation. This model was divided into two which are JC plasticity model and JC damage model. All the reference strain rate at 1.00. The interaction between tool and work piece need to specify where the first contact occur. The zorev’s stick slip contact friction was used with value 0.17 constant.

2.3 Boundary conditions

The type of interaction is general contact explicit. In this section, define the manipulated variable which are cutting speed. The tool set to move along the work piece with different speed in 3 simulation which are 185, 415, and 660, (m/min). Then, the work piece also was fixed by selecting the bottom of model. Full boundary condition is shown in Figure 3. Then, the job was created and submitted to run the simulation process.

3. Results and Discussions

3.1 Model and simulation of oblique cutting

Turning process was represented by modelling parts and interaction between cutting tool and work piece. The main objective is to model the moving cutting tool in axial direction towards work piece that is in static condition. Then, the progression of chip has shown agreeable with the position of cutting tool to work piece. Since the study using oblique cutting, the edge of the cutting tool that make contact with work piece are not immediately full contact. It starts contact from the right area and move along the edge to left side of cutting tool. Figure 4 (a) shows the machining process during simulation. The Figure 5 illustrates the progression of chip at three different state which are initial, middle and end.
3.2 Comparison between experiments and simulation (chip morphology)

For simulation validation, chip morphology from simulation was compared with chip morphology from experiments at three different speed (185 m/min, 415 m/min, and 660 m/min). Similarity gained from simulation and experiments is, continues chip was produced (Figure 6 and Figure 7). However, the result from the simulation is not showing the difference in terms of distance between curl for each velocity that show by the experimental. The distance between two curls is similar for every velocity. But, the width and thickness of chips are available to compare between both methods. The width and thickness of chip are recorded in this study. The simulation chip for width and thickness considered as ideal/constant value which are 2.0mm and 0.5mm respectively. Then, the width and thickness value for experimental obtained from direct measure on chip using Vernier caliper. The Figure 8 and Figure 9 shows the comparison for both techniques in term of chip width and chip thickness represents by percentage error.

Figure 4. Simulation of oblique cutting

Figure 5. Progression of chip formation during oblique cutting (a) initial, (b) middle, and (c) end

Figure 6. Experimental Chips at a) 185, b) 415 and c) 660, (m/min)

Figure 7. Simulation Chips at a) 185, b) 415, and c) 660, (m/min)

Figure 8. Chip width error between two techniques

Figure 9. Chip thickness errors between two techniques
The difference of width around 43.5% to 46.0% error as shown in Figure 9. The percentage error is considered high since the normal acceptable percentage error less than 30%. So, it indicates that the size of work piece is important and effect the gap between FEM and experimental in term of width. In this study, the width was reduced half from the width of the cutting tool. Then, after modification of the workpiece width, the difference between simulations and experiments are quite close and less than 2.5% error. For the chip thickness error (Figure 9), the difference between experiments and simulations in the range 4% to 16%. It shows a good and closer similarity in thickness of chip between these two techniques. From the results, the range of chip width and thickness are acceptable and proved that developed model is reliable and able to mimic the actual process of oblique cutting.

4. Conclusion
In this study, a developed model of oblique cutting using FEM software Abaqus/Explicit was used to mimic the real machining process of turning between stainless steel (316L) workpiece and tungsten carbide cutting tool. The simulation results interested and concerned on chip morphology during the cutting. The developed model was indicated and proved that Abaqus/Explicit are able to mimic the oblique cutting process. The chip formation between simulation and experimental show the good correlation and agreeable through the type of chip and the way chip evolved.

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