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THE ROLE OF FLOW STRESS AND FRICTION COEFFICIENT IN FEM ANALYSIS OF MACHINING: A REVIEW

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Abstract. Nowadays, finite element method (FEM) for machining processes is constantly attracting researchers and scientists to continuously understand the chip formation mechanisms, heat generation, tool-chip friction and quality of the machined surfaces. The current article presents a review on the role of flow stress and friction coefficient in FEM analysis of machining.

1. INTRODUCTION

Currently, metal cutting is one of the most common manufacturing processes and the finite element method has become the main instrument to simulate machining operations [1]. It constitutes a complex process involving a variety of physical phenomena, such as plastic deformation, frictional contact, thermo-mechanical coupling and chip and burr formation mechanisms [2]. Experimental approaches to study the machining processes are important but they can be replaced by FEM analysis, especially when a wide range of parameters is involved such as machining conditions, material of the workpiece, and tool types are involved. Process features such as tool geometry and cutting parameters directly influence cutting forces, chip morphology, tool life, and final product quality [3]. In Fig. 1, an example taken from Advantedge™ of plastic strain distribution in the chip and workpiece is shown. Also of relevance are the cutting and feed forces and maximum cutting temperature evolution along the time.

Experimental procedures are directly related with spending time and money in the workshop and there resides one of the advantages of using numerical simulation (it is possible to determine the thermo mechanical behaviour of both the tool and the workpiece). However, the accuracy of the obtained results with numerical simulation depends largely upon the accuracy of the input data. Sartkulvanich *et al.* [4] stated that the most important parameters that will influence the accuracy of the numerical simulations are the flow stress curve of the workpiece material and the friction coefficient along the tool-chip interface.

Computer simulation of the cutting process can potentially reduce the number of design iterations and that results in substantial cost savings. Therefore, considerable effort has been devoted to the development of computational models. In order to reduce costs and increase efficiency in mechanical cutting operations, understanding of the metal cutting process must be improved and an effective way is to model and simulate the process. Predictive models of cutting processes are used to forecast and evaluate cutting performance indicators such as chip formation, cutting force, cutting temperature, tool wear and surface finish [1,4-6]. Currently, numerical cutting simulations (in two and three-dimensions) are commonly used and

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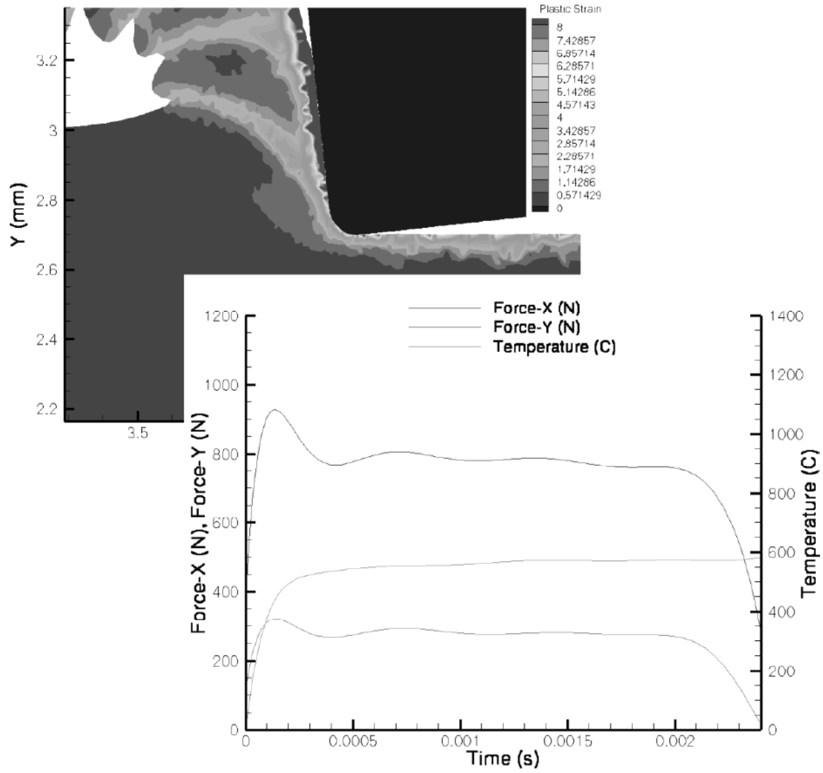

Fig. 1. FEM software with a prediction of cutting and feed forces and cutting temperature along the time and plastic strain distribution in the workpiece and chip (Advantedge™).

represent a very useful and powerful tool for understanding chip flow in machining and to obtain information that is difficult to acquire experimentally. In Fig. 2, an example of the applied mesh in 2D in the cutting tool, workpiece and chip is shown. Both cutting forces are displayed along the time.

Changing a cutting input parameter and examining its effects on the final solution allows researchers to isolate regions and physical quantities most affected by the change. This provides for a previous reasoning in the specific matter which can result in multiple solution data sets for comparison. Like already stated, the reliability of the results obtained with FEM simulation depend upon the accuracy of the input values. Among these inputs, flow stress data of the workpiece and the friction along tool–chip interface are of extreme importance for the prediction of cutting variables such as cutting forces, chip formation and temperature distributions [7-10].

2. FLOW STRESS AND FRICTION COEFFICIENT

Finite element method for machining processes is constantly attracting researchers and scientists to continuously understand the chip formation mechanisms, heat generation, tool-chip friction and quality of the machined surfaces. When cutting metal, the cutting force is felt in a small area of the tool rake face which is in contact with the chip (this is known as the tool-chip interface) [11]. Of note is that the tool-chip interface is the zone immediately ahead of the cutting tool that is in contact with the chip. To understand better where the tool-chip interface is located, Fig. 3 shows a scheme of the orthogonal cut with the respective location and some geometric aspects of the cut are also detailed.

When simulating machining processes, friction conditions at the tool-chip interface are one of the most important inputs to obtain reliable results. Despite of the development of high performance FEM software, simulating machining processes is a very hard task mainly due to the geometric complexity of the real tool-chip systems and the high cutting speed (requiring long simulation times). Because of these reasons, machining operations are not easy to simulate [12]. FEM predictions are greatly influenced by the friction coefficient and by the material flow stress, however, the friction coefficient is the most important aspect when modelling machining operations. FEM machining simulation is essential to make reliable predictions in cutting forces, temperatures, stresses and strains in the

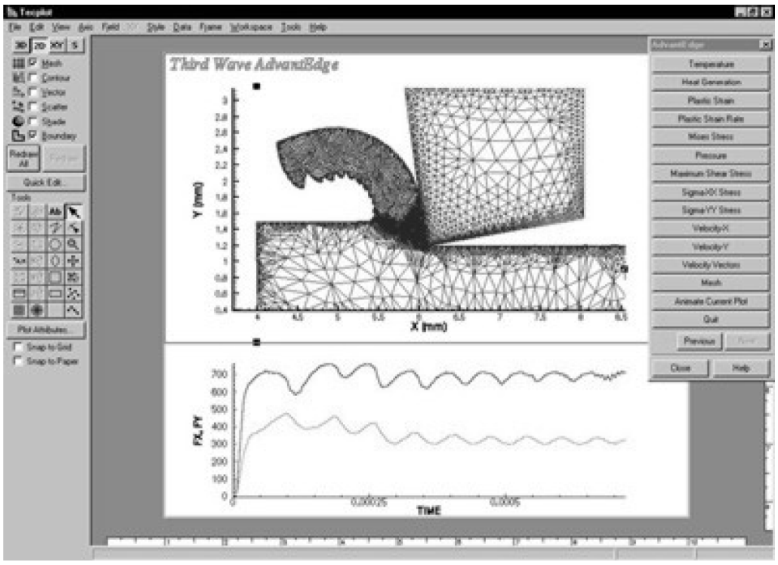

Fig. 2. Mesh in the tool, workpiece, and chip with the respective prediction of cutting and feed forces along the time (AdvantedgeTM).

chip, tool and machined surface. However, the reliability of the simulations is seriously compromised when the friction value is assumed. Friction is important in all engineering applications, wherever solid surfaces are sliding against each other. This relates directly with metal cutting processes, where a sliding pair of different surfaces are in contact and where plastic deformation of the softer material appear under high pressure. In orthogonal cutting, the frictional drag is encountered in the tool rake face (between the tool and the workpiece). The friction coefficient in these contact zones play a decisive role in chip formation, cutting forces, stresses, strains and work material flow in both the primary and secondary shear zones [12,13]. Asperities of different kind and different distributions are present in metal surfaces, the surface roughness. This has an influence in the friction properties because each tool and each workpiece material have a specific and characteristic roughness, especially at the beginning of the cut, until the asperities are flattened (at the beginning of the cut, the tool is only in contact with the asperities of the workpiece material).

With the flattening of the asperities, the workpiece contact with the cutting tool gets larger leading to a varying friction coefficient [14]. The amount of crystalline precipitates on the outer surface of the workpiece can define the surface roughness. It can then be said that the interfacial friction force should be considered the force that resists the motion of the layers between the tool and the workpiece [15]. Friction modelling is a challenging task that researchers have faced when metal cutting operations are involved. Friction modelling play a decisive role in residual stress prediction and residual stress is detrimental to determine fatigue life of a critical product [16,17]. Friction occur mainly in two zones, the primary shear zone (where the major shearing work takes place) and the secondary shear zone (adjacent to the tool-chip interface due to high stress contact conditions). Accurate predictions for variables such as forces, temperatures or stresses are of extreme importance to identify optimum cutting parameters, tool material and tool geometry in order to improve the quality of the final product. Therefore, a precise friction coefficient is crucial [3,4,7,10,12,18]. Geiger *et al.*

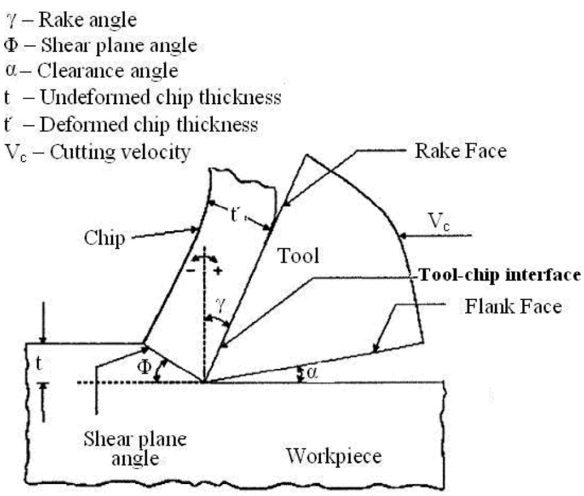

Fig. 3. General view of the orthogonal cutting process.

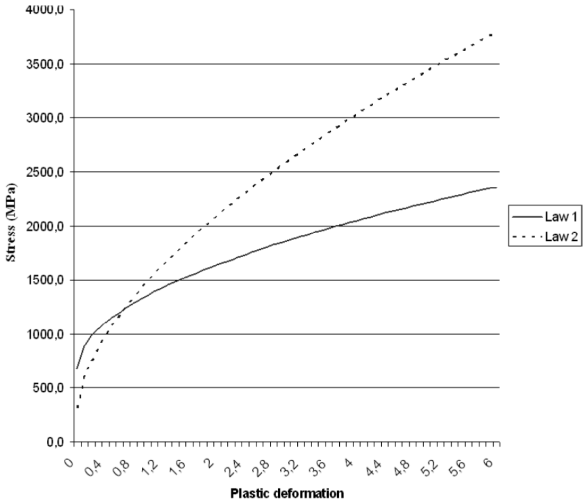

Fig. 4. Example of AISI 316 flow stress (Johnson-Cook Law) curves for a fixed temperature.

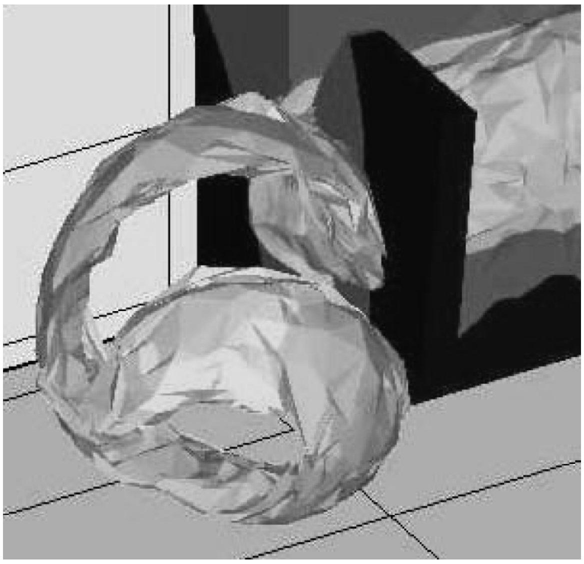

Fig. 5. Continuous chip formation in 3D, typical of Lagrangian models (Advantedge™).

[19] proved that the use of traditional friction coefficients can lead to erroneous results. A disagreement between the experimental and simulated results is usually present so it is very important to understand the influence of the input parameters upon the obtained results when dealing with FEM analysis (hence the sensitivity analysis of the friction coefficient in the FEM cutting simulations presented in this study). FEM simulation results show that the friction coefficient has a strong effect in cutting and feed forces, cutting temperature, stresses, strain, chip formations and tool wear predictions. An increase in the friction coefficient causes a larger tool-chip contact area and more work is required to form a chip (higher cutting forces are obtained). The cutting temperature also increases because more heat is generated [4]. Coulomb friction model is commonly used in most finite element analysis. This model contemplates a constant and average friction coefficient along the time and consists of the sticking region where the friction is constant and the sliding region where the friction varies linearly [20]. The amount of power consumed is a reflection of the friction and this have an impact in the tool wear. Therefore, an accurate predictive model of the friction boundary is critical for tool design and tool coatings. As the friction coefficient increases, sticking begins to occur at the tool tip and the slipline fields are modified to take care of the sticking and slipping friction in the interface [21].

Zorev *et al.* [22] proposed that shear and normal stresses can be assumed in the tool rake face. According to Zorev *et al.* [22], a sticking region appears in the tool-chip contact area (near the cutting edge) and the frictional shearing at the sticking region can be assumed equal to an average shear flow stress at the tool-chip interface. A sliding region forms over the remainder of the tool-chip contact area and the frictional shearing stress can be determined by using a friction coefficient μ. When the normal stress distribution over the rake face is fully defined and μ is known, the frictional stress can be determined. Accordingly, the shear stress distribution of the tool rake face can be represented in two distinct regions: the sticking and the sliding regions [23].

In machining processes, values of the mean friction coefficient can reach a level of 2, such as in aluminium machining with HSS tools having large positive rake angles. However, PCD drastically reduce the friction coefficient and nowadays 0.1 to 0.5 are typical values. When machining steels, the friction coefficient can vary from 0.6 to 1, depending on the machining conditions and cutting tools. The influence of the cutting speed and feed rate is felt in the friction coefficient. One can observe a substantial decrease in the friction coefficient with the increase of both the cutting speed and the feed rate. This fact can be explained by the thermal softening phenomenon with the increase in cutting speed and the rise of the normal load when varying the feed rate. Materials with low thermal conductivity generate higher contact temperatures and tend to produce higher friction coefficients [24].

The microscopic and macroscopic response of the material under high strain rate loadings is seriously affected by the plastic strain, plastic strain rate, temperature and microstructure of the workpiece material. Therefore, the knowledge of material constitutive behavior (material flow stress) under severe loading conditions is a requisite. The correct selection of the appropriate constitutive equation is often regarded as a critical step to predict variable with FEM software. In Fig. 4, Johnson-Cook constitutive law is presented for a fixed temperature but different constants. Therefore, for the same material, different constants can be found [25].

Like Ozel [10] stated, the uncertainty of the flow stress can be avoided by using Lagrangian numerical models. In Fig. 5, an example of a continuous chip formation can be seen in a 3D numerical simulation.

3. CONCLUSIONS

This review article reported some important aspects of the role of flow stress and friction coefficient in FEM analysis of machining. Based on the research reported above, the following conclusions can be draw:

- The accuracy of the obtained results with numerical simulation depends largely upon the accuracy of the input data being the flow stress and friction coefficient.
- The correct selection of the appropriate constitutive equation is often regarded as a critical step to predict variables with FEM software.
- Material response under high strain rate loadings is seriously affected by the plastic strain, plastic strain rate, temperature and microstructure.
- Coulomb friction model is commonly used in most finite element analysis.
- The use of traditional friction coefficient can lead to a disagreement between the experimental and simulated results.
- FEM is widely applied to predict the thermo mechanical behaviour of machining processes.

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