MODELING AND CHARACTERIZATION OF AISI S-7 STEEL USING THE JOHNSON COOK MODEL – AN EXPLICIT ANALYSIS

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Abstract: A two dimensional, uniformly distributed grains model has been developed for AISI S-7 grade steel and the orthogonal machining process, in the pursuit of determining the various effects of temperature rise, residual stresses, chip morphology, and strain hardening. A Johnson-Cook material model, along with a numerical, technique was used to simulate the machining process using ANSYS 15 academic license. The machining has been carried out at different velocities: 60, 70, and 80 ms\(^{-1}\) and with depths of cut of 2, 3, and 5 mm. Results revealed that the accumulation of tandem grains offers a maximum resistance ahead of the tool-chip interface due to the strain hardening effect, during the metal removal process. This effect leads to a maximum rise in temperature up to 912.59 °C, which has been observed in the secondary shear zone. Serrated chip flow was observed mainly at a low speed of 60 ms\(^{-1}\). The Strain hardening effect was more substantial at 60 ms\(^{-1}\) and 5 mm depth of cut compared to other machining parameters. A great deal of discussion has been made on the above material machining process that may serve as a useful resource to the tool designer and manufacturing scientist.

Keywords: Finite Element Technique; Residual stress; Strain hardening; Chip morphology.

1. Introduction

Sam Coppieters, et al. [1] have proposed a theory on the identification of strain hardening phenomena in sheet metal at large plastic strains. The post necking strain hardening phenomena in ductile sheet metal are presented based on the minimization of external and internal work in the tensile test. In other studies R.K.Gupta, et al.[2] have explained strain hardening effect in the aerospace alloys. In their investigations, an attempt is made to explain the differential behavior of various alloys. In their investigations Austenitic steel identified to exhibit significant-high strain hardening effect compared to other alloys. A similar type of quality investigations carried out on the S30408 Austenitic Stainless-Steel pressure vessel and found that there is a significant effect on strain rate and yield strength at cryogenic temperature [3]. Earlier several investigations have been carried out on Aluminum grades, Stainless steel grades and Titanium-based alloys using a Johnson-Cook mathematical Model applying the FEA technique. One such work proposed and carried out on the determination of cutting forces a chip morphology by D. Yameogo et al. using the Lagrangian approach and found that segmentation and recrystallization of chips principally developed in the adiabatic shear band [4].

Ramy Hussein et al. [5] have proposed a theory on chip morphology and delamination characterization for vibration-assisted drilling of carbon Fiber-Reinforced Polymer. The results obtained showed, 31% reduction in cutting temperature and a significant augmentation in exit delamination [6]. J. Gryn et al.[7] have explained about the residual stress in a Tungsten-chromium-vanadium (80WCrV8) steel grade after heat treatments and grinding. The result found that an annealed steel compressive residual stress is quite low. The relation between residual stress and temperature variation in a metal machining is of great technical significance especially in the study of metal machining and prediction of tool wear. Wen Chen et al. have carried out an experimental investigation on a lattice strain on the several families of grain in an additive manufactured (AM)316L stainless steel under the uniaxial condition and established a mechanistic connection between microscale residual stress and Mechanical behaviour of AM Stainless steel. An FEA study was carried out using Ahaqus software and an effort is made to described a relationship between stress-strain and column behavior of stainless steel and found that residual stress leads to an increase of load-carrying capacity with varying Ramberg-Osgood strain hardening factor (n)[8].
From the literature survey it is understood that strain hardening is an important parameter that needs to be understood well and found to play a significant role in the study of machining characterization and wear control due to changing residual stress and temperature rise. An attempt is made to understand the thermomechanical behavior (strain hardening chip morphology and temperature change) of a specifically designed J-C model and implementing the same to AISI S-7 grade steel using the Finite Element Technique.

2. Mathematical Modeling and Analysis

The machining was carried out at different velocities: 60, 70, and 80 ms⁻¹ with varying depths of cut viz. 2, 3, and 5 mm. The thermomechanical properties of the materials have been taken from the material library database of the ANSYS 15 academic license software. The essential material properties and J-C material constants have been shown in Table 1. The mathematical expression for the J-C model has been shown in Equation 1[9]. The terminologies related to the equation are as follows: $\bar{\sigma}$, $\dot{\varepsilon}$, $\varepsilon$, $\dot{\varepsilon}_0$, $T_{room}$, 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, and hardening modulus and work-hardening exponent, respectively. The constants $C$ and $m$ represent the strain rate hardening and thermal softening coefficient, respectively. For simplicity two-dimensional uniformly distributed grain model was developed. The quad-elements have been used to mesh the model. Approximately twenty thousand elements were generated for the numerical analysis. The essential dimensions and meshed models are shown in Fig.1 (a) & (b), respectively.

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

| Parameters                              | AISI S-7 |
|----------------------------------------|----------|
| Density, Kg/m³                        | 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        |

Table 1. Johnson-Cook material model used in numerical technique
3. Results and Discussion

Sliding and shearing of grains observed to be a common phenomenon in all the machining processes irrespective of the depth of cut & speeds. Remarkably, the highest average temperature rises of 912.59 °C observed at 60 ms$^{-1}$ at 5 mm depth of cut. The temperature versus time graph and numerical analysis results plot revealed that the accumulation of tandem grains found to offer a maximum resistance ahead of the tool-chip interface reason attributed to the collection of bulk grains leads to strain hardening. This strain hardening mainly observed near to the secondary shear zone and found to cross the value mentioned in the J-C Model, refer to Fig 2 (a) and Table 1. At 60 ms$^{-1}$ speed, as the depth of cut decreased, temperature found to be lessening. At 2 mm depth of cut, the average temperature found to vary linearly and commenced early compared to other depth of cut. Non-linearity in the temperature observed more prominent at a lower speed, i.e., at 60 ms$^{-1}$ compared to 70 and 80 ms$^{-1}$. As the cutting speed increased, the effect of grain orientation shadows the non-linear behavior in the temperature profile. The similar effect observed at 70 ms$^{-1}$ refers to Fig 2 (b). However, at a higher speed of 80 ms$^{-1}$, the significance of the depth of cut not found to have a significant role in the variation of temperature refer Fig 2. (c). The residual stress/von-mises stress found to vary in the range of 1.98e9 to 1.83e9 Pa. The residual stress found to accumulate in the primary shear zone irrespective of all the machining conditions and found to exceed the yield stress (A), i.e., at 1.539e9 considered in the J-C model parameter. In the present investigation, the flow stress was found to cross the assumed value, and it would be apt to address henceforth residual stress as flow stress. The flow stress was found to be more crucial at higher depth of cut. Comparatively thick chips found at 5 mm and thin chips have formed at 2 mm depth of cut refer to Fig. 3, 4 & 5. Relatively longer curvilinear chips observed at 80 ms$^{-1}$ also, at different depth of cut. Segmented short chips have seen at 70 ms$^{-1}$, and serrated chip flow followed at a low speed of 60 ms$^{-1}$. At this speed, the chips found to flow straight compared to other speeds. Also, the probability of breaking of chips found to be more consistent compared to different speeds, and depth of cut refers to Fig.4. A powerful relationship observed in the temperature plot with the flow stress plot. There is a change in the temperature with the breaking of grains. Early onset of breaking leads to more non-linearity in temperature versus time curve refer to Fig.2 & 3 (a). The continuous curvilinear chips were accountable in achieving constant steady-state conditions during the machining process refer to Fig.2 (a)(b), & (c). Depending on the machining requirements, the machinist may take prior precautions and guidelines to overcome the uncertainties during the machining process with the present set of simulation data.
Figure 2. Temperature versus time plot at 5, 3 & 2 mm depth of cut (a) 60 (b) 70 & (c) 80 ms⁻¹
**Figure 3.** Von-Mises stress/Residual stress and Temperature plot at 60 ms$^{-1}$ (a) 5 (b) 3, & (c) 2 mm depth of cut.
Figure 4. Von-Mises stress/Residual stress and Temperature plot at 70 ms\(^{-1}\) (a) 5, (b) 3, & (c) 2 mm depth of cut.

Figure 5. Von-Mises stress/Residual stress and Temperature plot at 80 ms\(^{-1}\) (a) 5, (b) 3, & (c) 2 mm depth of cut.
4. Conclusion

The machining was carried out at different velocities: 60, 70, and 80 ms\(^{-1}\) and with depths of cut of 2, 3, and 5 mm. Results revealed that the accumulation of tandem grains offers a maximum resistance ahead of the tool-chip interface due to the strain hardening effect, during the metal removal process. This leads to a maximum rise in temperature up to 912.59 °C which was observed in the secondary shear zone. Serrated chip flow was observed mainly at a low speed of 60 ms\(^{-1}\). The Strain hardening effect was more substantial at 60 ms\(^{-1}\) and at 5 mm depth of cut compared to any other machining parameters.

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