Mechanics of Grains Size and Orientation on the Machining of AISI S-7 Steel Grade Using Numerical Technique

Dillip Kumar Mohanta, Abhinav, Ardhendu Mouli Mohanty

Abstract*: Two-dimensional models namely homogeneous, uniformly distributed grains and non-uniformly distributed grains were developed for AISI S-7 steel grade metal, to investigate the effect of the grains size and orientation on the chip morphology and temperature rise during the orthogonal machining process. A Johnson-Cook model was used for the simulation study. The machining was done at a medium speed of 60 ms^{-1} and the depth of cut was maintained at 5 mm in all the above cases. Compared to other models, results showed that nonuniformly distributed grains develop alternate low and high shear bands and generate maximum temperature in the high shear band zone, which was found to be detrimental during the machining process compared to other models. Intergranular chip segmentation was observed in the case of uniformly distributed grains. For the same material, three different chip morphologies and temperature profiles were observed during the orthogonal machining process. Detailed discussion on the mechanics of machining of the above-said models was done that may be advantageous for material and tool design scientist.

Keywords: Orthogonal Machining, Grains, Johnson–Cook model, Numerical Technique.

I. INTRODUCTION

A number of simulations and experimental techniques have been initiated to envisage the chip morphology and its effect on tool life in an orthogonal machining process. Simulation techniques with finite element codes have been consistently proven and successfully executed on different grades of steel viz. 42CrMo4 Steel, carbide tool, Ti6Al4V Alloys, Al6061-T6 and were found give very promising results [1, 2, 3, 4]. For the understanding of chip morphology and its effect on tool wear, a number of featured models in FEA have been tried, namely Lagrangian formulation: includes nodes formation criterion to predict chip separation, lagrangian description of motion and adaptive remeshing: applied to simulate orthogonal cutting , Finite Element Eulerian formulations: to simulate continuous chip formation at steady state, Finite Element Arbitrary Lagrangian-Eulerian (ALE) the formulation in conjunction with adaptive mesh techniques etc. and successfully implemented [5]. Among the various featured mathematical models, the ALE model was found to have promising features due to combining features of both the pure Lagrangian analysis and Eulerian analysis. After several iterations, it was found that in the ALE model, mesh motion is independent of material motion, and it is likely to reserve a high quality of finite element mesh, during the numerical simulation of the machining process [6]. Thermo-mechanical interaction between the tool and workpiece is an important factor to realize a satisfactory result, because metal machining is complemented with a large amount of heat dissipation, and the same is transferred to the tool [7]. To cater to the need of the machining problems (simulation), the Johnson-Cook material model has been recommended. Earlier many works have been reported on the JC model and one such experimental work has been also reported on AISI-1045 medium carbon steel [8].

Steel is the most widely used engineering material in industries. The study has shown that thermo-mechanical properties of steels are significantly influenced by the microstructures that include grains/crystals [9]. In solid-state at room temperature, metals contain a range of grain sizes and may vary from very fine to coarse depending upon the type of metal and heat treatment [10]. Microstructures, especially grain size and orientation were found to play a pivotal role in deciding the tool wear during the machining process. AISI S-7 grade steel is considered to exhibit the highest hardenability of shock resistance and is extensively used in tool dies, plastic mold dies, powder metal dies, drill plates, die-casting dies, and shear blades, etc. [11]. Due to the limited literature on the effect of grains size on the morphology and temperature rise on the machining of AISI S-7 grade steel, an attempt was made to understand the mechanics of grains size and orientation on temperature rise using a finite element simulation technique. For better understanding the orthogonal machining process, different zones are identified and are shown in Fig.1, with the terminology.

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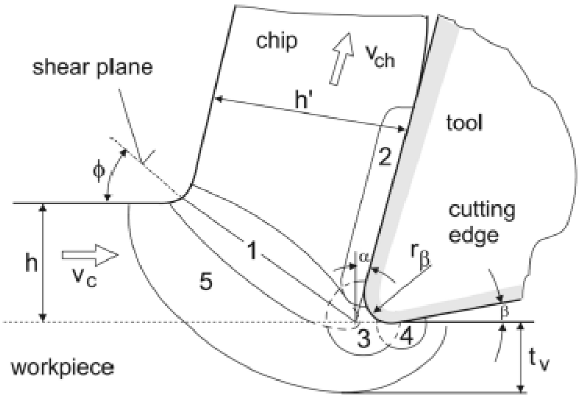


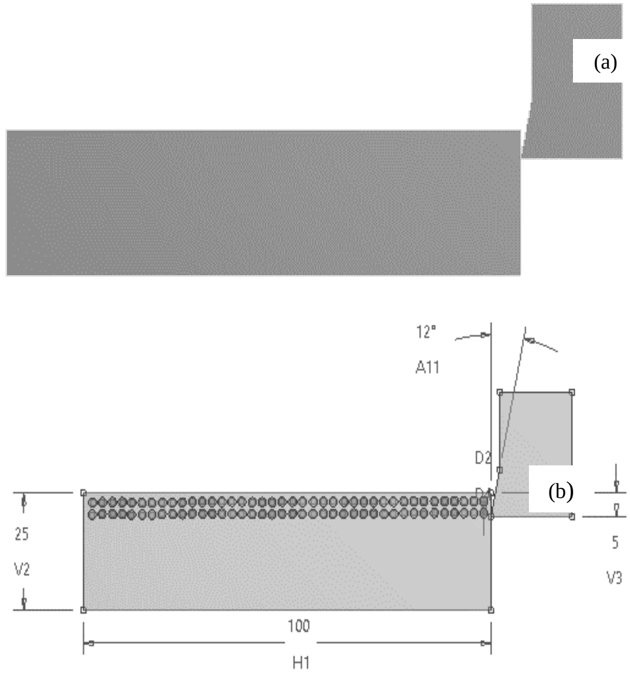
Fig.1. Chip formation zones and terminology related to orthogonal machining process1: primary shear zone 2: secondary shear zone at rake face 3: secondary shear zone at the stagnation zone 4. secondary shear zone at the flank face 5. Preliminary deformation zone, α: rake angle, β: clearance angle, ϕ: shear angle, t_v: deformation depth [12]

II. PROCEDURE FOR PAPER SUBMISSION

A. Modeling and Assumptions

Three different two dimensional models namely: homogeneous, uniformly distributed grains and non-uniformly distributed grains were developed for AISI S-7 steel grade materials. The models were designed using academic license, Ansys software,v.19. For simplicity, only 20% of the area was utilized and modeled with grains. In the case of the homogeneous model, no grain size was modeled and considered as an ideal material. On the other hand, uniformly distributed grain size was maintained at 1 mm and for the non-uniformly distributed model, the grain size varied from 0.01 to 1 mm. The size of grains (but not limited to) was unique, just to understand the mechanics of grain size on the temperature rise during the machining process.The schematic of the three models namely, homogeneous, uniformly distributed grains and non-uniformly distributed grains are shown in Fig.2 (a), (b) and (c) respectively. The schematic of the meshed model is also shown in Fig.3.The quad element was used to mesh the model. The size of the element was considered as 0.001 mm. The machining simulation was achieved at a constant speed of 60 ms^{-1} and the depth of cut was maintained at 5 mm for all the models. The selection of the above operating parameters was based on the machining of ductile materials [13]. The simulation was achieved with the following assumptions: the tool was considered to be a rigid body, the workpiece was constrained at the bottom (all degree of freedom assigned to zero), tool rake angle (α): 12° clearance angle (β): zero for simplicity. The details of the Johnson-Cook damage initiation criterion for AISI S-7 grade steel were taken from Ansys software material database and are shown in Table 1. The mathematical expression for Johnson-Cook damage model is shown in equation 1 with the following meaning: Where, T_{room} and T_{melt} are flow stress, plastic strain, effective strain rate, reference strain rate ($1s^{-1}$), room temperature, and melting temperature, respectively. A, B (in MPa) and n represents the yield stress of the material at room temperature, strain hardening also popularly known as hardening modulus and work-hardening exponent, respectively[14]. The constants C and m represent the strain rate hardening and thermal softening coefficient, respectively.

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



All the dimensions are in mm

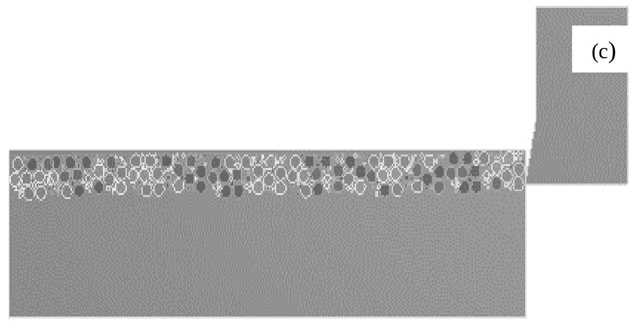


Fig.2. Schematic of two dimensional model (a) Homogeneous material (b) Homogeneous material with uniformly distributed crystals (c) Homogeneous materials with Non-uniformly distributed crystals.

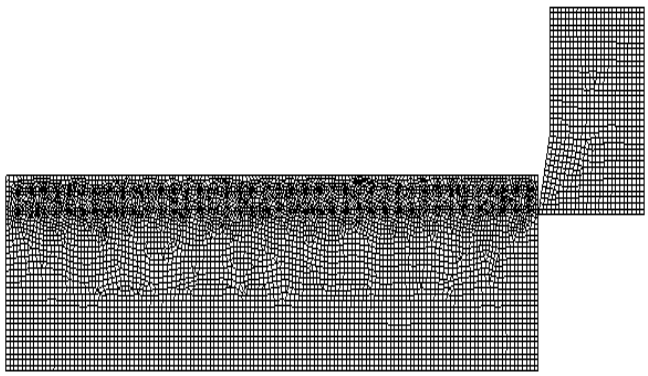


Fig.3. Schematic of meshed model

Table- I: Material properties of S-7 grade steel [15]

Parameters	S-7
Density, Kg/m^3	7750
Specific Heat, J/kg/°C	477
Shear Modulus, Pa	8.18e10
Melting Temperature °C	1489.9
Johnson -Cook Material Constant	
A Pa	1.539e9
B Pa	4.77e8
n	0.18
c	0.012
m	1

III. RESULT AND DISCUSSIONS

Results obtained from the machining simulation of S-7 grade steel showed that homogenized material (considered ideal in the present study) develop continuous chip with constant chip thickness over a period of time. The temperature profile gradually increased across the chip thickness. The maximum concentration of temperature can be seen at the outer periphery of the continuous chip near to the secondary zone of the tool-chip interface and was 548.61°C refer to Fig.4 (a). The continuous chip morphology has been also noticed earlier, in the case of ductile machining especially, at the low and medium cutting speed [16]. In this model, thermal softening and plastic flow of material was found to be simplified compared to the other two models. In the case of uniformly oriented grains, the machined model manifested with irregular, segmented chips, with varying thickness. The thickness of the chip continuously decreased towards the leading edge of the chip. The segmented chip was found to chip-off easily, thereby decreasing the chip tool contact time. Due to early chip-off, the tool wear was expected to be reduced. However, continuous coolant may be a prerequisite to remove the burrs for smooth finishing and heat transfer. More or less, a uniform temperature gradient was observed on the discontinuous segmented chip. In this model, strain hardening effect was manifested due to blockage of tandem grains ahead of the secondary zone at the tool-chip interface. Due to the agglomeration of the grains ahead to the tool, an obstruction resulted in an increase in the temperature. The temperature rise of 912.59 °C and frequent chip-off was noticed for the above-said model, refer to Fig.4 (b). Also, no significant temperature concentration was found on the segmented chip compared to a continuous chip refer, Fig.4 (a) and (b). The temperature was found to be distributed more uniformly (587-425°C) in case of the segmented chip. Inter-granular failure of chip was noticed in this model. In case of a non-uniformly distributed grain of varying size models, a cyclic chip with low shear strain and high shear strain zones were found to be formed and identified as a serrated chip. For the same material characteristic, it has been found that non uniform grains of different sizes (0.01-1 mm) plays a significant role in the understanding of temperature flow and determination to tool life. The serrated chip of alternating low and high shear zones was triggered at a constant speed of 60 ms^{-1}. In this kind of shear mechanism, cyclic bands are often expected to be detrimental in the machining process that may reduce the machining efficiency and increase the machining cost. This kind of shear band was also found in the machining of Titanium alloy (Ti–6Al–2Sn–2Zr–3Mo–1Cr–2Nb) at high speed of 100 m/min with a depth of cut 0.2 mm [17]. High shear strain coupled with a high temperature of 932.29 °C manifested in the primary shear zone in this case. It is understood that heterogeneity (grain size and distribution) in the ductile material may offer the highest resistance during the orthogonal machining at a medium speed of 60 ms^{-1}and may require prior machining attention.

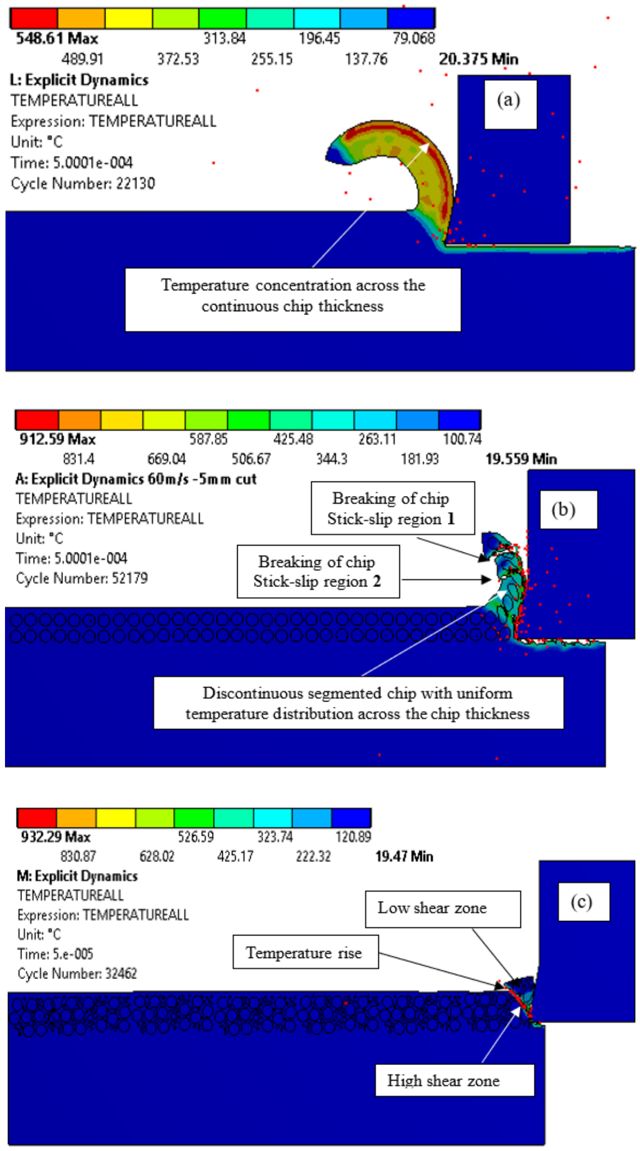


Fig.4. Schematic of temperature change in S-7 steel grade (a) Homogeneous material (b) Homogeneous material with uniformly distributed grains (c) Homogeneous materials with non-uniformly distributed grains.

IV. CONCLUSION

The role of grain size and grain configuration was found to play a significant role in the determination of tool wear and tool life. From the simulation study of the three models of the same material (AISI S-7 Steel grade) namely homogeneous, uniformly distributed grains and non-uniformly distributed grains following conclusion can be drawn:

1) Three different types of chip morphology manifested namely homogeneous model: continuous chip, uniformly distributed grains model: discontinuous segmented chip with unique stick-slip regions and non-uniformly distributed grains: serrated chip with low and high shear zones predicted for the same material characteristics.
2) Non-uniformly distributed grains were found to develop a maximum temperature rise of 932.29 °C in the primary shear zone and were found to be detrimental among all the models. The rise in temperature accompanied with serrated chips resulted due to the strain hardening effect manifested primarily in the primary shear zone in the orthogonal machining process.
3) Three different temperature profiles were obtained. Temperature concentration was found more at the periphery of the chip in the case of a continuous chip. However, in case of discontinuous segmented chip the temperature distribution was found more or less uniformly across the chip thickness and in case of non-uniformly distributed grains, temperature concentration manifested nearer to the primary (high) shear zone.
4) Orthogonal machining of ductile metals may not necessarily produce continuous chips, but depended on grain size and orientation in the crystalline solid state at room temperature.

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