MODELING OF CUTTING PROCESS AND FLOW STRESS UNDER HIGH STRAIN RATE

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ABSTRACT

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In the recent past, advances in analytical modeling and finite element methods (FEM) based numerical modeling of metal cutting have resulted in capabilities of predicting the physical phenomena in metal cutting such as forces, temperatures and stresses generated. FEM modeling has emerged as one of the most effective tools that could substitute the conventional time consuming and expensive experimental tests to a great extent. However, accuracy and reliability of these predictions rely on a work material constitutive model describing the flow stress, at which work material starts to plastically deform and the frictional boundary conditions at the tool/chip interface.

This work presents an experiment investigation of the overall influence of different cutting condition of orthogonal cutting process on FEM simulation performance to identify and predict the flow stress of workpiece under high strain rate. The overall influence of different cutting condition considers such as different cutting speed, feed rate and rake face angle. The objective of this research works is to model and investigate two critical factors during orthogonal cutting, namely the flow stress characterization of work material and friction characteristics that applicable for FEM simulation.

Firstly, an orthogonal cutting test was conducted with variety and large range of cutting condition. Then, the same cutting condition was conducted for two-dimensionsal cutting process of FEM simulation. To identify the flow stress of workpiece under high strain rate for FEM simulation, Johnson-Cook flow stress model had been applied. Johnson-Cook flow stress model had been exploited using commercial available software DEFORM™. Johnson-Cook flow stress have five material constants included A, B, C, n and m. The material constants of A, B, and n can be identified using tensile or compress test. While material constants of C and m were identified using inverse calculation by DownHill method. The Johnson-Cook flow stress model had been applied to understand the flow stress of JIS S45C. However, regarding this method only principal force is in good accuracy between experiments and FEM simulation results. The thrust force error result was big which about 40%.

Secondly, to improve the previous proposed method an improvement method to identify flow stress and friction characteristics had also been studied and discussed. Some of the improvement method was identification of repeated time necessary for
unsteady state simulation and steady state simulation. Identification of mesh average length, tool radius roundness, tool rake angle and clearance angle were also been studied. Thus, to improve the thrust force result of FEM simulation, friction characteristics had also been identified. Shear friction model had been applied in this study. As a result from this improvement method the thrust force error between experiment and FEM simulation was about 23%. Lower than then previous proposed method. However, the principal force error between experiment and FEM simulation had getting bigger.

Thirdly, a new method to identify friction characteristics during low-speed orthogonal cutting process had been proposed. Low-speed orthogonal cutting process was conducted. Then, the same cutting condition of experiment had been applied to two-dimensional cutting process of FEM simulation but with different value of friction characteristics. Identification value of friction characteristics had been conducted. As a result from this method, principal force error was about 8.9% and thrust force error was about 22%. Which both result was better and smaller than previous proposed method.

Lastly, a new method to identify flow stress of workpiece and at the same time friction characteristics between tool/chip can be negligible under high strain rate for FEM simulation also been developed and proposed. In this chapter, a new method to identify Johnson-Cook flow stress model by shear-slitting method had been developed. This is because the proposed method can identify flow stress of workpiece under high strain rate and at the same time friction characteristics can be negligible. The result of experiment shows that this method can achieve high strain rate as same as cutting process and the error of flow stress between experiment and FEM simulation is in good accuracy.

KEYWORDS:
Orthogonal Cutting, Johnson-Cook Flow Stress, Friction Characteristics, Shear-slitting
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CHAPTER 1

INTRODUCTION

1.1 Cutting Process

Cutting process is a process in which, by action of a cutting edge of a tool, unnecessary material is removed. It is one of the most common manufacturing processes for producing parts and obtaining specified geometrical dimensions and surface finish. Many studies and experiments were performed since beginning of the 20th century. One of the most basic machining processes is turning, meaning that the part is rotated while it is being machined. Turning processes, which typically are carried out on a lathe or by similar machine tools (Figure 1.1). These machines are highly versatile and capable of a number of machining processes that produce a wide variety of shapes. The performance of a cutting process is greatly influenced by cutting conditions such as cutting speed, feed rate and rake angle of cutting tool (Serpe K., 2010). During cutting process, workpiece deforms due to high strains, high strain rates and high temperatures. Those elements of flow stress are very crucial and important to be understood to be applied to FEM simulation.

To be useful in cutting process of FEM simulation, flow stress data must be obtained at high strain rates (up to $10^6 \text{ s}^{-1}$), high temperature (up to 1000 °C) and large strain (up to 4) (B. Geoffrey, 1981). These data are difficult if not impossible to obtain reliably with conventional tensile and compression tests. Most popular method of measuring the stress-strain relationships at high strain rate is Hopkinson bar method. Strain rate range can be achieved in this test method is only $10^2 \text{ s}^{-1} \sim 10^4 \text{ s}^{-1}$, but the effort it takes to experiment is very large and difficult to conduct. Therefore, a great demand to identify flow stress of workpiece under high strain rate and high temperature during cutting process that is applicable for FEM simulation. Furthermore, a new method that can identify flow stress and at the same time friction between tool-chip formations can be neglected is necessary.
1.2 Principles of Finite Elements Model

The finite element method (FEM) is a numerical technique for finding approximate solutions to boundary value problems for partial differential equations. The application of Finite Elements Model (FEM) has become popular due to the advancement in computer hardware and the development of complex codes. In the past decade, finite element method (FEM) has been widely used to analyze cutting process. The analysis can be in the form of two-dimensional or even in three-dimensional. Early analyses were made by analyzing the steady-state orthogonal cutting process. FEM is used as an approximate model to predict the system behavior such as heat, stress, and force. This process involves the generation of mathematical formulation followed by a numerical solution of the mathematical model. There are three stages in FEM process, namely pre-processing, processing, and post-processing. In pre-processing stage, all information such as coordinates, boundary conditions, loading, and material properties have been identified. The processing stage involves stiffness generation and modification, solution of equation, remeshing, and evaluation of nodal variables. Lastly, post-processing stage involves the output of the calculated formation.

Until the mid-1990s, most of the researchers used to develop in-house finite
element code for their own particular theoretical problem (Obikawa and Usui, 1996). These developments have contributed to investigate various aspects of the fundamental modeling of the machining processes. In addition, researches that used commercial codes are concentrated on two dimensional cutting, which represented as the orthogonal cutting. However, only few research papers are available which offers accurate predictions and allow simulating of workpiece flow stress during cutting process (S. Mahmoud, K. Christian, A. Taylan, 2001).

1.3 Shear-slitting Process

In this study, we proposed a new method shear-slitting machine which is believe can solve the problem of friction between tool/chip formation and at the same time it can deformed material under high strain rate. Shear-slitting is the most versatile and commonly used method to slit flexible web materials. It is also the most demanding, requiring careful attention to control specific operating variables for high quality slitting. Fig. 1.2 shows an overview of general slitting process. Slitting process is a process for cutting the longitudinal direction the sheet material by rotation round blade tool pair of upper and lower roller. By shearing the material, the tool is rotated. The relative speed of the tool and workpiece is zero. Even where it was sheared at high-speed tool, it is possible to ignore the friction between tool and workpiece.

![Figure 1.2 General slitting processes](image)

1.4 Rational and Motivation of the Present Works

The understanding of interactions during the cutting process is a fundamental task
where this knowledge enables tool makers to evaluate the performance of the cutting tool design. Many experimental observations with trial and error are needed for the optimization of cutting conditions. Several studies have been published looking at the optimization flow stress of the cutting process for FEM simulations. The results have shown an improvement on determination of material characteristics but still the results is not satisfaction. Furthermore, repeating the experiment to achieved desired optimized cutting condition will be expensive and time consuming.

As has been previously noted, conventional tensile, compression tests and Hopkinson bar method to obtain reliably range of material characteristics applicable for FEM simulations during cutting process are time consuming and very large. Those conventional methods don not cover the real range of cutting process which is high strains, high strain rates and high temperatures. Hence, FEM is an effective method as it would decrease experimentation and reduce cost.

Furthermore, a new methods need to be proposed to identify the material characteristics that can cover as same as deformation characteristics during cutting process. At the same time, a new method also can neglect the effect of friction characteristics between too/chip.

1.5 Research Objectives and Approaches

The main objective of this research is to identify and investigate the workpiece flow stress during cutting process applicable for FEM simulation. The secondary objective is to validate and upgrade the method that been proposed. The specific research tasks to fulfill the objectives of this thesis are summarized as follows:

i. To identify workpiece flow stress on high-speed orthogonal cutting process using commercial available software, 2D DEFORM V10.1™.

ii. To upgrade the accuracy of proposed method identifying workpiece flow stress on high-speed orthogonal cutting process.

iii. To develop new method of identifying workpiece flow stress on high-speed deformation characteristics.

iv. To validate the developed new method of identifying workpiece flow stress on high-speed deformation characteristics by comparing cutting forces.
1.6 Organization of the Dissertation

Chapter 1 “Introduction and Overview”
Introduction and overview of cutting process, FEM simulation and shear-slitting process had been discussed.

Chapter 2 “Literature Review”
This chapter gives a literature survey on machining process especially orthogonal cutting process, overview of Finite Element Model (FEM) of cutting during high-speed deformation characteristics and lastly overview of shear-slitting method that applicable for high-speed deformation characteristics for FEM.

Chapter 3 “Identification of Johnson-Cook Flow Stress Model on High-speed Orthogonal Cutting Process”
This chapter describes the experimental and FEM simulation methods to identify Johnson-Cook flow stress model on high-speed orthogonal cutting process.

Chapter 4 “Improvement of Accuracy for Identification Johnson-Cook Flow Stress Model Cutting Process”
This chapter includes methods, results and discussions of upgraded the accuracy of identification Johnson-Cook flow stress model on high-speed orthogonal cutting process.

Chapter 5 “Low-Speed Orthogonal Cutting Process to Identify Friction Characteristics Applicable for FEM simulation”
This chapter includes the results and discussions for proposed method to identify flow stress of workpiece.

Chapter 6 “Development and Identification of Johnson-Cook Flow Stress Model by Shear-slitting Method”
This chapter introduces a shear-slitting method that applicable to identify high-speed deformation characteristics for FEM simulation.

Chapter 7 “Conclusions and Future Recommendations”
This chapter includes the overall summary of the present work and future recommendations regarding of this study.
This chapter presents a review of literature related to experimental and numerical procedures, finite element method (FEM) in cutting process. Since finite element simulation is nowadays assuming a large relevance, many studies on this topic have been published. The present chapter starts with mechanics of cutting process. Early attempts from the previous researchers considering development of FEM method to identify workpiece flow stress model and friction characteristics are also being discussed. Critical demands of new method to identify high-speed deformation characteristics are also being discussed.

2.1 Machining process

Machining process is the process of removing unwanted material from the workpiece to obtain a part with high quality surfaces and accurate dimensions with acceptable tolerances. This process has represented a very large segment in industry since last century. It is estimated that 15 percent of the value of all mechanical components manufactured worldwide is derived from machining operations. The machining process includes different forms grinding, turning, milling, sawing, etc. The cutting forces vary with tool angles and accurate measurement of forces is helpful in optimizing tool design (Edward, 2000). For all these types of machining, the productions of chips have different forms and each process has unique chip morphology. Therefore, it is important to understand the mechanism of cutting process in order to understand the machining process.
2.1.1 Mechanics of Cutting Process

All cutting processes can be likened to the process shown in figure 2.1 and figure 2.2, where the tool is wedge-shaped, has a straight cutting edge and is constrained to move relative the workpiece in such a way that layer of metal is removed in the form of a chip (Geoffrey B., 2006) Cutting process consists of orthogonal and oblique cutting. In an orthogonal cutting process (Figure 2.1), the cutting edge of the tool is perpendicular to cutting direction. It is assumed that the chip flows upward to the surface of the wedge-shaped tool with the chip velocity parallel to the direction of the workpiece. Chip formation is related to the shear angle in the shear plane. The theory of the metal cutting process assumed that a continuous plastic deformation with a high strain rate under the compressive stress exerted by a wedge-shaped cutting tool.

The oblique cutting process (Figure 2.2) represents a three dimensional process due to the cutting edge is inclined at an angle to a line drawn by at right angles to the direction of the velocity of the workpiece. The assumption of the chip flowing up the surface of the wedge-shaped cutting tool with the chip velocity parallel to the direction of the velocity of the workpiece is no longer applicable. This situation makes the analysis of cutting action more complicated. (E. Ceretti, 1999) studied about FEM simulation of orthogonal cutting: serrated formation. The results obtained from the FEM simulation show potential of the customized FEM software DEFROM 2D in predicting cutting variables and serrated chip formation.

Figure 2.1 Orthogonal cutting geometry
2.1.2 Workpiece Deformation in Cutting Process

The easiest way to present the fundamentals of the orthogonal cutting process is by the two dimensional cutting geometry a shown in Figure 2.3. As the workpiece starts moving, the cutting edge penetrates into the workpiece and forces the chip to grow up so that the chip will be formed and moved along the rake face of the tool. This process causes high pressure and plastic deformation is expected to take place in the front of the cutting edge. (Sung-Han Rhim, 2006) suggested a new flow stress model based on some assumptions on large deformation process with high speed and high temperature during cutting process and attempt to predict the serrated chip formation. The shape of the formed chip will be affected by the cutting conditions (cutting speed, feed and depth of cut), tool geometry and material properties. Thus, (Woei-Shyan Lee, 2006) studied the effects of temperature and strain rate on the dynamic flow behavior of different steels.

The uncut chip thickness ($t_0$) is known as the feed while the deformed chip has a different chip thickness ($t_c$). The tool will be defined by rake angle ($\alpha$) and relief or clearance angle ($\beta$). The rake angle is defined to be positive on the right side (clockwise from vertical) and negative on the left side (counter clockwise). The contact length ($l_c$) is defined as the distance from the tip of the tool to the point where the chip loses contact with the tool on the rake face. The friction between the chip and the tool plays a significant role in the cutting process because of the heat energy that is transferred into the workpiece (Chandrakanth, 2000). It may be reduced by optimized tool geometry, tool material, cutting speed, rake angle, and cutting fluid. Because of the high pressure and temperature, a built up edge (BUE) may exist near the tool tip.
In orthogonal machining the shearing action takes place along the shear plane so the chip will start to flow over the rake face. The shearing zone has been modelled using either one of two assumptions. Merchant developed an orthogonal cutting model by assuming the shear zone to be thin. Once the material approaches the shear plane, the plastic deformations begins. A thin shear zone is usually created at high cutting speeds. Some researchers had different assumptions where the shear zone would be thick as shown in Figure 2.4. This kind of shear zone is more complicated and normally seen when using low cutting speeds. Both models have been used to analyze cutting processes where the thin shear zone relates to the shear plane angle, cutting condition, material properties, and friction behavior, while the thick shear zone model is based on the slip-line theory.
There are three deformation zones in the cutting process as shown in Figure 2.5:

- **Primary shear zone (A-B):**
  
The chip formation takes place firstly and mainly in this zone as the edge of the tool penetrates into the work-piece. Material on this zone has been deformed by a concentrated shearing process.

- **Secondary shear zone (A-C):**
  
The chip and the rake face of the tool are in contact from A to C. When the frictional stress on the rake face reaches a value equal to the shear yield stress of the work-piece material, material flow also occur on this zone.

- **Tertiary shear zone (A-D):**
  
When the clearance face of the tool rubs the newly machined surface deformation can occur on this zone as shown in Figure 2.5.

![Figure 2.5 Deformation zones in metal cutting](image)

**2.2 Finite Element Modeling of Cutting Process**

One way to study the contact and friction stresses on the rake face is by direct measurement. However, this is difficult because the stresses are large and the contact area is small (T. H. C. Childs, 2001). The earliest use of finite elements was probably
that of the geometer. More than two thousand years ago, mathematicians were interested in such problems as determining the perimeter and area of a circle. In the meantime, amazingly accurate results were found by introducing approximate problems employing finite elements (Harold C. M., 1973). (Domenico U., 2008) studied about finite element simulation of conventional and high-speed machining of Ti6Al4V alloy. The results indicated that a good prediction of both principal cutting force and chip morphology can be achieved only if the material constants for the Johnson-Cook’s constitutive equation were identified using experimental data obtained by the methodology which permits to cover the ranges of true strain, strain rate and temperature similar to those reached in conventional and high speed machining.

In the middle of the 19th century, the old (trial and error) experimental method was the earliest way to develop models of the metal cutting process (J. Mackerle, 2003). The simplified models were also presented and used based on the shear zone theory. The chip formation was assumed to take place as the result of shear actions in the shear zone. Later, finite element analysis was utilized, trying to optimize cutting processes. This opened a new way to investigate the state of stresses, strains, temperatures, and feed and cutting forces in the deformation zones. These models provide a better understanding of metal cutting and provided ways to do detailed studies of the effect of different parameters where the magnitude of some parameters such as the temperature cannot be easily measured experimentally. The efficiently and accuracy of simulation is depends mainly on strain, strain rate and temperature during cutting process (G. R. Johnson et al., 1983). (Jaspers, 2002) studied the effect of strains, strain rates and temperatures in chip formation during metal cutting. It appears that that the feed rate and cutting speed hardly influenced the shear plan temperature which friction characteristics between tool/chip cannot be neglected during FEM simulation of cutting process.

2.2.1 Model Formulation

The application of FEM has become popular due to advancement in computer hardware and the development of complex code. As mentioned in previous section, cutting process consists of orthogonal and oblique cutting. The orthogonal cutting can be simulated by two dimensional simulations (Figure 2.1), meanwhile three dimensional simulation can be used for oblique cutting (Figure 2.2). Material characteristics are of concern to a variety of parties that have differing interest. Consequently, it is imperative that there be some consistency in manner which tests are conducted and in the interpretation of their results (William D. C. Jr, 2010) (Aviral Shrot, 2012). (A.S. Milani,
in this paper, it stated that by identification of Johnson-Cook material parameters reduce the number of experiments necessary for the identification of model parameters.

Recent advances in modelling of metal machining processes had been discussed by (P. J. Arrazola, 2013). This paper presents the state of the art in predictive performances models for machining and identifies the strengths and weaknesses of current models. This includes a critical assessment of the relevant modelling techniques and their applicability and/or limitations for the prediction of the complex machining operations performed in industry. (E. Ceretti, 1996), investigated where FE code DEFORM 2D was applied to simulate a plain strain cutting process. Then, (E. Ceretti, 2000) tried to simulate turning simulations using a three-dimensional FEM code. However, three-dimensional FEM simulation required a big effort in computational time.

General-purpose FEM codes capable of modelling the machining process include NIKE2D, ABAQUS/Standard, ABAQUS/Explicit, MARC, ALGOR, FLUENT, LSDYNA etc. Unfortunately those FEM codes still can’t be able to predict high strains, high strain rates and high temperatures during cutting process. There are specially developed FEM codes, such as DEFORM 2D, FORGE2D, AdvantEdge, which are capable of simulating segmented, continuous and discontinuous chip formation. A comparison of orthogonal cutting data from experiments with three different element models was done by (Halil, 2004). Estimated cutting thrust forces, shear angles, chip thicknesses and contact length on the rake face by MARC, DEFROM 2D and explicit code Thirdwave AdvantEdge are compared with experiments performed in this study. (Mamalis, 2001), used MARC to study chip formation in orthogonal cutting process. The shape of the chip and the stress, strains and strain rates distributions in the chip and workpiece, as well as the temperature fields in the workpiece, chip/tool are determined. (Guo, 2003) also proposed an integral method to determine the mechanical behavior of materials in metal cutting. In this study, the developed approach is valid for machining with continuous chips at variety of cutting speeds.

(a) Eulerian

In FEM, three main formulations are used in finite element simulation of metal cutting: Lagrangian, Eulerian and Arbitrary Lagrangian-Eulerian (ALE). In the Eulerian method, the material flows through the FE mesh and is recommended for fluid-flow analysis. This method assumed that the chip formation is continuous and the shape of the chip is known in advanced. The unknown material variables are calculated at present locations as the material flows through mesh.
(b) Lagrangian

Advances in computation accessories, such as faster processors and larger memory have encouraged researchers to use Lagrangian formulation for cutting simulation. The principal advantages of this approach are (1) the tool can be simulated from initial state to steady state cutting and (2) the chip geometry together with workpiece residual stress can be predicted. In the Lagrangian analysis, the FE mesh is attached to the workpiece and the computational grid deforms together with the material. The Lagrangian calculations embed a computational mesh in the material domain and solves for the position of the mesh at discrete points in time. Compare to Eulerian, the calculation time for Lagrangian method is much faster due to no transport material through the mesh needs to be calculated. The geometry of the material boundaries (or chip shape) does not have to be predetermined, but is developed during the course of the analysis entirely as a function of the physical deformation process, machining parameters and material characteristics. Disadvantage of Lagrangian mesh is increasing time step or a stability loss when the distortion of elements is too high. (Shuji U., 2014) presented a finite element scheme using a nonlinear, large deformation Lagrangian method with an explicit time integration, which is employed with cohesive element insertion and structured mesh element splitting of carbon fiber composite orthogonal cutting and drilling. (M. H. Dirikolu, 2001) also studied about finite element simulation of chip flow in metal machining using Lagrangian formulation. The changes to the simulation method considered here are the structure of the finite mesh, the measures of judging when the flow is fully developed, how the chip separates from the work at the cutting edge and the friction laws used during the approach to fully developed flow.

(c) Arbitrary Lagrangian-Eulerian (ALE)

The best features of Lagrangian and Eulerian formulations have been combined and called arbitrary Lagrangian-Eulerian (ALE). In ALE formulation, the FE mesh is neither fixed spatially nor attached to the work piece material. The mesh follows the material flow and problem is solved for displacements in Lagrangian step, while the mesh is repositioned and problem is solved for velocities in Eulerian step. The idea used in metal cutting simulation is to utilize Eulerian approach for modelling the area around the tool tip where cutting process occurs. Therefore, severe element distortion is avoided without using remeshing. Lagrangian approach is utilized for the unconstrained flow of material at free boundaries. Furthermore shape of the chip occurs as a function of plastic deformation of the material. This approach is shown in figure 2.6
Figure 2.6 Eulerian and Lagrangian boundary conditions in ALE simulation
(Ozel, 2007)

(A. J. Haglund, 2007), in this paper an exploration of friction models for the tool/chip interface using an arbitrary lagrangian-eulerian finite element model had been discussed. A finite element model, based on the ALE approach, was developed for orthogonal cutting and used to study the conditions prevailing at the tool/chip interface for hardened tool. The ALE approach does not require any chip separation criteria and enables an approximate initial chip shape to smoothly evolve into reasonable chip formation, while maintaining excellent mesh properties. In this study, we applied both Eulerian and Lagrangian method.

2.2.2 Modeling of Material Characteristics

Material model is essential to solve the problem related to material separation on the explicit algorithm and the fracture of each element. John-Cook (JC) model appears to be the best solution for cutting process. This model describes the material characteristics such as strain-hardening, thermal softening and strain rate dependence as given in equation 2.1. The first term in the bracket gives the dependence on strain, which represents strain-hardening effect. The second bracket means instantaneous strain rate sensitivity which represents strain rate hardening. Lastly, the third bracket is the temperature dependence of stress such as thermal softening effect.

\[ \sigma = (A + B\varepsilon^n)(1 + C\ln\dot{\varepsilon})(1 - T^m) \]  

(2.1)
where $T^* = \frac{T - T_{room}}{T_{melt} - T_{room}}$

Where $\sigma$ is the stress (MPa), $\varepsilon$ the strain, $\dot{\varepsilon}$ the strain rate (s$^{-1}$), $T$ the temperature (°C), and $A, B, C, n, m$ are the material flow stress parameters. In the Johnson-Cook flow stress model, the parameter $A$ is in fact the initial yield strength of the material at room temperature and a strain rate of 1/s and represents the equivalent plastic strain. The strain rate is normalized with the reference strain rate. Temperature term in JC model reduces the flow stress to zero at the melting temperature of workpiece, leaving the constitutive model with no temperature effect. In general, the parameters $A, B, C, n$ and $m$ of the model are fitted to data obtained by several material test conducted at low strain rates and at the room temperature. (Ding N., 2015) applied improved Johnson-Cook flow stress model for 7075-T6 aluminum allow and matched the experiment result very well. The improved Johnson-Cook model by modifying the strain rate hardening term. (Haidong Y., 2009) discussed about rate-dependent behavior and constitutive model strain rate from $10^{-4}$ s$^{-1}$~$10^{3}$ s$^{-1}$. The new rate-dependent constitutive model for steel at various strain rates was developed and implement into the ABAQUS by using material subroutine VUMAT. (S. A. Hosseini Kordkheili, 2014) also proposed new method of rate-dependent constitutive equation for 5052 aluminum diaphragms. The JC model provides good fit for strain-hardening behavior of steel and it is numerically robust and can easily be used in finite element simulation models (Monzer, 2014). While, (An H., 2013) studied about constitutive analysis to predict high temperature flow stress in 20CrMo continuous casting billet.

To perform this simulation with relevant accuracy, influences of cutting parameters such as cutting speed, rake angle, and depth of cut also studied. Later, the computed cutting force, temperature, deformations and chip geometry have been compared with cutting experiments (Monzer, 2014). (Xiangyu W., 2013) studied dynamic behavior and modified Johnson-Cook constitutive model on Inconel 718 at high strain rate and elevated temperature. (Uma, 2014), conducted a study with two constitutive models, modified Johnson-Cook and modified Zerilli-Armstrong model that formulated considering the combined effects of strains, strain rates and temperature on flow stress. (Y. Prawoto, 2011) also applied Johson-Cook model on dual phase steel. The result shows that the difference in mechanical property was not only due to the variation of the ferrite parts in material but also due to the shapes of the constituents. It tends to follow the continuum mechanics rule. It is also concluded that modeling using
two-dimensional approach is sufficient to estimate the properties of the dual phase structure.

(Xuemei W., 2013) target material behavior was modeled by the Johnson-Cook material model that induced both plastic deformation and damage mechanism. Good agreement was obtained between the experimental measurements and numerical predictions for all testing conditions. A comparative study on Johnson-Cook, modified Johnson-Cook and Arrhenius type constitutive models to predict the high temperature flow stress in 20Crmo alloy steel (An H., 2013). A modified Johnson-Cook model for tensile behaviors of typical high-strength alloy steel also studied by (Y. C. Lin, 2010). Johnson-Cook and Arrhenius type models, which consider the coupled effects of strain rate and deformation temperature, could give a precise prediction of high temperature flow stress for the studied steel. Johnson-Cook constitutive equation is also implemented to determine residual stresses on the machined surface with five different sets of material constants (D. Umbrello, 2007). (Seshadri R., 2013) assess and validate the performance of the Johnson-Cook constitutive equation in modeling the deformation behavior of Al 2024-T351 Aerospace alloy.

### 2.2.3 Friction Models

A general concept of friction can be considered as the tangential force generated between two surfaces. Friction can be represented as the resistance force acting on the surface to oppose slipping. Figure 2.7 (a) shows a simple example of friction where a block is pushed horizontally with mass $m$ over rough horizontal surface. As showing in the free body diagram, Figure 2.7 (b), the body has distributions of both normal force ($N$) and friction force ($F_f$) along the contact surface. From the equilibrium, the normal force ($N$) acts to resist the weight force of the mass $mg$ and the friction force ($F_f$) acts to resist the force $F$.

![Friction](image)

Basically, there are two types of friction, which are static and kinetic as shown in Figure 2.8. By increasing the force, $F$, friction force ($F_f$) increases. The blocks cannot move until the force $F$ reaches the maximum value. This is called the limiting static fractional force. Increasing of the force $F$ further will cause the block to begin to move. In the static portion, the limiting friction force can be expressed as:

$$F_{static} = \mu_s N$$  \hspace{1cm} (2.2)
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![Diagram of contact between two surfaces](image)

Figure 2.7 Explanation of contact between two surfaces (a) Two bodies with friction after applying load (b) Free body diagram for the block on rough surface.

Basically, there are two types of friction, which are static and kinetic as shown in Figure 2.8. By increasing the force, $F$, friction force ($F_f$) increases. The blocks cannot move until the force $F$ reaches the maximum value. This is called the limiting static frictional force. Increasing of the force $F$ further will cause the block to begin to move. In the static portion, the limiting friction force can be expressed as:

$$F_{\text{static}} = \mu_s N$$  \hspace{1cm} (2.2)

Where $\mu_s$ is called the coefficient of static friction.

When the force $F$ becomes greater than $F_{\text{static}}$, the frictional force in the contact area drops slightly to a smaller value, which is called kinetic frictional force. Cutting models generally just consider the kinetic friction coefficient which can be calculated by the following equation;

$$F_{\text{kinetic}} = \mu_k N$$  \hspace{1cm} (2.3)
2.2.4 Friction Models for Cutting Process

In early cutting analysis, friction characteristics at the tool/chip interface were neglected or the simple Coulomb friction law was considered on the whole contact zone, using a constant coefficient of friction. The friction characteristic is essential in cutting simulation to represent the contact at the tool-chip interface (Filice, 2007). This contact is influenced by cutting speed, chip thickness, rake angle and workpiece material. (Tugrul, 2006), in this paper the influence of friction models on finite element simulations of machining had been discussed. In the analysis of orthogonal cutting process using finite element (FE) simulations, predictions are greatly influenced by two major factors; a) flow stress characteristics of work material at cutting regimes and b) friction characteristics mainly at the tool/chip interface (Tugrul O, 2005). An updated Lagrangian finite element formulation is used to simulate continuous chip formation process in orthogonal cutting of low carbon free-cutting steel. Experimentally measured stress distributions on the tool rake face are utilized in developing several different friction models. (Pedro, 2010), studied the effects of friction modeling in finite element simulation of machining. The influence of limiting shear stress on the tool/chip contact friction characteristics was explored and validity of friction modeling approaches was examined.

(a) Constant Coulomb

It is major input determining the independent variables such as chip geometry, cutting forces and temperature. Coulomb friction law is prevalently used in FE metal cutting simulation. The law can be expressed by means of the $\mu$
\[ \tau = \mu \cdot \sigma_n \]  

being \( \tau \) the frictional stress and \( \sigma_n \) the normal one. (P. J. Arrazola, 2008) showed in this study the inadequacy of using constant Coulomb’s friction coefficient in FEM.

(b) Constant Shear

Another well-known friction model is the constant shear model, which neglects altogether the low stress variation of \( \tau \) with \( \sigma_n \). In this case, a constant frictional stress on the rake face is assumed, equal to fixed percentage of the shear flow stress of the working material \( k \)

\[ \tau = m \cdot k \]  

(c) Constant Shear in Sticking Zone and Coulomb in Sliding Zone (Hybrid Model)

A more realistic model is related to the actual distribution of stresses on the rake face. The latter is rather complicated and it is typically non-linear. The normal stress decreases from the tool edge to the point where the chip separates from the tool. According to previous research, the normal stress decreases from the tool edge to the point where the chip separates from the tool. On the contrary, the frictional stress is equal to the shear flow stress near the tool edge and then decreases. According to this distribution the existence of two distinct regions on the rake face was proposed as shown in figure 2.9.

In the first region, named sticking zone, the normal stress is very large and the frictional stress is assumed to be equal to the shear flow stress of the material being machined. In latter, on the contrary, the normal stress is small and Coulomb friction law is able to provide a suitable model of the phenomenon. This can be expressed by means of the following formulation:

\[ \tau(x) = \mu \cdot \sigma_n(x) \quad \text{ when } \quad \tau < k \]  

\[ \tau(x) = k \quad \text{ when } \quad \tau \geq k \]  

Friction in cutting process was studied in detail by many researchers. To achieve this goal, researchers study the contact and friction stress on the rake face by using direct measurement.
Shirakashi (1990) derived an empirical equation as a friction model, which relates the frictional stress $\tau_f$ to the normal stress $\sigma_n$:

$$\tau_f = k \left[ 1 - \exp \left( \frac{\lambda \sigma_n}{k} \right) \right]$$

(2.7)

Where $k$ is the shear flow stress of the workpiece and $\mu$ is a friction coefficient experimentally obtained for different workpiece-tool material combination. (Usui, 1960) measured the distribution of the shear ($\tau$) and the normal ($\sigma$) stress on the rake face of the tool. In this study, we applied this proposed method to calculate cutting force.

As shown in Figure 2.9, they found the shear stress remains constant over about the half of tool-chip contact nearest the cutting edge but it decreases to zero over the rest, reaching zero of course at point C where the chip leaves contact with the tool. The normal stress was found to decrease and reach zero from the cutting edge to point C. Zorev (1963) found also similar results from his experiments. Over the length AB, normal stress is sufficiently high and contact area to total area ratio approaches unity and metal adheres to the rake face. This region is called the sticking region and plastic deformation occurs in the chip. The coefficient of friction in the sticking region is not constant, but it depends on the magnitude of the normal load. The value of the coefficient of friction in this region is lower than the value under sliding friction conditions. In the length from B to C, which extends from the end of the sticking region to the point where chip loses contact with the tool rake face, the contact area to total area ratio is less than unity, so coefficient of friction is constant, and sliding friction occurs.

The measured coefficient of friction in metal cutting is an average value based on both regions. Any changes in cutting conditions that may change lengths AB and BC will change the value of coefficient of friction.
A comparison of different friction characteristics with three different element models (MARC, DEFROM 2D and explicit code Thirdwave AdvantEdge) was done by (Halil, 2004). (Ship-Peng L., 2002) investigated of sticking behavior on the tool/chip interface using thermos-elastic-plastic finite element method. In this study, they proposed a variant pseudo-friction coefficient concept modify the large deformation finite element formulation and develop a stress analysis model of the tool/chip interface to solve the problems of the shear stress, normal stress and variant pseudo-friction coefficient on tool/chip interface. In spite of the high-speed micro-cutting, the effect high strain rates and high temperatures will produce the sticking phenomenon on the rake face of the tool. Not only will the sticking phenomenon shorten tool life, but also will have an effect on the machining accuracy in precision diamond cutting. (Tugrul, 2000), proposed a method to determine of workpiece flow stress and friction for FEA of machining using orthogonal cutting tests. High-speed cutting experiments and process simulation were utilized to determine the unknown parameters in flow stress and friction model. The friction conditions in sticking and sliding regions at the tool-chip interface are estimated using Zorev’s stress distribution model. (Tugrul, 2004), this paper utilizes a metal cutting model developed by Oxley and presents an improved methodology to characterize workpiece flow stress and friction at primary and secondary deformation zones around the cutting edge by utilizing orthogonal cutting tests.

2.3 Inverse Calculation Method

(H. Cho, 2003), (Hyunjoong C., 2005) proposed a new method by finite element based on inverse calculation method to simultaneously identify flow stress and interface friction. The inverse problem is defined as the minimization of the differences between experimental measurements and the corresponding FEM predictions. The interest in defining the flow stress of workpiece during orthogonal cutting process in easy and fast way without using complicated dynamic characterization tests lead to analyze the inverse identification of flow stress employing cutting process (Pujana, 2007). (William K. R., 1997) studied a method to economically estimate all eight coefficients of the revised strength model using Johnson-Cook flow stress model. The behavior of the revised strength model at high strain rates also compared favorably with independent predictions from an analytical model calibrated with the Taylor impact data.
2.4 Shear-slitting Method

Slitting is a concise and economically reasonable method with high productivity for cutting material compared to other cutting methods. Slitting method is suitable for cutting elongated products at reasonable cost when cutting line is assumed to be straight (T. Kuboki, 2011).

2.4.1 Shearing Method

Shearing is a metal fabricating process used to cut straight lines on flat metal stock. During the shearing process, an upper blade and a lower blade are forced past each other with the space between them determined by a required offset. Normally, one of the blades remains stationary.

The shearing process characteristics include:

- Its ability to make straight-line cuts on flat sheet stock
- Metal placement between an upper and lower shear blades
- Its trademark production of burred and slightly deformed metal edges
- Its ability to cut relatively small lengths of material at any time since the shearing blades can be mounted at an angle to reduce the necessary shearing force required.

Figure 2.10 shows a two-dimensional look at a typical metal shearing process. Note how the upper shear blade fractures the metal workpiece held in place by the workholding devices. The sheared piece drops away. (Wang, 2006) studied the effect of constitutive parameters on adiabatic shear localization for ductile metal based on Johnson-Cook and gradient plasticity models. (Junhang G., 2013) proposed a modified Rousselier model which can predict shear failure as well as tension failure for Al-Alloy 5052.
Slitting is also a shearing process, but rather than making cuts at the end of a workpiece like shearing, slitting used to cut a wide coil of metal into a number of narrower coils as the main coil is moved through the slitter (50). Slitting is a type of metal cutting process where large rolls, or coils, of sheet metal stock are cut using extremely sharp rotary blades. In metal slitting, straight lines are cut lengthwise into the large coil to create strips of metal that are narrower in width. As the coil runs through the slitter, circular blades – one upper, the other lower – make the cuts. These are commonly called knives and can be moved to make sheet metal strips of differing widths (51).

There some research works on slitting. (Taizo M., 1977-2) developed of burr-free slitting. This new proposed method describes successful conditions of the method as bellows:-

1) The overlap of the cutters in the first step should be selected deeply enough so that shearing force on the cutters shows a substantial maximum value to ensure the material to be separated during the second step but not so deeply that the material will be normally slit during the first step.

2) The clearance of the cutters should be selected with the zero or minus range to ensure the material to be separated without burr during the second step.

(Masao M., 1978-9), proposed a method on how to consider shearing-slitting method. Then, (Masao M., 1978-9) analyzed proposed method both experimentally and numerically shearing force acting on the cutter. (Aoki, 1983) proposed a new slitting method using urethane flat rolls at the downstream from slitting process to suppress burr and surface damage of the slit materials. (Wisselink H. H., 2004) presented a
computational method for the 3D FEM simulations of stationary metal forming process. They applied the method to slitting and rolling as examples without comparison to experimental results. (Ghosh S., 2005) conducted a parametric study on the effect of rake angles on burr height experimentally and numerically in a normal shearing process. However, there are still few research works on experimental and numerically examination in a complete slitting.

2.4.3 Shear-slitting in Finite Elements Modeling

In recent trend of requirements for clarification of characteristic of slitting would become important. (Tanaka A., 2008) proposed a new shearing method where the cutting tool moves in horizontal direction to realize flexible cutting lines. This proved that shear-slitting method is one of good cutting process and also can be applied to FEM simulation to understand the flow stress of workpiece. An analysis model to simplify the shearing and blanking process was developed. Based on the simplified model, the shearing process was simulated by FEM and analyzed for various clearances. (Kazutoshi T., 1980-9), by shearing process during calculation of FEM simulation, friction between tool/chip is neglected. An optimum clearance in the process was determined by new approach based on orientation of the maximum shearing stress on the characteristics line linking two blades, according to the law of crack propagation and experiments (Qin S., 2003). (Shanshank A., 2005), a three-dimensional model of the slitting process had been conducted to study the effect of blade and web parameters.

(A. Rusinek, 2001), studied about shear testing of a sheet steel at wide range of strain rates and a constitutive relation with strain rates and temperature dependence of the flow stress. They involve two major contributions, one in the industrial filed by bringing a method capable of simulating the visco-plastic behavior of mild steels and more exactly sheet metals. Very wide ranges of strain rates and temperatures are possible. On the other hand, application of new experimental and technique made it possible to study the low and high strain rates in order to develop a visco-plastic constitutive relations. The constants of the material entering into the proposed constitutive relation can be identified quite easily and precisely in order to describe the visco-plasticity for wide range of strain rates and temperatures.

The standard composition of slitting process is exaggeratedly shown in figure 2.11. This image is built up by a pre-processor of a commercial code of the finite element method by enlarging the ratio of the blade diameter to the workpiece so that the processing would be easily understood. A pair of cylindrical roll-shaped blade rotates
around axes at a certain distance $S$. Overlap $L_P$ between the two blades are adjusted by controlling the distance $S$. The two blades are places with clearance $C_L$ in the width direction. Overlap $L_P$ and clearance $C_L$ are the main parameters in process. Lower and upper fingers clamp split workpiece with upper and lower blades in actual operation lines. However, these fingers were not used in the present study so that the workpiece might be cut partway easily for observation.

Many numerical solutions and techniques have appeared in the last decade following the great surge of interest in crack problems (George C. S., 1973). (Kazutake M., 1997-2) studied to clarify ductile fracture phenomena in bulk metal forming by analyses and experiments. They developed a computer based on a conventional computer program of FEM by which behavior of crack propagation after ductile facture can be analyzed. The phenomenon that a material is divided into two by shearing has been simulated by the program . (Yoshinori, 2003-7), performed the deformation of shearing analysis involving crack nucleation and propagation. Regarding previous researchers achievement, it proved that material deformation of shear-slitting method can be identified using FEM simulation.

![Exaggerated image of slitting process](image_url)

Figure 2.11 Exaggerated image of slitting process
2.5 Punching Model

2.5.1 Punching process

The punching process can be considered to include a series of phases in which the sheet metal undergoes deformation and separation, as seen in Figure 2.12.

Contact of the punch: The punch first touches the fixed sheet. At impact, a compressive stress rapidly builds on the punch and sends a shock wave through it.

Elastic and plastic deformation: The punch penetrates into the sheet, first causing an elastic and then plastic deformation.

Shearing and crack formation: When the stresses increase, shearing occurs followed by fracture. Fracture begins from both the punch end and die end of the sheet. They usually meet and complete fracture of the material takes place.

Breakthrough: If the sheet material has a high strength or is thick, a large force is required for the blanking process. During shear and fracture, compressive forces are stored in the tool. When complete fracture occurs, there is an instant release of these compressive forces. These generate shock which can lead to breakage of the punch in some cases.

Stripping: The punch moves down to the bottom dead center and ejects the part / slug. At the bottom dead center, the direction of punch motion is reversed. There is friction between the stock and the surface of the punch, which causes the sheet to lift along with the punch. A stripper or blank holder strips the blank from the punch.

Figure 2.12 Phases of punching process (Schuler Handbook, 1998)

High speed blanking simulations require flow stress data of materials at very high
strains (~3) and strain rates (up to $10^5$). Currently, materials are not tested to very high strains and strain rates at the same time. Tensile tests can be conducted for very high strain rates, however necking starts to occur at strains much lower than 1, especially at high strain rates. Torsion tests are available, but they do not reach high strains of ~3 either. Hence, material models with extrapolated data are used in modeling the material for simulations. The accuracy of material data and hence the accuracy of simulations at higher strains and strain rates is unknown. (C. Husson) applied finite elements simulations of thin copper sheet punching: Study of punching parameters on sheared edge quality. The finite elements simulations have been used to assess the influence of pinch-die clearance as well as the influence of tool wear and friction on sheared edge quality.

2.5.2 Effect of punch-die clearance

In general, as the clearance between punch and die increases, the roll over zone, fracture zone, fracture angle and burr increase while the shear zone decreases. Insufficient clearance produces secondary shear i.e the cracks originating at the punch and die do not meet. Hence, a ring of material is further stressed to its shear limit, expending more energy. Excessive clearance causes large plastic deformation, large burr and high fracture angle. Furthermore, tool life also lowered by improper clearance. There are studies which have studied the effect of punch-die clearance on part edge quality and punch life. (Qin S., 2003) simplified a model on shearing process. A new technique is developed, by which reasonable optimizing clearance can be obtained accurately without determining initial crack position. (C. Husson, 2008) conducted punching simulations of copper alloy of sheet thickness 0.58mm and compared it with experimental results. The effect of punch-die clearance on the part edge quality was studied in the range of 15 $\mu$m (2.5%) to 11 $\mu$m (19%) during punching of 3.5mm diameter holes. From the FEM simulations, it was found that rollover and shear edge increase and fractured edge decrease with increase in punching clearance as shown in Figure 2.13.
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Figure 2.13 Effect of punching clearance on part edge as predicted with finite element simulations on 0.58 mm.

The fracture angle increase significantly with clearance. (Wiedenmann R., 2009) conducted punching studies on DP590, 1.4 mm thickness. The effect of clearances on part edge quality in the range 5%-20% was studied during punching of 10 mm diameter holes. Roll over and fracture increase with clearance while the shear zone decreases with clearance. All the studies have shown consistently similar result for the effect of punch-die clearance on punching edge quality and punch wear.

2.5.3 Effect of punch corner radius

The effect of punch corner radius and punch-die clearance on punch stress was studied by (Picas I., 2010) experimentally. Blank material used was DP1000, 2 mm thickness. Punch material was a cast steel (D2) tempered and hardened to 60-62 HRC. The simulations indicated that the effect of punch corner radius on Von Mises stresses generated in the punch is more dominant than effect of clearance. The maximum stresses in the punch show a decrease of 500 MPa when the corner radius is increased from 10% to 20% (Figure 2.14).
Figure 2.14 Maximum Von Mises stress shown for 10%, 15% and 20%

Figure 2.15 shows the punching load does not change significantly with change in corner radius. Experiment reveal that the punch ran for only a few hundred strokes before showing the first signs of wear and 3000 strokes before fracture with the 0.01 mm corner radius. The punch with 0.1 mm corner radius ran for 15000 strokes without showing any signs of damage. 30000 strokes showed some wear and edge chipping.

Figure 2.15 Experimental load-displacement diagrams at the corner radius 0.1mm and 0.01mm (Picas I., 2010)
2.6 Summary

Finite element simulation of orthogonal cutting is become very popular nowadays and there are many research were conducted on this subject. A lot of work has been carried out to developed successful models of orthogonal cutting process. A better understanding of friction modelling is required in order to produce more realistic finite element models of machining processes to support the goals of longer tool life and better surface quality. The FEM is more accurate due to ability to incorporate more realistic assumptions of material behavior and the influence of friction. Therefore, this work is intended to upgrade the optimization of material flow stress and friction characteristics during cutting process of FEM simulation. After that, is to propose a new method that can solve the problems during cutting process of FEM simulation.
CHAPTER 3

IDENTIFICATION OF JOHNSON-COOK FLOW STRESS MODEL ON HIGH-SPEED ORTHOGONAL CUTTING PROCESS

High-speed orthogonal cutting experiments were conducted to evaluate the performance of different cutting speed, feed rate and rake angle of cutting tool. In this chapter, identification flow stress of workpiece on high-speed orthogonal cutting are presented. Then, method to identify of Johnson-Cook flow stress model on high-speed orthogonal cutting process also presented.

3.1 High-speed Orthogonal Cutting Process (Model A)

3.1.1 Experimental Setup

High-speed orthogonal cutting tests were performed using TECHNOWASHINO-C5 (Figure 3.1). Model A was using side facing bits as shown in figure 3.2. Cemented carbide bits (Sumitomo 33-3 ST30E) was used as a cutting tool for model A and inserted to the jig. Figure 3.2 shows facing bits been prepared with three different rake angle. The workpiece material 0.45% carbon steel (S45C) was chucked to machine. Model A were conducted on the workpiece prepared as shown in figure 3.3 with a diameter 99 mm and width of cutting was 3 mm. The jig was mounted on multicomponent dynamometer (Kistler 9257B) as shown in Figure3.4. The dynamometer was connected to the charge amplifier and data logger system (Keyence N600) to measure the cutting force as shown in figure 3.5. In this experiment, the cutting speed and rate for type A cutting process is shown in Table 3.1. The range of cutting speed and speed rate was choosen depends on low, middle and high. It is because to make sure that the cutting conditions can cover wide range of different high
strain rate.

Figure 3.1 Lathe machine for the experiment

Figure 3.2 Side facing bits for type A cutting process
Figure 3.3 Prepared material (S45C) for type A cutting process

Figure 3.4 Tools and dynamometer fixing method
Figure 3.5 Connection diagram

Table 3.1 Cutting conditions for model A cutting process

<table>
<thead>
<tr>
<th>2D Cutting</th>
<th>Material</th>
<th>Rake angle</th>
<th>Width of cut mm</th>
<th>Cutting speed m/min</th>
<th>Feed rate mm/rev</th>
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<tbody>
<tr>
<td>1</td>
<td></td>
<td>0</td>
<td>3.0</td>
<td>100</td>
<td>0.10</td>
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<tr>
<td>2</td>
<td></td>
<td>0</td>
<td>3.0</td>
<td>100</td>
<td>0.25</td>
</tr>
<tr>
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<td></td>
<td>0</td>
<td>3.0</td>
<td>200</td>
<td>0.10</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>0</td>
<td>3.0</td>
<td>200</td>
<td>0.25</td>
</tr>
<tr>
<td>5</td>
<td>S45C</td>
<td>10</td>
<td>3.0</td>
<td>100</td>
<td>0.10</td>
</tr>
<tr>
<td>6</td>
<td>S45C</td>
<td>10</td>
<td>3.0</td>
<td>100</td>
<td>0.25</td>
</tr>
<tr>
<td>7</td>
<td>S45C</td>
<td>10</td>
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<tr>
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<tr>
<td>12</td>
<td>S45C</td>
<td>20</td>
<td>3.0</td>
<td>200</td>
<td>0.25</td>
</tr>
</tbody>
</table>
3.1.2 Results and Discussions

As results from the high-speed orthogonal cutting, cutting forces (principal force, thrust force), chip thickness and tool-chip contact length were evaluated. Those results are average results. Figure 3.6 and figure 3.7 shown principal forces results when cutting speed was 100m/min and 200m/min for model A of cutting process. As the rake angle of tool cutting increase, the principal forces decrease respectively.

Figure 3.6 Result for principal force at cutting speed 100m/min

Figure 3.7 Result for principal force at cutting speed 200m/min
Figure 3.8 and figure 3.9 shown thrust forces results when cutting speed was 100m/min and 200m/min for modal A of cutting process. As same as principal forces, for thrust force with different cutting speed, the patter of graph is the same. As rake angle of cutting tool increase, the principal forces decrease respectively.

![Figure 3.8 Result for thrust force at cutting speed 100m/min](image)

![Figure 3.9 Result for thrust force at cutting speed 200m/min](image)
Chip thickness was also evaluated. Chip thickness was measured by using micrometer. Figure 3.10 shows the example of chip formation for cutting parameters rake face: 0deg, feed rate: 0.1 mm/rev and cutting speed: 100 m/min. Figure 3.11 and 3.12 show that as rake angle of tool cutting increase, the chip thickness decrease, respectively.

![Chip formation](image)

Figure 3.10 Chip formation

![Chip thicknesses against rake angle](image)

Figure 3.11 Chip thicknesses against rake angle at cutting speed 100m/min
Figure 3.12 Chip thicknesses against rake angle at cutting speed 200m/min

Next, is tool-chip contact length result. The tool-chip contact length was observe by using a microscope at the tool cutting edge. The average values of part that was abrasion and not was considered. In order to make it easy to understand, a color pen were applied to the tool cutting edge. Figure 3.13 show the example of tool cutting edge that been applied with pen color.

Figure 3.13 Tool cutting edge with color
Figure 3.14 and 3.15 show results for tool-chip contact length at different cutting speed. Both figures show that as rake angle of tool cutting increase, the tool-chip contact length decrease, respectively.

**Figure 3.14 Result for tool-chip contact length at cutting speed 100m/min**

**Figure 3.15 Result for tool-chip contact length at cutting speed 200m/min**
Figure 3.16 and 3.17 show results for shear angle at different cutting speed. Both figures show that as rake angle of tool cutting increase, the shear angle increase, respectively.

![Figure 3.16 Shear angle against rake angle at cutting speed 100m/min](image1)

![Figure 3.15 Shear angle against rake angle at cutting speed 200m/min](image2)
Chapter 3  Identification of Johnson-Cook Flow Stress Model on High-speed Orthogonal Cutting Process

3.2 Two-Dimensional Finite Element Modeling Setup

3.2.1 Johnson-Cook Model

In this study, we applied Johnson-Cook Model (JC model) to understand the material characteristics of flow stress during cutting process. The JC model has the following form:

\[
\sigma = (A + B\varepsilon^n)(1 + C\ln\dot{\varepsilon})(1 - T^m)
\]

where \( T^* = \frac{T - T_{room}}{T_{melt} - T_{room}} \) (Rafal, 2005)

The five material constants A, B, C, m and n are fit to data collected for a particular material. The first expression in equation (3.1) represents the work hardening response of the material at the reference strain rate, while the second and third expressions account for the strain rate and temperature sensitivity, respectively. This model is easily implemented in computational codes due to its simplicity. All the parameters are coupled due to the multiplicative nature of the model. Furthermore this model assumes that strain rate and temperature sensitivity are independent of each other, while real materials display a strain rate sensitivity which is dependent upon temperature.

Compression test was carried out to identify the A, B and n value of flow stress parameters. The material used for testing purpose was S45C and size was \( \phi 10\text{mm} \), length was 15mm. The speed of compression test was 0.1 mm/sec. As a result of compression test for S45C following parameters were obtained; A: 343.4602, B: 640.3234 and n: 0.2926. Figure 1 shows the flow stress at room temperature and low strain rate. Those values were then applied for JC model for FEM simulation.
At the beginning, to run all simulation, an initial value of $C$ and $m$ concerning strain rate and temperature value of JC model was 0.01 and 1.0. Those values were chosen arbitrary (C. Z. Duan, 2011). Thus, the $T_{\text{room}} = 20^\circ\text{C}$ , $T_{\text{melt}} = 1600^\circ\text{C}$ was also applied.

### 3.2.2 Overview of DEFORM

DEFORM is a Finite Element Method (FEM) based process simulation system designed to analyze various forming and heat treatment processes used by metal forming and related industries. By simulating manufacturing processes on a computer, this advanced tool allows designers and engineers to:

1. Reduce the need for costly shop floor trials and redesign of tooling and processes.
2. Improve tool and die design to reduce production and material costs.
3. Shorten lead time in bringing a new product to market.
Unlike general purpose FEM codes, DEFORM is tailored for deformation modeling. A user friendly graphical user interface (GUI) provides easy data preparation and analysis so engineers can focus on forming, not on learning a cumbersome computer system. An essential component of this is a fully automatic, optimized remeshing system tailored for large deformation problems. DEFORM-HT adds the capability of modeling heat treatment processes, including normalizing, annealing, quenching, tempering, aging, and carburizing. DEFORM-HT can predict hardness, residual stresses, quench deformation, and other mechanical and material characteristics important to those that heat treat.

In this study, we applied DEFORM because it provided many material characteristics in material library. It is very important element in this study since we need to identify the flow stress of material characteristics under high strain rate. The interface to set material characteristics for S45C of JC model in pre-process is as shown in figure 3.17.

![Figure 3.17 Interface inside DEFORM to set material characteristics](image)

### 3.2.3 Boundary Conditions Setup

The parameters configuration of the two-dimensional cutting simulation is shown in table 3.2. FEM simulation was run for twelve sets of simulation for different cutting conditions as shown in Table 3.1 same as cutting condition applied in high-speed orthogonal cutting test. FEM simulation studies, commercial available software, DEFORM™ V10.1 was used. Figure 3.18, figure 3.19 and figure 3.20 show the boundary conditions setup using DEFORM 2D which is important boundary condition need to be setup before running the simulation. Those figures are cutting condition for rake angle: 0°, cutting speed: 100m/min and feed rate: 0.25 mm/rev. Figure 3.21 shows
the ratio mesh window size for workpiece and set up for friction characteristics between tool/chip formations.

Table 3.2 Simulation conditions

<table>
<thead>
<tr>
<th>Object type</th>
<th>Workpiece</th>
<th>Plastic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool</td>
<td>Rigid</td>
<td></td>
</tr>
<tr>
<td>Workpiece material</td>
<td>S45C(JC model)</td>
<td></td>
</tr>
<tr>
<td>Yield function type</td>
<td>Von Mises</td>
<td></td>
</tr>
<tr>
<td>Hardening rule</td>
<td>°C</td>
<td>Isotropic</td>
</tr>
<tr>
<td>Workpiece length</td>
<td>mm</td>
<td>2</td>
</tr>
<tr>
<td>Workpiece thickness</td>
<td>mm</td>
<td>0.6</td>
</tr>
<tr>
<td>Temperature</td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>W/(m²·°C)</td>
<td>59</td>
</tr>
<tr>
<td>Heat capacity</td>
<td>MJ/(m³·°C)</td>
<td>15</td>
</tr>
<tr>
<td>Edge radius</td>
<td>mm</td>
<td>actual value</td>
</tr>
</tbody>
</table>

Figure 3.18 Boundary conditions setup for velocity
Figure 3.19 Boundary conditions setup for thermal

Figure 3.20 Boundary conditions setup for temperature
Chapter 3  Identification of Johnson-Cook Flow Stress Model on High-speed Orthogonal Cutting Process

Figure 3.21 Boundary conditions setup for mesh

Every twelve set of simulations, boundary condition setup for velocity, thermal and temperature need to be setup. As shown in figure 3.18 boundary condition setup for velocity need to be setup for X-axis and Y-axis. As for the example of this cutting condition which cutting speed: 100m/min, X-axis = 1666.66 mm/sec, Y-axis = 0 mm/sec (fixed) was applied. Figure 3.19 is the interface to setup the heat exchange with the environment for thermal. Figure 3.20 shows the interface to setup boundary conditions for temperature. For every cutting conditions, the workpiece is setup to 20°C. Figure 3.21 shows the mesh windows that been setup for the simulation. Every cutting condition was setup with three size of mesh window. Every mesh window has different size of mesh which was set automatically once we set the mesh window size in the interface. The average size of relative element size of mesh for different mesh window is 0.05mm, 0.1mm and 1mm. The smallest size of mesh was set near to tool/workpiece or cutting area. The biggest size of mesh was set at the area that the cutting process is not conducted in the workpiece. This method was applied because to cut the time consuming during the unsteady state simulation and steady state simulation. When, the value of velocity error, force error and average strain rate are not satisfied than the specific/input user value, the remeshing process will start automatically to separate a tool cutting edge along the cutting process. In the same figure shows the area that friction characteristics had been setup. The heat transfer coefficient was set at 100000
Friction work and plastic work is the heat source. Next, after boundary condition had been setup is to run the FEM simulation. This method, repeated the unsteady state simulation and steady state simulation for two times.

### 3.2.3 Unsteady state simulation

Cutting conditions for the simulation were same as those in the orthogonal cutting tests and the total number of simulation set were twelve. Unsteady state simulation and steady state simulation were conducted before the optimization of parameters $C$ and $m$. During the unsteady state simulation the deformation process and temperature distributions were obtained. This calculation was more similar to real machining process, and strain distribution, strain rate distribution and chip formation were obtained. However, unsteady state simulation was time consuming to simulate and require long cutting process to reach steady state temperature field. To reduce the calculation time, when chip deformation had formed after several millimeters were cut and material deformation was closer to steady state, the following steady state simulation was conducted.

### 3.2.4 Steady state simulation

During steady state simulation, not only temperature field but also strain rate, nodal velocity, nodal force was calculated. Heat source was plastic deformation and frictional work on tool rake face. As a result, steady state temperature distribution, strain rate and temperature distributions can be obtained. Figure 3.22 shows temperature distribution where rake angle: 0°, cutting speed: 100m/min and feed rate: 0.1mm/rev. The left side of figure 3.22(a) shows the result of the unsteady state simulation and the right side of figure 3.22(b) shows steady state simulation. As it can be seen from figure 3.22(a), after 2~3 millimeters of material were cut, only temperature near/around to chip deformation area was high. In contrast, it can be observed from figure 3.22(b) that temperature was high near/around chip deformation and inside edge of tool area. As a result, cutting forces, strain rate and temperature distributions had been obtained. Then, the unsteady state simulation and steady state simulation was repeated again in order to identify result more nearer to the extual orthogonal cutting experiment.
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Figure 3.22 Temperature distribution in cutting simulation

(a) Unsteady state simulation  (b) Steady state simulation

After that, from the steady state simulation where strain rate and temperature distributions were obtained, only six sets of simulation were chosen to identify the parameters $C$ and $m$ using inverse calculation method among the twelve sets of simulation. Cutting conditions for the optimization process were chosen considering strain rate and temperature. To achieve higher optimization accuracy, it is better that the input data has wide range of strain rate and temperature. Therefore, from the twelve sets of cutting conditions, simulation results which shows maximum strain rate (1), minimum strain rate (2) and middle strain rate (3) were chosen for the optimization. Strain rate is largely dependent on the rake angle, cutting speed and depth of cut. In the same way, simulation results which shows maximum temperature (4), minimum temperature (5) and middle temperature (6) were chosen for the optimization. Figure 3.23 and figure 3.24 show the result of strain rate and temperature by point for twelve set of simulations. As shown in figure 3.25 and figure 3.26 show the parameters that been chosen for the optimization of strain rate and temperature using inverse calculation method. Table 3.3 the summarize of cutting condition number that been choosen for optimization.
Figure 3.23 Strain rates distributions for twelve set of simulation

Figure 3.24 Temperatures distributions for twelve set of simulation
Figure 3.25 Selected strain rate distributions for optimization of flow stress

Figure 3.26 Selected temperatures distributions for optimization of flow stress
3.3 Inverse Calculation Method and Results

3.3.1 DownHill Simplex Method

To identify $C$ and $m$ material constants for JC model, we applied DownHill Simplex Method. The Downhill Simplex Method is a commonly applied numerical method used to find the minimum or maximum of an objective function in a many dimensional space. It is applied to nonlinear optimization problems for which derivatives may not be known. (R.John Koshel, 2002) discussed this method of optimization. It also stated that the simplex method in $N$ dimensions uses $N+1$ points within the merit space to define the simplex. Selection of these points can be prescribed, but random selection allows the potential to fully investigate the merit space. The function values are found at each of these points. The points with the low ($P_L$), high ($P_1$), and second high ($P_2$) function values are determined. Next, the centroid of the points except $P_1$, $\bar{P}$, is determined. The simplex method essentially has four steps possible during each iteration: reflection, contraction in one dimension, contraction around the low vertex, and expansion. The basis for each step is provided here:

(1) Reflection: A reflected point, $P_R$, is found by reflecting $P_1$ through $\bar{P}$ with the equation

$$P_R = (1+\alpha) \bar{P} - \alpha P_1$$

(3.2)

where $\alpha$ is the reflection factor ($\alpha = 1$). $P_R$ replaces $P_1$ if $f(P_L) < f(P_R) < f(P_1)$.

Table 3.3 Cutting condition for optimization of Johnson-Cook flow stress model by inverse calculation method

<table>
<thead>
<tr>
<th>Trials</th>
<th>Rake angle [°]</th>
<th>Width of cut [mm]</th>
<th>Feed rate [mm/rev]</th>
<th>Cutting speed [m/min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>3.0</td>
<td>0.10</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
<td>3.0</td>
<td>0.25</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>3.0</td>
<td>0.10</td>
<td>200</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>3.0</td>
<td>0.25</td>
<td>100</td>
</tr>
<tr>
<td>11</td>
<td>20</td>
<td>3.0</td>
<td>0.10</td>
<td>200</td>
</tr>
</tbody>
</table>
(2) Expansion: if \( f(P_R) < f(P_L) \) then the simplex grows along the centroid direction with the hope that the expansion point, \( P_E \), is better than \( P_L \). The expansion is determined with the equation
\[
P_E = (1 - \gamma) \bar{P} + \gamma P_R
\]
where \( \gamma \) is the expansion factor (\( \gamma = 2 \)). \( P_E \) replaces \( P_1 \) if \( f(P_E) < f(P_L) \).

(3) 1D Contraction: if \( f(P_R) > f(P_2) \) then the simplex contracts along the centroid direction with the hope that the contracted point, \( P_C \), is better than \( P_2 \). The 1D contraction is determined with the equation
\[
P_C = (1 - \beta_1) \bar{P} + \beta_1 P_0
\]
where \( \beta_1 \) is the 1D contraction factor (\( \beta_1 = 0.5 \)) and \( P_0 \) is the selection of \( P_1 \) or \( P_R \) which has the lowest function value. \( P_C \) replaces \( P_1 \) if \( f(P_C) < f(P_0) \).

(4) Full contraction: if \( f(P_C) > f(P_0) \) then 1D contraction does not suffice, and the whole simplex is contracted around \( P_L \). The full contraction is determined with the equation
\[
P_i = (1 - \beta_2) P_L + \beta_2 P_i
\]
where \( \beta_2 \) is the full contraction factor (\( \beta_2 = 0.5 \)) and \( P_i \) represents all the points except \( P_L \).

Typically, when a point replaces \( P_1 \) the current iteration is completed. Next the termination condition is checked. If the tolerance is not met then the next iteration is started. If the tolerance is met, then the optimization is done. In this study, the functions and subroutines are FORTAN’s subprograms. The objective functions is cutting force curve. Therefore using the DownHill Simplex Method, \( C \) and \( m \) value was run freely and was repeated for 60 times. Among those repeated times value that give the minimum different between principal force from experiment result and FEM simulation were chosen for identified \( C \) and \( m \) value.

### 3.3.2 Inverse Calculation Method

Figure 3.27 illustrates the flow chart showing optimization of flow stress parameters \( C \) and \( m \). If the initial values of \( C \) and \( m \) apart from the optimized values, computation time will increase and it may be unable to find the optimal value. It will become more difficult if it was going to find the parameters \( C \) and \( m \) simultaneously at the same time.
To evaluate the parameter $C$, three sets of simulation were run. Cutting conditions (1), (2) and (3) were applied. When applied the three sets of simulation, the value of $C$ and the error value of the force at that time were an output result of the process in which the optimal value was looked by using *DownHill Simplex Method* applied in subroutine. Objective value of the optimization was the principal force of orthogonal cutting. We decide to optimize only the principal force of orthogonal cutting because during cutting process only principal force that give major effect for the energy during cutting. While, the effect of thrust for that create energy during cutting process is minor. Then, using the first evaluation value of $C$, the parameter $m$ was identified. Another three set of simulation were run. Cutting conditions (4), (5) and (6) were used. The method to identify parameter $m$ was similar to the one discussed in parameter $C$. Next, $C$ and $m$ were optimized simultaneously. Using the first evaluated value of $C$ and $m$ as the start value of the optimization, this time all the six sets of simulation with cutting conditions (1), (2), (3), (4), (5) and (6) were run together. Down Hill method is also applied to optimization $C$ and $m$ simultaneously. Finally, the cutting simulation again conducted for six sets of cutting conditions (1), (2), (3), (4), (5) and (6) using the optimized value of $C$ and $m$. The result applied of optimized value of $C$ and $m$ were compared with the experimental results. In this study, we managed to gain result for principal force and thrust force after the optimization of $C$ and $m$. Five sets of cutting conditions used for optimization of $C$ and $m$ are shown in Table 3.3.

![Flow charts of inverse calculation setting method](image.png)

**Figure 3.27** Flow charts of inverse calculation setting method

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Generally, strain rate is influenced largely by cutting speed and depth of cut of orthogonal cutting test. Moreover, temperature is correlated to rake angle and cutting speed (J. Paulo Davim, 2008). The optimization of $C$ concerning the strain rate, parameters number 1, 2 and 3 were chosen, and for the optimization of $m$ concerning temperature, parameters number 1, 6 and 11 were chosen.

3.3.3 Results

For parameter $C$, the initial value was 0.01 and first optimized value was $6.565938 \times 10^{-3}$. In addition, for parameter $m$, the initial value was 1.0 and first optimized value was 1.261195. Then, both $C$ and $m$ were optimized simultaneously. Figure 3.30 shows the variation of optimization parameters of $C$ and $m$ value. It can be seen from the figure that optimization starting from initial value and end at optimized value where $C$: $2.428813 \times 10^{-3}$ and $m$: 1.248193. Figure 3.28 shows the result for optimization of first $C$ value, $m$ with intial value. Figure 3.29 shows the result for optimization of first $m$ value, $C$ with first optimized value. Figure 3.30 show the result for optimization of $C$ and $m$ value, $C$ and $m$ with first optimized value. Figure 3.31 show the result of the optimization value to check wheater the optimization value was correct or incorrect. This checked wheater the identified value is correct or incorrect, we need to make a graph to observe that the loop to identified value is succefficient or not.

![Figure 3.28 Shows the result for optimization of first C value, m with intial value](image-url)
Figure 3.29 Shows the result for optimization of first $m$ value, $C$ with first optimized value.

Figure 3.30 Variation of $C$ and $m$ during optimization process.

Figure 3.31 Result from the optimization of $C$, $m$ value.
3.4 Simulations Results of Two-dimensional Cutting Process

3.4.1 FEM Prediction of Cutting Forces

Figure 3.32 and figure 3.33 show the cutting force after the optimization of the parameters $C$ and $m$. The predicted principal forces were within 6.3% error of experiment (average) values as shown in figure 3.32. Meanwhile, figure 3.33 shows that the predicted thrust forces were considerably low, approximately 50% lower than the experimental values.

![Figure 3.32 Final result of principal force](image1)

![Figure 3.33 Final result of thrust force](image2)
3.4.2 FEM Prediction of Chip Thickness and Tool/Chip Contact Length

In the simulation, the tool-chip contact length was calculated by showing the contact node in FEM simulation for example as shown in figure 3.34. Figure 3.35 and figure 3.36 show the chip thickness and tool-chip contact length after the optimization of the parameters $C$ and $m$.

Figure 3.34 Show contact node during FEM simulation

The predicted chip thickness was within 20% error of experiment (average) values as shown in figure 3.34 and figure 3.35 shows that the predicted tool-chip contact length was approximately 10% lower than the experimental values.
From figure 3.32 to figure 3.36 show the final result after the optimization of workpiece flow stress. Principal forces, chip thickness and tool/chip contact length the error was within 20% error of experiment (average) values. However, predicted thrust forces were considerably low, approximately 40% lower than the experimental values. This underestimation of predicted with large errors of thrust force is already highlighted by many researchers (Filice L., 2007) (Klocke, 2013). DEFORM itself has already attributed to the reduce number of element in the secondary shear zone (numerical issues) (User’s manual, 2012).
3.5 Summary

This chapter detailed the experimental procedure used to address the goals of this research and the process used to identify flow stress of workpiece during cutting process. Finite element approach is used to study the effect of machining conditions on cutting forces, strains, strain rates and temperatures distribution. A commercially available software code (DEFROM 2D) is used to accomplish the task. The simulation is carried out as same as high-speed orthogonal cutting conditions. Final result from this method showed that the principal forces and chip thickness compared with the experimental results and are a good agreement. However, result for the thrust force and tool/chip contact length are still not satisfaction. The following chapter will provide methods and results for improvement of this method.
CHAPTER 4

IMPROVEMENT OF IDENTIFICATION ACCURACY OF JOHNSON-COOK FLOW STRESS MODEL ON CUTTING PROCESS

High-speed orthogonal cutting experiments were conducted to evaluate the performance of different cutting speed, feed rate and rake angle of tool surfaces. In this chapter, the experiments designed for evaluating the influence of cutting parameters on cutting forces, temperature and tool related performance are presented with different method. Method to improve current method to identify Johnson-Cook flow stress model during cutting process also presented.

4.1 High-speed Orthogonal Cutting Process (Model B)

4.1.1 Experimental Setup

High-speed orthogonal cutting tests were performed using TECHNOWASHINO-C5 (Figure 4.1). Model B was using cut off bits (Figure 4.2). Model B were conducted on the workpiece with a diameter 99 mm and width of cutting was 3 mm as shown in figure 4.3. Cemented carbide bits (Sanwa Brazed Tools 20-3P20) was used as a cutting tool for model B and inserted to the jig. The jig was mounted on multicomponent dynamometer (Kistler 9257B) as shown in Figure 4.4. The dynamometer was connected to the charge amplifier and data logger system (Keyence N600) to measure the cutting force as shown in figure 4.5.

In this experiment, the cutting speed and rate for cutting condition for model B cutting process are shown in Table 4.1.
Chapter 4  Improvement of Identification Accuracy of Johnson-Cook Flow Stress Model on Cutting Process

Figure 4.1 TECHNOWASHINO-C5 lathe machine

Figure 4.2 Cut off bits for model B cutting process
Figure 4.3 Prepared material (S45C) for model B cutting process

Figure 4.4 Tools and dynamometer fixing method
Chapter 4  Improvement of Identification Accuracy of Johnson-Cook Flow Stress Model on Cutting Process

Figure 4.5 Connection diagram

Table 4.1 Cutting conditions for model B cutting process

<table>
<thead>
<tr>
<th>2D Cutting</th>
<th>Material</th>
<th>Rake angle</th>
<th>Width of cut mm</th>
<th>Cutting speed m/min</th>
<th>Feed rate mm/rev</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>0</td>
<td>3.0</td>
<td>100</td>
<td>0.10</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>0</td>
<td>3.0</td>
<td>100</td>
<td>0.25</td>
</tr>
<tr>
<td>3</td>
<td>S45C</td>
<td>0</td>
<td>3.0</td>
<td>200</td>
<td>0.10</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>10</td>
<td>3.0</td>
<td>100</td>
<td>0.25</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>20</td>
<td>3.0</td>
<td>200</td>
<td>0.10</td>
</tr>
</tbody>
</table>
4.1.2 Results and Discussions

As results from the high-speed orthogonal cutting, cutting forces (principal force, thrust force), chip thickness and tool-chip contact length were evaluated. Those results are compared with model A. Figure 4.6 and figure 4.7 show result comparison between model A and model B of cutting forces.

Figure 4.6 Principal forces result for model B

Figure 4.7 Thrust forces result for model B
Figure 4.8 and figure 4.9 show result comparison between model A and model B of chip thickness and tool/chip contact length. From figure 4.6 to figure 4.8 shows that result for cutting forces and chip thickness were lower for model B of orthogonal cutting process. As results, model B of orthogonal cutting process were used for the comparison of principal force in inverse calculation method.

Figure 4.8 Chip thickness result for model B

Figure 4.9 Tool/chip contact length result for model B
4.2 Improvement of Finite Element Method Setup

4.2.1 Effect of Unsteady State and Steady State Simulation

Figure 4.10 and figure 4.11 shows the graph of principal forces and thrust forces when unsteady state simulation and steady state simulation were repeated more than three times. As shown from those figure when the unsteady state simulation and steady state simulation were repeated the cutting force is getting steady.

Figure 4.10 Principal forces for repeated unsteady state and steady state simulations more than two times

Figure 4.11 Thrust forces for repeated unsteady state and steady state simulations more than two times
From both figures shows that to get stable FEM calculation the unsteady state simulation and steady state simulation need to be repeated more than two times. However, there was no big different of cutting forces comparing the average result between two times and three times repeated of unsteady state simulation and steady state simulation.

### 4.2.2 Effect of Mesh Average Length

Figure 4.12 shows an example of mesh average length. Figure 4.13 shows the graph of principal forces and thrust forces with different mesh average length.

![Mesh Average Length Example](image)

Figure 4.12 Show an example of mesh average length between tool/chip deformations

From figure 4.13 shows that there were no big different between principal forces and thrust forces with different mesh average length. This indicated that the proper mesh average length is between 0.057mm. Which mean that the total mesh number of workpiece is between 2500 to 3000.
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Figure 4.13 Result of cutting forces effect on different mesh average length

4.2.3 Effect of Cutting Tool Roundness

Figure 4.14 shows an example of cutting condition number 11 from Table 1. Effect of cutting tool roundness been studied using this cutting condition. In previous method, this effect was neglected. (Okuyama, 2013) stated that general cutting tool roundness is around 24~26 $\mu$m. Figure 4.15 shows the result of cutting condition number 11 with different cutting tool roundness for, $r$: 0.01, 0.02 and 0.03 mm. From figure 4.15 shown that as the cutting tool roundness increase, the cutting forces also increase respectively. Regarding this result, cutting tool roundness geometry for FEM simulation was same as the measured bits used in orthogonal cutting process. The cutting tool roundness was measured by laser microscope.
Figure 4.14 Cutting tool roundness geometry in FEM simulation

Figure 4.15 shows the result of cutting condition number 11 with different cutting tool roundness
4.2.4 Effect of Rake Angle and Clearance Angle Cutting Tool

Figure 4.16 shows an example of cutting condition number 6 from Table 1. Effect of rake angle and clearance angle cutting tool studied using this cutting condition. In previous method, this effect was neglected. Figure 4.17 and 4.18 shows that the cutting forces increased, when the rake angle and clearance angle increased, respectively. However, from figure 4.17 for cutting forces when rake angle is 11 degree the result was not satisfaction. This is can be solve if the same calculation with same cutting condition was conducted again. From both result shows that as the rake angle and clearance angle getting bigger, the cutting force will increase. Therefore, the measured value by laser microscope was applied for rake angle and clearance angle during FEM simulation.

Figure 4.16 Cutting tool rake and clearance geometry in FEM simulation
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Figure 4.17 Rake angle effects on cutting forces

Figure 4.18 Clearance angle effects on cutting forces
4.3 Inverse Calculation Method and Results

Considering the effect of finite simulation setup discussed above, next approach was conducted for six of simulation parameters selected in Table 1. Next, was to identify $C$ and $m$ of Johnson-Cook flow stress model. For parameter $C$, the initial value was 0.01 and first optimized value was $3.506256 \times 10^{-3}$. In addition, for parameter $m$, the initial value was 1.0 and first optimized value was 1.029063. Then, both $C$ and $m$ were optimized simultaneously. Figure 5 shows the variation of optimization parameters of $C$ and $m$ value. It can be seen from the figure that optimization starting from initial value and end at optimized value where $C$: $3.506256 \times 10^{-3}$ and $m$: 1.076562.

4.4 Identification of Friction Characteristics

Next after the optimization to identify $C$ and $m$ of Johnson-Cook flow stress model was conducted. In this study, friction characteristics proposed by Shirakashi (1990) was applied. The friction characteristics derived an empirical equation as a friction model, which relates the frictional stress $\tau$ to the normal stress $\sigma_n$

$$\tau_f = k \left[ 1 - \exp \left( \frac{\lambda \sigma_n}{k} \right) \right]$$  (4.1)

Where $k$ is the shear flow stress of the workpiece and $\mu$ is a friction coefficient experimentally obtained for different workpiece-tool material combination. This equation was setup using subroutine and for the setup in the interface during pre-processor is as shown in figure 4.19. The user can define the friction characteristics by inserting the value in the interface. We chose to apply this friction model because it is more suitable to identify for steel/S45C compare to others friction characteristics.
Cutting condition number 11 was chosen because it was the easiest among those six sets of simulation for the convergence properties of the simulation. For cutting condition number 11, $\lambda = 0.4, 0.6, 0.8, 1.0$ and 1.2 were analyzed. For the FEM simulation, $\lambda = 1.4$ was also calculated. But, during the unsteady state simulation the calculation were time consuming and hard to convergence. As a result, $\lambda = 1.4$ was considered not suitable and not the true result of coefficient friction value for cutting condition number 11. Figure 4.20 shows the effect of different coefficient of friction value for principal force and thrust force. As shown, if coefficient friction values increases, the principal force and thrust force also increased, respectively.

Figure 4.21 shows the effect of different coefficient of friction value on shear angle for cutting condition number 11. Shear angle also increased with coefficient of friction value, respectively. In this study, shear angle is calculated using equation 4.2.

\[
\phi = \tan^{-1}\left(\frac{\frac{t_1}{t_2} \cos \alpha}{1 - \frac{t_1}{t_2} \sin \alpha}\right)
\]

\[
\phi = \text{Shear angle,} \quad t_1 = \text{Feed rate (m/rev)}
\]
\[
\alpha = \text{Rake face angle,} \quad t_2 = \text{Chip thickness (mm)}
\]
From figure 4.20 for thrust force at $\lambda = 1.2$, the value was decreased less than expected. This can be solved if the unsteady state and steady state simulation been repeated again. From figure 4.21 for shear angle at $\lambda = 0.6$, the FEM simulation result was lower than shear angle at $\lambda = 1.0$. As the results, when $\lambda$ was from 0.8 to 1.0, the analysis results of cutting forces and shear angle were close to the experiment results. Then, $\lambda = 1.0$ was considered as the frictional condition between tool and workpiece as it gave the least error between experiment and FEM simulation.

Figure 4.20 Friction characteristics effect on cutting force for cutting condition number 11

Figure 4.21 Friction characteristics effect on shear angle for cutting condition number 11
4.5 Results and Discussions

Finally, when $C, m$ value for JC model flow stress and friction characteristics had been identified, those value were applied again to cutting condition as shown in Table 4.1. Figure 4.22 shows the result of principal force. As shown the predicted principal forces were within 34% error of experiment values. Figure 4.23 shows the result of thrust force with the same coefficient of friction value. The result were considerably low, approximately 9.7% lower than the experimental values.

![Figure 4.22 Final result of principal force](image)

![Figure 4.23 Final result of thrust force](image)
Figure 4.24 shows that the predicted shear angle were within 13.1% error of experiment values. Which mean that current methodology is appropriate to estimate the flow stress and friction characteristics of workpiece. From this method, it proved that predicted thrust forces can be improved compare with previous method. On the other hand, principal force and shear angle for predicted result is not satisfaction.

![Figure 4.24 Final result of shear angle](image)

### 4.6 Summary

High-speed orthogonal cutting experiments were conducted to evaluate the performance of different cutting speed, feed rate and rake angle of tool surfaces. Method to improve current method to identify Johnson-Cook flow stress model during cutting process also discussed.
Low-speed orthogonal cutting experiments were conducted to evaluate the performance of different cutting speed. In this chapter, experimental and FEM simulation method were discussed to identify friction characteristics and flow stress applicable for FEM simulation. This method can also be referred to author’s previous published journal (Norfariza, 2015).

5.1 Experimental Setup

Low-speed orthogonal cutting tests were performed using customized machine (Figure 5.1). Cemented carbide byte (Sumitomo 33-3 ST30E) was used as a cutting tool and inserted to the jig. The workpiece material 0.45% carbon steel (S45C) was prepared as shown in figure 5.2. The jig was mounted on multicomponent dynamometer (Kistler 9257B) as shown in Figure 5.3. The dynamometer was connected to the charge amplifier and data logger system (Keyence N600) to measure the cutting force as shown in figure 5.4. Cutting conditions are shown in Table 1.
Chapter 5  Low-Speed Orthogonal Cutting Process to Identify Friction Characteristics Applicable for FEM simulation

Figure 5.1 Customized machine for low-speed orthogonal cutting

Figure 5.2 Prepared workpiece for S45C
Figure 5.3 Tools and dynamometer fixing method

Figure 5.4 Connection diagram
Table 1 Cutting conditions for cutting process

<table>
<thead>
<tr>
<th>Trials</th>
<th>Rake angle [°]</th>
<th>Width of cut [mm]</th>
<th>Feed rate [mm/rev]</th>
<th>Cutting speed [m/min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>20</td>
<td>0.2</td>
<td>0.10</td>
<td>0.1</td>
</tr>
</tbody>
</table>

5.2 FEM Simulation Setup

Next, cutting condition shown in Table 1 was run for FEM simulation. The same friction characteristics proposed by Shirakashi (1990) was applied. The friction characteristics derived an empirical equation as a friction model, which relates the frictional stress $\tau$ to the normal stress $\sigma_n$

$$\tau_f = k \left[ 1 - \exp \left( \frac{\lambda \sigma_n}{k} \right) \right]$$  \hspace{1cm} (4.1)

where $k$ is the shear flow stress of the workpiece and $\mu$ is a friction coefficient experimentally obtained for different workpiece-tool material combination. $\lambda$ = 0.4, 0.6, 0.8, 1.0, and 1.2 were employed. For the FEM simulation, $\lambda$ = 1.4 was also used. But, during the unsteady state simulation the calculation was time consuming and hard to convergence. As a result, $\lambda$ = 1.4 was considered not suitable and not the true result of coefficient friction value for cutting condition.

5.2.1 Results and Discussions

Figure 5.5 and figure 5.6 show the result of effect of frictional characteristic constant on cutting force respectively. From figure 5.5 and figure 5.6 the value of $\lambda$ that gave minimum difference between predicted and measured results of cutting force was chosen. As the results, when $\lambda$ was from 0.8 to 1.2 the analysis gave minimum average difference between predicted and measured. Then, $\lambda$ =1.0. as the friction characteristics between tool and workpiece was considered and used the value in the optimization for JC model using inverse calculation because it gives the less average error between experiment and FEM simulation for cutting forces and shear angle.
Figure 5.5 Effect of frictional characteristic constant on principal force

Figure 5.6 Effect of frictional characteristic constant on thrust force
5.3 Inverse Calculation Method and Results

After that, flow stress parameters of JC constitutive equations and friction characteristics were applied again to optimize the FEM simulation result using inverse calculation method. The same method that been introduced in (Norfariza, 2014) was conducted. Six parameters that been chosen as shown in Table 1 from chapter 4 were applied to inverse calculation method. The optimization of $C$ concerning the strain rate, parameters number 1, 2 and 3 were chosen, and for the optimization of $m$ concerning temperature, parameters number 1, 6 and 11 were chosen. For parameter $C$, the initial value was 0.01 and first optimized value was $3.506256 \times 10^{-3}$ (figure 5.7). In addition, for parameter $m$, the initial value was 1.0 and first optimized value was 1.029063 (figure 5.8). Then, both $C$ and $m$ were optimized simultaneously. Figure 5.9 shows the variation of optimization parameters of $C$ and $m$ value. It can be seen from the figure that optimization starting from initial value and end at optimized value where $C$: $3.506256 \times 10^{-3}$ and $m$: 1.076562.

![Graph showing optimization parameters](image)

Figure 5.7 Shows the result for optimization of first $C$ value, $m$ with initial value
Figure 5.8 Shows the result for optimization of first $m$ value, $C$ with first optimized value

Figure 5.9 Variation of $C$ and $m$ during optimization process
5.4 Results and Discussions

Figure 5.10 and figure 5.11 show the cutting force after the optimization of the parameters $C$ and $m$. The predicted principal forces were within 8.9% error of experiment (average) values as shown in figure 5.10. Meanwhile, figure 5.11 shows that the predicted thrust forces were 22.4% lower than the experimental values.
The predicted shear angle was within 7.4% error of experiment (average) values as shown in figure 5.12.

![Figure 5.12 Final result of shear angle](image)

Figure 5.12 Final result of shear angle

Figure 5.13 and figure 5.14 show the validity of proposed method applied in other cutting conditions from table 3.1. Cutting condition number 4, 8 and 12 was chosen which cutting speed and feed rate is the same but different rake angle value. It is to study either this method is applicable with different cutting conditions or not.

![Figure 5.13 Final result of principal force](image)

Figure 5.13 Final result of principal force
Chapter 5  Low-Speed Orthogonal Cutting Process to Identify Friction Characteristics Applicable for FEM simulation

Figure 5.13 show the average different for principal force of experiment and FEM simulation with selected cutting condition was 11.3% and figure 5.14 show the average different for thrust force of experiment and FEM simulation with selected cutting condition was 49.0%. Regarding this results, principal force difference between experiment and FEM simulation is good, however thrust force difference between experiment and FEM simulation is still big.

5.4 Summary

Low-speed orthogonal cutting experiments were conducted to evaluate the performance of different cutting speed, feed rate and rake angle of tool surfaces. In this chapter, experimental and FEM simulation method were discussed to identify friction characteristics and flow stress applicable for FEM simulation. The results showed in this chapter proved that the flow stress and friction characteristics identified with this method are more accurate than previous method.
CHAPTER 6

IDENTIFICATION OF JOHNSON-COOK FLOW STRESS MODEL BY SHEAR-SLITTING METHOD

In this chapter, the aim is to develop a new shear-slitting machine that can achieve strain rate same or higher range of cutting process which at the same time tool-chip friction characteristics should be ignored. Next, regarding the proposed shear-slitting method identification flow stress of workpiece will be discussed.

6.1 Development of Shear-slitting method

In this study, to perform high-speed shear deformation by slitting processing was performed instead of cutting process. Figure 6.1 shows a schematic diagram of general slitting process.

![Shear-slitting process](image)

Figure 6.1 Shear-slitting process

The slitting processing is a processing to shear the sheet material in the longitudinal
direction by a pair of upper and lower rotating circular blade tool. Slitting process is high productivity and low cost than laser cutting, a water jet machining. It can be said that slitting is the optimum processing method for the production of thin steel sheet. In this study, using the same concept during slitting, a shear-slitting machine had been developed. Shear-slitting by inserting the workpiece into two cutter with small clearance. When the workpiece is shearing, the rotating speed of the workpiece and the tool is zero. Therefore even when the workpiece was sheared at high speed it is possible to ignore the effects of friction between the workpiece.

6.1.1 Outline of Processing Phenomenon in Shear-slitting Machine

This aim of this study is to develop a machine that can achieve high strain rate during shearing and at the same time tool/chip friction characteristics can be ignored. Moreover, to be able to arbitrarily change the various parameters such as strain rate, temperature, etc. in the two-dimensional shear simulation. It required its own regulatory mechanisms to the machine. Therefore, this machine had been developed which can be applied to NC lathe. Figure 6.2 is an enlarged view of the processing point in shear-slitting machine.

![Figure 6.2 Entry of the workpiece to slitting point](image)

(a) Side view  
(b) Overall view

In general, there are two methods in slitting, namely drive cutting and pull cutting. The influence of slitting method and the slitting condition on cutter wear were
investigated in slitting of hardened steel strips with a miniature testing slitter. The results of slitting test revealed that there is little difference in wear shape and wear amount of cutters and in burr height of slit products between drive cutting and pull cutting, if the clearance and the overlap of cutters are the same. Thus, it was found that material slips toward cutting on circumferential face of cutter in both cases of slitting. In case of drive cutting, the amount of the slip toward cutting edge can be calculated from the circumferential slip rate of material and the trace of slip on cutter face. It was also found that the nearer to cutting edge, the larger this slip amount on cutter face becomes (Teizo M, 1978-3).

Roller is used as a rotating circular blade tool. It is supported by a bearing, thereby enabling shearing by pull cut method. A thin workpiece is rotated by attaching and using a dedicated jig in the main axis of the NC lathe. The workpiece feed from the z-axis direction in the overlap portion of the two rollers. The workpiece is sheared by causing bite into the edge of the upper roller. The shear-slitting machine clearance overlap has a possible adjustment of the strain rate by changing the spindle rotational speed of the NC lathe. Rolling force is defined as a force for shearing the specimen thickness direction. Therefore, it is measured using a piezoelectric force sensor a force in the x-axis direction component corresponding to the pressing force applied to the upper roller. External view of the shear-slitting machine is as shown figure 6.3. Figure 6.4 is a block diagram of shear-slitting machine which compose from many parts from upper view.

Figure 6.3 Overall view
In this experiment, Tecno Wasino Co. NC lathe C5 same machine that been used for high-speed orthogonal cutting process had been applied. Allowable maximum rotational speed $1800\text{min}^{-1}$, center distance between 800mm, swing over bed is 550mm. During the experiment, compound tool rest need to be removed and the shear-slitting machine is attached to the cross-slides. Compound tool rest of NC lathe and vertical slide, after removed is shown in figure 6.5. Figure 6.6 show how the shear-slitting machine had been setup for the experiment.
Figure 6.6 The experiment setup set on NC lathe machine

As connection diagram of shear-slitting experiment from the piezoelectric dynamometer goes to X, Y and Z charge up then date logger NC 200 and to the PC. A5052 was used as the workpiece of the experiment. Workpiece were prepared by using wire EDM machine (Sodic Co. AQ360L). The size of workpiece is 220mm diameter, thickness 0.5mm. A hole of 20mm diameter was made in order to pass a bolt in the center as shown in figure 6.7. The workpiece was fixed by sandwiching with two disc and the jig was chuck spindle of the NC lathe machine.

Figure 6.7 Workpiece and jig
6.1.2 Strain Rate Calculated in The Shear-slitting Machine

Processing region in the shear-slitting machine is sheared very small and fast. Therefore a large strain rate can be achieved. Each parameter in the shear-slitting machine is defined as shown in figure 6.8. In this case, the workpiece enters the y-axis specimen peripheral speed in the direction \( v \) mm / sec in the along sides of the low roller. Shearing starting point \( y_0 \) contact point of the workpiece and the upper roller, the shearing end point are at roller edge intersection.

The thickness of the workpiece \( d \) mm, the clearance between the rollers is \( c \) mm. Strain \( \gamma \) of the workpiece can be represented by the following equation.

\[
\gamma = \frac{d}{c}
\]  

(6.1)

The time required to shear is determined by the workpiece peripheral velocity \( v \) mm / sec. The spindle speed: \( n \) min\(^{-1}\), the specimen radius: \( R \) mm

\[
v = \frac{2\pi R n}{60}
\]  

(6.2)

When the amount of displacement \( l \) mm, which is sufficiently smaller than the roller radius \( r \) mm, \( l \) as shown in figure 6.9 can be regarded as the base of an isosceles triangle made from the center of the upper roller. Therefore, from the cosine theorem

\[
l = \sqrt{r^2 + r^2 - 2r \cos \theta}
\]  

(6.3)

\( l \) can be determined. If a fixed value \( r = 22.5 \) mm, and by substituting \( \theta = 1.8 \) °, \( l \) is determined to be \( l = 0.71 \) mm. Therefore shear required time \( t \) sec is from the equation 7.2 and 7.3

\[
t = \frac{l}{v} = \frac{60 \times 0.71}{2\pi R n}
\]  

(6.4)

Therefore, strain rate \( \dot{\gamma} \) sec\(^{-1}\) can be formulated from equation 6.1 and 6.4 can be determined.
\[
\dot{\gamma} = \frac{\gamma}{t} = \frac{d}{c} \cdot \frac{2\pi Rn}{60 \times 0.71} = \frac{\pi Rnd}{21.3c}
\] (6.5)

Circumferential speed : \( n \)  
Clearance : \( c \)  
Workpiece radius : \( R \)  
Workpiece thickness : \( d \)  
Roller radius : \( r \)  

Figure 6.8 The parameters of slitting

Slitng displacement : \( l \)  
Slitting angle : \( \phi \)  
Roller radius : \( r \)  

Figure 6.9 The parameters of slitting
The strain rate can be achieved for each experimental condition was calculated from each experimental condition and expression from equation 6.5 is shown in Table 6.1.

<table>
<thead>
<tr>
<th>No.</th>
<th>Spindle speed $n$ min$^{-1}$</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Clearance $c$ mm</td>
<td>0.05</td>
<td>0.04</td>
<td>0.15</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Circumferential speed $v$ mm/sec</td>
<td>1.38×10$^3$</td>
<td>6.91×10$^2$</td>
<td>2.76×10$^3$</td>
<td>1.38×10$^3$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Strain rate $\dot{\gamma}$ s$^{-1}$</td>
<td>1.82×10$^4$</td>
<td>4.55×10$^3$</td>
<td>3.67×10$^4$</td>
<td>2.27×10$^4$</td>
<td>6.06×10$^3$</td>
</tr>
</tbody>
</table>

From equation 6.5, strain rate is proportional to the rotational speed of the spindle. It is seen to be inversely proportional to the clearance. In this conducted experimental conditions, has a strain rate of $4.55 \times 10^3$ – $3.67 \times 10^4$ orders, it is possible for high strain rate range that occurs in cutting process.

### 6.1.3 Results and Discussion of Shear-slitting Force Experiments

The experimental conditions for shear-slitting machine are shown in table 6.2. Spindle rotation speed in this experiment is to examine the impact on the slitting due to the change in the clearance. The slitting condition 1 is a reference in this experiment, to investigate the effect on slitting and by changing the spindle rotational speed in conditions 2 and 3. Varying the clearance in conditions 4 and 5 is to investigate the effect on slitting. Measured value is assumed to be steady state as it approaches the end processing is evaluated by the average value of the machining before the end 1 second.
Table 6.2 Slitting conditions of experiments

<table>
<thead>
<tr>
<th>No.</th>
<th>Spindle speed ( n ) min(^{-1} )</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clearance</td>
<td>( c ) mm</td>
<td>0.05</td>
<td>0.04</td>
<td>0.15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feed rate</td>
<td>( f ) mm/rev</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rake angle</td>
<td>( \theta ) degree</td>
<td>45</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Workpiece radius</td>
<td>( R ) mm</td>
<td>220</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Workpiece thickness</td>
<td>( d ) mm</td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roller radius</td>
<td>( r ) mm</td>
<td>22.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Circumferential speed</td>
<td>( \nu ) mm/sec</td>
<td>( 1.38 \times 10^3 )</td>
<td>( 6.91 \times 10^2 )</td>
<td>( 2.76 \times 10^3 )</td>
<td>( 1.38 \times 10^3 )</td>
<td></td>
</tr>
<tr>
<td>Strain rate</td>
<td>( \dot{\gamma} ) s(^{-1} )</td>
<td>( 1.82 \times 10^4 )</td>
<td>( 4.55 \times 10^3 )</td>
<td>( 3.67 \times 10^4 )</td>
<td>( 2.27 \times 10^4 )</td>
<td>( 6.06 \times 10^3 )</td>
</tr>
</tbody>
</table>

(a) Shear-slitting impact due to the change in the rotational speed of the spindle

Strain rate to be realized in shear-slitting machine was developed in this study will be increased in proportion to the spindle speed. Strain rate in the cutting of metal are very high as \( 10^4 \sim 10^5 \) s\(^{-1} \), it is necessary to realize a strain rate equivalent order as it in the machine. To examine the effect of the spindle rotation speed, the slitting conditions 1, 2 and 3 were compared. Slitting condition 1 in \( n = 120 \) min\(^{-1} \), condition 2 in \( n = 30 \) min\(^{-1} \) and slitting condition 3 in \( n = 240 \) min\(^{-1} \). Three component force measurement data of slitting conditions 1, 2 and 3 is shown in figure 6.10.
The distance of sending a workpiece when shearing the z-axis to be constant at 20mm. As the spindle rotation speed is increase, the processing time will be short. Temporarily extreme x-axis and y-axis direction increase of shear-slitting force thought to be caused by entrainment of chips formation during the experiment. For spindle rotation speed is relatively small for slitting condition 2, it has become a stable/steady waveform. When a large shear-slitting force in the z-axis direction observed during processing start the specimen enters the z-axis direction, shows that it takes time to engage with the roller because it adopts the pull cutting scheme. Since large shear-slitting force is not generated, it is considered the workpiece is slitting. The average value of the measured x-axis direction of the shear-slitting force as the rolling force is shown in figure 6.11.
Although there are standard deviations differences due discharge speed of the chips cut as described above, a large influence on the shear-slitting force due to the change in the rotational speed of the spindle was not affected. Figure 6.12 a shear cut surface of the workpiece after the experiment for slitting condition number 1,2 and 3. Even with different rotational speed, there was no significant difference of shear plane in all conditions. Almost 90% of the results were shear plane at difference slitting conditions. Therefore, effects of spindle rotation speed is given to the shear area of the shear cut can be estimated that there is almost no effect.

(b) Shear-slitting impact due to the change in the clearance

Strain rate to be realized in shear-slitting machine was developed in this study will
be increased in inverse proportion to the clearance. To examine the effect of clearance provided to slitting, the slitting conditions number 1, 4, and 5 were compared. Slitting condition 1, \( c = 0.05 \) mm, slitting conditions 4, \( c = 0.04 \) mm and slitting condition 5, \( c = 0.15 \) mm. Three component shear-slitting force measurement data of slitting conditions 1, 4 and 5 is shown in figure 6.13.

![Figure 6.13](image)

(a) No.1

(b) No.4

(c) No.5

Figure 6.13 Shearing force at slitting condition no.1, no.4 and no.5

From the figure, the swell of waveform with small clearance occurs and becomes large enough when big clearance. In general slitting process, workpiece is sent only in the penetration direction of the roller. However, in this shear-slitting machine to have a slitting with NC lathe for high strain rate implementation, the workpiece is also sent in addition to the entering direction of the roller to the thickness direction of the roller. Therefore impact due to the bending occurs. When the clearance is large, it is considered that there is a swell in processing for larger degree of freedom in the bending
direction.

The average value of the measured x-axis direction of the shear-slitting force is shown in figure 6.14. The machining end near slitting condition 5 because swell is large, the average value between 1.5 ~ 2.5 sec were taken. From figure 6.14 it can be seen that as clearance increase, the shear-slitting force will decrease.

Figure 6.15 show a shear cut surface of the workpiece after the experiment for slitting condition number 1, 4 and 5. Slitting condition number 5 is larger percentage of the area of the fracture surface as compared to the slitting condition number 1. There are variations in multiple places and the proportion of the fracture surface and the shear surface. Slitting condition number 4 is entire shear surface as compared to the slitting condition number 1. More like a general punching process, it can be seen that as the clearance is smaller the percentage of the shear area will increase.

Figure 6.14 Average of force in the X direction at slitting conditions no.1, no.4 and no.5

Figure 6.15 Sheared edges at slitting condition no.1, no.4 and no.5
6.1.4 Summary

A shear-slitting machine that enables sharing corresponding to the high strain rate range of cutting process had been developed. Using the developed machine, impact of shear slitting force was studied changing the spindle rotational speed and the clearance of slitting condition. As for the result, the ratio of the shear plane at a shear cut surface affect by different clearance not by different spindle rotational speed. However, spindle rotational speed controls the strain rate of shear-slitting that can be achieved by this method. In the future, experiments conducted by small clearance is needed so that it can respond to a further high strain rate, also consider the design effect of the bending of the workpiece is reduced. Regarding the result from the experiment, the ability of developed shear-slitting machine to sheared low strength aluminum/A5052 is proved. It is believed that the same methodological is also applicable to steel/S45C. However, it is almost impossible to find steel plate that is below than 0.5 mm thickness which is applicable for the developed shear-slitting machine.

6.2 Development of Shear-slitting FEM Analysis

To compare with the shear-slitting force of the high-speed shearing by slitting a FEM simulation had been applied. For analysis by three-dimensional finite element method it takes a lot of computation time. Therefore, comparative approach of shear-slitting performs is by replacing three-dimensional slitting to two-dimensional shear simulation. In this chapter, two-dimensional shear simulation model construction as a result of the analysis. Replaced technique from the two-dimensional shear simulation of three-dimensional to slitting also will be discussed.

6.2.1 Two-dimensional Shearing Simulation

The shear-slitting that have been deformed workpiece is divide every minute with width dy and considered as two-dimensional punching shear simultaneously. The shear-slitting phenomena that occurred and two-dimensional punching share comparative is shown in figure 6.16. When generated shear-slitting workpiece as two-dimensional punching shear, lower roller pressing workpiece and upper roller as punch are continuously shear-slitting the workpiece. Shear-slitting force applied to the surface when it is divided into minute width in three-dimensional shear-slitting is applied to the upper roller at the same time. Therefore, by determining finite element
Chapter 6  Development and Identification of Johnson-Cook Flow Stress Model by Shear-slitting Method

analysis of two-dimensional punching shear force at split position and sum it, it is possible to get similar shear-slitting force as experimental. In this study, commercial available software DEFORM (TM) -2Dv10.21 been used to perform a finite element analysis of a two-dimensional punching shear. Geometry is created from the plane strain.

![Figure 6.16 Experimental shear-slitting method and two-dimensional punching shear](image)

The parameters configuration of the two-dimensional punching-shear simulation is shown in table 6.3 and figure 6.17.

<table>
<thead>
<tr>
<th>Object type</th>
<th>Workpiece</th>
<th>Elastic plastic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top die</td>
<td>Rigid</td>
<td></td>
</tr>
<tr>
<td>Bottom die</td>
<td>Rigid</td>
<td></td>
</tr>
<tr>
<td>Workpiece material</td>
<td>A5052(20-480C)</td>
<td></td>
</tr>
<tr>
<td>Yield function type</td>
<td>Von Mises</td>
<td></td>
</tr>
<tr>
<td>Hardening rule</td>
<td>°C</td>
<td>Isotropic</td>
</tr>
<tr>
<td>Workpiece length</td>
<td>$l$</td>
<td>mm</td>
</tr>
<tr>
<td>Workpiece thickness</td>
<td>$t$</td>
<td>mm</td>
</tr>
<tr>
<td>Temperature</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>W/(m·°C)</td>
<td>180.2</td>
</tr>
<tr>
<td>Heat capacity</td>
<td>MJ/(m³·°C)</td>
<td>2.43</td>
</tr>
<tr>
<td>Edge radius</td>
<td>$r$</td>
<td>mm</td>
</tr>
</tbody>
</table>
6.2.2 Calculation of Two-dimensional Punching Shear Speed

When replacing three-dimensional shear-slitting, as same as experiments tool speed, punching speed of the top die is determined as \( V \) mm/sec. As discuss in this chapter 6.1.2, the workpiece peripheral velocity is same as roller circumferential speed from the experiment \( v \) mm/sec. The \( x \)-axis direction component of the roller circumferential speed is shown in figure 6.18.
As upper roller angle of experiment had be set as $45^\circ$, the $\gamma = v \cdot \sin 45^\circ$. Since the upper roller radius compared to thickness of workpiece is sufficiently large, slitting-shear of $x$-axis direction component is calculated as constant speed from the beginning to the end of processing.

### 6.2.3 Result and Discussions for Two-dimensional Punching Shear Simulation

From previous chapter, it is cleared that clearance impact the shear-slitting force. Therefore, for the two-dimensional punching shear simulation, slitting conditions number 1, 4 and 5 been selected to be compared with experiment shear-slitting force. Table 6.4 shows the selected slitting conditions.

When it reaches to 0.5mm, stroke of the top die will stop in the FEM analysis. Shear-slitting force obtained by slitting condition number 1, 4 and 5 simulations is shown in figure 6.18. In this case the length of the depth of the simulation are all unit length (1mm), the shear-slitting force per unit length is defined as $f_s$ N/mm. From figure 6.19 shows that when the shear-slitting force increased, clearance decreased, respectively.
Chapter 6 Development and Identification of Johnson-Cook Flow Stress Model by Shear-slitting Method

Table 6.4 Slitting conditions of simulation

<table>
<thead>
<tr>
<th>No.</th>
<th>Clearance $c$ mm</th>
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</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.05</td>
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<td></td>
</tr>
<tr>
<td>4</td>
<td>0.04</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>0.15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Punching speed $V$ mm/sec</td>
<td>899</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Workpiece material</td>
<td>A5052(20-480C)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Workpiece length $l$ mm</td>
<td>110</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Workpiece thickness $t$ mm</td>
<td>0.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temperature $^\circ$C</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal conductivity W/(m$^\circ$C)</td>
<td>180.2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat capacity MJ/(m$^3$°C)</td>
<td>2.43</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Edge radius $r$ mm</td>
<td>0.05</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Figure 6.19 Simulated Force per unit length

Figure 6.19 shows the results for strain rates and temperatures distribution for slitting condition number 1 at stroke 0.1~0.4 mm. Strain rate occurs only in shear zone, maximum strain rate was $1.48 \times 10^4$ s$^{-1}$. Temperature bottom die side increase is larger in proportion to the stroke.

Figure 6.20 shows the results for strain rates and temperatures distribution for slitting condition number 5 at stroke 0.1~0.4 mm. Compared to slitting condition number 1, when clearance increased, strain rates and temperature decreased, respectively. Maximum strain rate was $8.60 \times 10^3$ s$^{-1}$. 

---

No. 1 4 5
Clearance $c$ mm 0.05 0.04 0.15
Punching speed $V$ mm/sec 899
Workpiece material A5052(20-480C)
Workpiece length $l$ mm 110
Workpiece thickness $t$ mm 0.5
Temperature $^\circ$C 20
Thermal conductivity W/(m$^\circ$C) 180.2
Heat capacity MJ/(m$^3$°C) 2.43
Edge radius $r$ mm 0.05

No. 1 4 5
Clearance $c$ mm 0.05 0.04 0.15
Workpiece material A5052(20-480C)
Workpiece length $l$ mm 110
Workpiece thickness $t$ mm 0.5
Temperature $^\circ$C 20
Thermal conductivity W/(m$^\circ$C) 180.2
Heat capacity MJ/(m$^3$°C) 2.43
Edge radius $r$ mm 0.05

Figure 6.19 Simulated Force per unit length

Figure 6.19 shows the results for strain rates and temperatures distribution for slitting condition number 1 at stroke 0.1~0.4 mm. Strain rate occurs only in shear zone, maximum strain rate was $1.48 \times 10^4$ s$^{-1}$. Temperature bottom die side increase is larger in proportion to the stroke.

Figure 6.20 shows the results for strain rates and temperatures distribution for slitting condition number 5 at stroke 0.1~0.4 mm. Compared to slitting condition number 1, when clearance increased, strain rates and temperature decreased, respectively. Maximum strain rate was $8.60 \times 10^3$ s$^{-1}$.
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(a) Strain rates distribution at slitting condition number 1

(b) Temperatures distribution at slitting condition number 1

Figure 6.20 Strain rates and temperature distribution
Chapter 6  Development and Identification of Johnson-Cook Flow Stress Model by Shear-slitting Method

Figures 6.21 Strain rates and temperature distribution

(a) Strain rates distribution at slitting condition number 5

(b) Temperatures distribution at slitting condition number 5
6.2.4 Two-dimensional Punching Shear Simulation to Shear-slitting

Research that analogy the shear-slitting force in slitting processing has already been performed (Masao M., 1978-9). It is by assuming all stroke of two-dimensional punching shear is happening all at the same time in the shear-slitting process. Assuming that slitting as a kind of shearing process, the stress distribution of the processing area in the longitudinal direction of the material from the punching shear can be determined. It is calculated the shear-slitting force by graphically integrating the shear stress distribution. The expected distribution diagrams of a shear stress to the roller along the material longitudinal direction in each point in slitting as shown in figure 6.22. The expression of the pressure force calculation formula is (6.6) and (6.7).

\[
F_v = \int x_0^x \tau dx = t \int x_0^x \tau dx = tS = tS_0 \times \frac{S}{S_0} = tk(\sqrt{R(t + L)} - \sqrt{RL}) \times \frac{S}{S_0} \quad (L \geq 0) \quad (6.6)
\]

\[
F_v = \int x_0^x \tau dx = t \int _0^x \tau dx = tS = tS_0 \times \frac{S}{S_0} = tk\sqrt{R(t + L)} \times \frac{S}{S_0} \quad (L < 0) \quad (6.7)
\]

**Figure 6.22** Distribution diagram of shear slitting

- \( r \): Cutter radius \hspace{1cm} \text{mm}
- \( d \): Workpiece thickness \hspace{1cm} \text{mm}
- \( L \): Overlap \hspace{1cm} \text{mm}
- \( s \): Displacement \hspace{1cm} \text{mm}
- \( w \): Displacement length \hspace{1cm} \text{mm}
- \( k \): Shear strength
- \( \gamma \): Punch stroke (=s/t)
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The slitting begins from contact between cutter and workpiece until beginning of overlap between two cutters. In this situation, the y-axis direction length is \( w \) depending on cutter radius \( r \), specimen thickness \( d \), the overlap amount \( L \). On the other hand, the length of the y-axis direction in developed shear-slitting machine depending on roller radius \( r \), the specimen thickness \( d \) and the roller tilt angle \( \theta \). When roller tilt angle \( \theta \) is \( \theta > 0 \), it meet the wrap amount of condition of equation (6.6) \( (L \geq 0) \).

It is assumed that the method applied in shear-slitting machine it can ignore almost friction characteristics between workpiece and roller outer peripheral surface. Therefore, force applied to each point of the roller edges went toward the center of the roller.

In this study, the same method as (Masao M., 1978-9) had been applied to replace two-dimensional punching shear simulation to shear-slitting force. Shear-slitting force that occurred at each point of roller edge can be identified using two-dimensional punching shear simulation, then from the two-dimensional punching shear simulation, shear-slitting force can be calculated. In this developed method, workpiece enters the vertical y-axis direction along the sides of the lower roller. The position of the shear in the y-direction is started \( y_0 \) and position to be end at \( y_1 \). As workpiece enter the y-axis direction, the x-axis direction displacement is also given. The distance of divided surface \( y_0 \) in every minute of width \( dy \) is defined as shear length \( y_s \). The shear length \( y_s \) consist of roller radius \( r \), roller angle \( \theta \), stroke \( s \) is expressed as follows.

\[
y_s = \sqrt{r^2 - (s - r \cos \theta)^2} - r \sin \theta
\]  \( (6.8) \)

From equation (6.8) it can be understand the y-direction of shear-slitting force per unit length \( f_x \) N/mm distribution. Therefore shear-slitting force divided surface can be represented as \( f_x dy \). It can be compared with the measured value of the experiment by replacing to three-dimensional. Shear-slitting force was replaced with three-dimensional is expressed by the following equation.

\[
F_x = \int_{y_0}^{y_1} f_x dy
\]  \( (6.9) \)

From equation (6.9) three-dimensional shear-slitting force it is possible to compare the punching shear process of the two-dimensional and three- dimensions shear-slitting force.

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6.2.5 Summary

Using DEFORM (TM) -2Dv10.21, two-dimensional punching shear was constructed. The FEM simulation of the two-dimensional punching shear determined the shear-slitting force per unit length of each condition. A method for replacing shear-slitting force measured by developed machine to two-dimensional punching shear simulation had been proposed. Then, method comparison between two-dimensional punching shear and three-dimensional shear-slitting had also been proposed. Thus, it is believed that it possible to compare the shear-slitting force and punching shear load that is calculated by FEM simulation.

6.3 Comparative Approach of Shear-slitting Method

Comparison of the shear-slitting force and two-dimensional punching shear simulations by slitting. High-speed shear-slitting experiments and comparative method of two-dimensional punching shear simulation will be described. The punching shear of the workpiece and two-dimensional slitting is shown in figure 6.16.

As shown, it is considered that three-dimensional slitting and dividing the workpiece being slitting per minute width dy is a set of two-dimensional punching shear. Shear-slitting force $F_x$ N obtained by replacing the three dimensions using a punching shear force $f_x$ N/mm per unit length in the y-axis direction determined by the two-dimensional punching shear simulation. It be expressed as equation (6.9). In this case the position $y_0$ shear in the y-axis direction is starting point, $y_1$ indicates the end position.

6.3.1 Comparative Method of Two-dimensional Punching Shear Simulation and High-speed Shear-slitting Experiments

The divided dy between plane width $y_0$ distance is defined as the shear length $y_s$. In this study, the fracture by analysis is not considered. Therefore, the end position $y_1$ shear is unknown. By observing the high-speed shear slitting experiments after the test, the same conditions was determined from the shear zone in the thickness direction. Shear length of each condition is shown in table 6.5.

Default value inside DEFORM was applied for A5052 in the simulation. As default value, Young’s modulus : 68900 N/m$^2$, Poisson’ ration: 0.33, thermal conductivity : 180.195 W/(m $\cdot$ °C), heat capacity : 2.43329 MJ/(m$^3$ $\cdot$ °C) however, at
this stage the value of A, B and n is applied using default value from below graph shows in figure 6.23. In addition, since the impact of shear-slitting force is lost in the fracture surface, shear-slitting force per unit length in the \( y_s > y_f \) becomes zero. The shear length considering the share surface is shown in figure 6.24.

Figure 6.23 Graph that applied strain – flow stress value

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<tr>
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<td>4</td>
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</tr>
<tr>
<td>5</td>
<td>0.39</td>
</tr>
</tbody>
</table>
Chapter 6  Development and Identification of Johnson-Cook Flow Stress Model by Shear-slitting Method

(a) Simulated Force per unit length at slitting condition number 1

(b) Simulated Force per unit length at slitting condition number 4

(c) Simulated Force per unit length at slitting condition number 5

Figure 6.24  Simulated Force per unit length
6.3.2 Results and Discussions

As shown in figure 6.25, a comparison of the high-speed shear-slitting force and two-dimensional punching shear simulation by slitting process.

![Figure 6.25 Force in the X direction by Simulation and Experiment](image)

As well as the shear-slitting experimental results, clearance tends to increases when getting smaller. Thus, simulation results under all conditions are smaller compare to shear-slitting force of experimental results. This seems to be due to undergoing bending effects other than shearing, such as the rolling force measured during the workpiece in the experiment. Each error between FEM simulation and experiment for slitting conditions number 1, 4 and 5 is 6%, 14% and 12%.

6.4 Identification Method of Material Flow Stress

In this section, method to identify material flow stress will be discussed. Thus, validation of proposed method will also be explained.

6.4.1 Tension Test

As material is very thin, to identify $A$, $B$ and $n$ value of flow stress parameters tension test had been conducted using the optical full-field strain measurement technique called digital correlation method (hereinafter DICM) to measure strain. DICM is a technique using a digital image taken by the camera the specimen before and after the deformation, it is possible to measure a wide range of displacement distribution.
and strain distribution by analyzing (Onodera, 2000). DICM technology was introduced by researchers at the University of South Carolina in the early 1980s. DICM is based on the randomness of the pattern measurement object surface by which a digital image obtained by photographing the measuring object surface before and after deformation. For example, a CCD camera to capture image processing, deformation throughout the measurement ranges of the magnitude and direction.

(a) Creation of Test Pieces

The material used for testing purpose was A5052 and thickness 0.5 mm (JIS 13B). The speed of tensile test was 0.05 mm/sec. Test piece was cut from a plate of A5052 having a thickness of 0.5mm by a wire electrical discharge machining. Test piece shown in figure 6.26 were nine. Three kinds of tension orientation against the rolling direction were employed. Namely, 0, 45, 90° direction were tested.

![Figure 6.26 JIS13B type specimen for uniaxial tension test](image)

The thickness of each specimen was measured and the average of three measurements excluding the maximum and minimum values and thickness. The thickness of the measurement results are shown in Table 6.6.

<table>
<thead>
<tr>
<th>No</th>
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</tr>
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<td>0.4857</td>
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<td>0.488</td>
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<td>0.483</td>
<td>0.485</td>
<td>0.483</td>
<td>0.4837</td>
</tr>
</tbody>
</table>
(b) Tensile Test Procedures and Strain Measuring Method According to DICM

The random nature of a test piece was attached to the surface of the pattern as shown in figure 6.27. We installed a light source and two cameras on the side where pattern is on it. The brightness of the other portions that are attached to the pattern by photographing with applying a strong light is detected high, then the analysis of pattern was performed. The tensile testing machine was Shimadzu AUTOGRAPH AG250kNG. The tensile test conditions are shown in Table 6.7.

![Workpiece with random pattern on surface](image)

Figure 6.27   Workpiece with random pattern on surface

<table>
<thead>
<tr>
<th>Control method</th>
<th>Crosshead displacement control</th>
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<tr>
<td>Sampling period</td>
<td>sec</td>
</tr>
<tr>
<td>Tension speed</td>
<td>mm/min</td>
</tr>
</tbody>
</table>

Three types of rolling direction of tensile test under the above conditions was performed three times each. The rolling direction 0 ° of test pieces No.1 ~ 3, 45 ° of test pieces No.4 ~ 6, 90 ° of the test pieces and No.7 ~ 9.
(c) Tensile Test Results

The measurement results of the tensile test by DICM are shown in Figure 6.28. No.1, 7 are omitted for analysis has not done enough.

(a) Stress-Strain diagram of No.2

(b) Stress-Strain diagram of No.3

(c) Stress-Strain diagram of No.4
Chapter 6  Development and Identification of Johnson-Cook Flow Stress Model by Shear-slitting Method

(d) Stress-Strain diagram of No.5

(e) Stress-Strain diagram of No.6

(f) Stress-Strain diagram of No.8
(g) Stress-Strain diagram of No.9

Figure 6.28 Stress-Strain diagram of A5052

It appeared stepped stress fluctuation, similar to the serrations deformation in all specimens, also the size of the appearing distortion approximately equal. Serrations are explained by the interaction between the solute atoms and dislocation, but all description has been difficult phenomenon also many reports have not been elucidated (Onodera, 2000).

(d) Identification Method of Material Constants $A$, $B$, $n$

From stress-strain diagram determined in the tensile test, the material constants $A$, $B$, and $n$ was identified. Constant $A$ stress - equal to the yield stress $\sigma_y$ in strain diagram, constant $B$ is true stress - plastic coefficient of expression of Swift obtained the true strain of the relationship from a log-log graph, $n$ is equal to the work hardening exponent.

From the specimen No.2, material constant $A$ was determined. The true stress of Young's modulus $E$ of the elastic deformation range of the true strain was determined. It is shown in figure 6.29 the graph obtained the Young's modulus. It was found that $E = 68741$ Pa = 68.741 MPa.
Then calculate the yield stress $\sigma_y$ by using the offset method. Since the present study is not observed a clear yield point was the yield point determined for the 0.2% yield strength from the Young’s modulus. Is than the yield stress $\sigma_y = 206.1$ MPa this understanding, the material constant $A = 206.1$ guided. Material constants $B$, true stress to guide $n$ - is shown in figure 6.30 the double logarithmic graph of true strain diagram.

Plastic coefficient of expression of Swift from a log-log graph, we find the work hardening exponent. The Swift model is shown as below.

$$\sigma_t = K \varepsilon_t^n \quad (6.10)$$
Chapter 6  Development and Identification of Johnson-Cook Flow Stress Model by Shear-slitting Method

！[](image)

$\sigma_t$: true stress  $\epsilon_t$: true strain

$n$: work hardening exponent  $K$: plastic coefficient

A first order approximation straight line at the maximum strain range does not include the position of serration deformation seen in the tensile test as shown in figure 6.30. Coefficient of expression that was approximated by the green of the plot range $\log K$, intercept is $n$. Therefore $\log K = 2.08$ than the material constant $B = 120.6$, $n = 0.284$ has been derived. Figure 6.31 shows the result of pattern of graph when applied the average $A$, $B$ and $n$ value of JC model.

<table>
<thead>
<tr>
<th></th>
<th>No.2</th>
<th>No.3</th>
<th>No.4</th>
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<tr>
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<td>206.1</td>
<td>210.5</td>
<td>199.8</td>
<td>180.1</td>
<td>195.3</td>
<td>199.8</td>
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<tr>
<td>$B$</td>
<td>120.6</td>
<td>81.6</td>
<td>93.1</td>
<td>113.3</td>
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<tr>
<td>$n$</td>
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<td>0.255</td>
<td>0.210</td>
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<td>0.218</td>
<td>0.231</td>
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</table>

Material constant $A$ is falls within the range of 180-210, it is appropriate yield stress. Although the material constant $n$ is a little variation between 0.17 to 0.28, work hardening index A5052 which light metal Association derived is $n = 0.26$, $n = 0.23$ that was identified in this study seems not to be widely separated values.
6.4.2 Identification of Parameters $C$, $m$

Next, the material constant of the Johnson-Cook flow stress, $C$ and $m$ parameter will be identified. The $A$, $B$ and $n$ value of Johnson-Cook flow stress as identified in previous section and the initial value is $C = 0.01$, and $m = 1$. During this calculation of FEM simulation DEFORM (TM) -2Dv10.21 was applied. The boundary conditions $T_{\text{melt}} = 643^\circ\text{C}$, thermal conductivity 138 W/(m·°C) (Y. Farazila, 2011), specific heat 2.36 MJ/(m$^3$·°C) are in the literature (T. Murakami, 2013) (F. Yusof, 2012). The optimal value of slitting conditions number 1, 4 and 5 is shown in table 6.9. Figure 6.32 shows the optimal value of $C$ in the three conditions is 0.15. The shear-slitting force which is determined by the high speed shear-slitting machine $Fe(i)$, a punching shear force by replacing the three-dimensional simulation is $Fs(i)$, the evaluation function $R$ is defined as follows. In this calculation, $i = 1, 2, 3$ which means $c = 0.04, 0.05, 0.15$

$$R = \sum_{i=1}^{3} \sqrt{(Fe(i) - Fs(i))^2} \quad (6.10)$$

From figure 6.30 shows that the optimum value with $C = 0.15$. While fixed with $C = 0.15$, the clearance $c = 0.04, 0.05, 0.15$, the optimum value of $m$ in the three conditions is shown in table 6.10. Figure 6.33 shows that the optimum value of $m = 0.96$. Error between shear-slitting experiment results and punching shear simulation results was about 6.45% in three slitting conditions of varying the clearance. It can be said to be a sufficient accuracy.

<table>
<thead>
<tr>
<th>Table 6.9 Identification of optimal material constant $C$</th>
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Chapter 6  Development and Identification of Johnson-Cook Flow Stress Model by Shear-slitting Method

Figure 6.32 Identification of optimal material constant $C$

Table 6.10 Identification of optimal material constant $m$

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Figure 6.33 Identification of optimal material constant $m$
6.4.3 Identification $A$, $B$, $C$, $n$, and $m$ Parameters

Finally, identified value of $A$, $B$, $C$, $n$ and $m$ of flow stress parameters were applied again to FEM simulation. Figure 6.34 shows punching shear force per unit length at clearance 0.05mm. Default curves are labeled as is the simulation result using the default values in the DEFORM, and a simulation result of the material constant curves are labeled as optimal.

![Figure 6.34 Simulated force per unit length](image)

Figure 6.34  Simulated force per unit length

Figure 6.35 shows result force in x-axis direction. Optimal peak processing force in a short stage of the stroke compared to the Default. Magnitude decreases from the peak of the force is close to Default. Punching shear force when replacing the three dimensions are substantially equal, but there is a possibility that the error is large, such as by changes in the shear plane.
6.5 Summary

A new shear-slitting machine that can achieve strain rate same and higher range of cutting process which at the same time tool-chip friction characteristics can be ignored had been developed. A method to identify flow stress of workpiece using this new method had also been discussed. The result shows that this method can achieve acceptable accuracy of flow stress of workpiece during high strain rates. However, C identified for A5052 with this method is bigger than S45C. There is a possibility that there is a strain rate dependency. This is because this proposed shear-slitting machine can achieve high strain. Therefore, it results that the C for strain rate of A5052 is higher than S45C. In the future, this proposed method of identification flow stress under high strain rate can be applied to ultra precision where we need to consider the deformation of material under high strain rate in normal temperature.
CONCLUSIONS AND FUTURE RECOMMENDATIONS

7.1 Research Summary

The need to understand the material characteristics of workpiece during machining process available for FEM simulation is in great demands due to time consuming and cut costs. Alternatively, commercial available software has become alternative option to understand and solve the problems. A series of studies was performed to propose and evaluate a new method to identify material characteristics of workpiece under high strain rate and high temperature during cutting process.

Major research findings presented in this dissertation are listed as follows:

i. Identification of material characteristics by using inverse calculation method were performed under high strain rate and high temperature during orthogonal cutting process. The result from the proposed method of FEM simulation show that the error of principal forces is in good accuracy. Meanwhile, error of thrust forces is regarding the proposed method is still big.

ii. The method to improve previous proposed method was also discussed. Effect of the unsteady state and steady state FEM simulation, effect of mesh average length, effect of cutting tool roundness and effect of rake angle and clearance angle cutting tools be studied. However, among those effects friction characteristics give a major effect on thrust force result of orthogonal cutting process. The effect of friction characteristics on cutting force had also been studied.

iii. To identify friction characteristics under high strain rate and high temperature a low speed orthogonal cutting process had been proposed. This method proved
that it is better to identify friction characteristics during low speed orthogonal cutting process. Then, the flow stress of workpiece was identified using high speed orthogonal cutting process.

iv. A new method to identify flow stress of workpiece under high strain rate and high temperature during cutting process had been proposed. The method shows it originality. Thus, the final result shows that method to identify flow stress from proposed method can be identified.

7.2 Future Recommendations

This research has opened doors to several more venues that need to be studied further. Based on the results of this work, some recommendations can be drawn for future research:

i. The proposed method need to be considered on effect of else then cutting forces. For example, tool wear and residual stress.

ii. The proposed new shear-slitting method need to be considered under high temperature.

iii. The new developed shear-slitting machine needs to be modified to make sure it can measure more smaller value of clearance.
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