A 3D study of the influence of friction on the Adiabatic Shear Band formation during High Speed Machining

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ABSTRACT: Adiabatic Shear Band (ASB) may form at very high speeds with materials having poor thermal conductivity. It results from the competition between plastic hardening and strain softening and initiates when the latter becomes predominant. Because of high speeds, the heat created does not have sufficient time to propagate, leading to the formation of high strain localized zones. Starting from a previous description of the ASB formation process where the friction phenomenon has been considered as negligible, the aim of this paper is to describe the influence of the latter on the ASB formation process. Consequently, using a very general 3D finite element code where mesh adaptation is triggered by an error estimator within an Arbitrary Lagrangian Eulerian formulation, the formation of several ASB has been simulated in 3D High Speed Machining taking friction into account. The results obtained allow proposing a description of its influence on both the ASB build up process and the final chip geometry.

Key words: Adiabatic Shear Band, High Speed Machining, Segmented Chip, Friction, Adaptive Remeshing.

1 INTRODUCTION

Adiabatic Shear Band (ASB) is a well known material alteration which takes place at very high speeds with materials having poor thermal conductivity. It results from the competition between plastic hardening and strain softening. Its formation can be divided into three stages. In the first one, the hardening is predominant with respect to softening. In the second, both phenomena become equivalent, and the ASB begins to form. During the latest stage, a very large drop of stress (about 80% of the maximum value) is followed by a huge rise of temperature (about 500-700°C) leading to the creation of a very thin band (about a few microns wide) of high temperature and large deformations.
Although many researches have been carried out on the ASB phenomenon itself, only a few of them concern forming processes [4, 5, 6, 7], and very few studies [3, 9, 10] propose numerical investigations that be used to better understand the ASB phenomenon. In [9, 10], Bäker *et al.* investigated the influence of material parameters on ASB formation, which made them able to show their great influence on the ASB features. More recently, we have studied both the temperature and strain rate evolutions in a high speed machining configuration to show that the ASB formation process is strongly dependent upon the interaction of two distinct bands of localisation: the temperature and the strain rate ones [3]. In this paper, we investigate the influence of friction on this phenomenon. After a brief description of both physical and numerical models, the previously detailed numerical [2] and physical [3] results are recalled, before studying the actual influence of friction.

2 MODEL

2.1 Physical Model

The utilized constitutive equation for the Ti6Al4V is presented in more details in [2, 3, 4, 6] and written as:

$$\begin{cases} \bar{\sigma}\left(\bar{\varepsilon},\dot{\bar{\varepsilon}},T\right) = K^{*}\Psi(T)\bar{\varepsilon}^{\,n^{*}\Psi(T)}\left(1 + C\ln\left(\dfrac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0}\right)\right) \\ \Psi(T) = \exp\left(-\left(\dfrac{T}{T_{MT}}\right)^{\mu}\right) \end{cases} \quad (1)$$

Where $\bar{\sigma}$ and $\bar{\varepsilon}$ respectively are the equivalent stress and strain. $K^{*}, n^{*}, T_{MT}, \mu$ and C are constant material values that are given in [9]. Because of extreme temperature rise in ASB, material parameters like conductivity and heat capacity are regarded as temperature dependent. A linear interpolation between values estimated at 24°C and 1200°C is used, which details can be found in [2, 3].

It is assumed that there is no heat transfer between the deformed material and the cutting tool, this latter being considered as perfectly rigid. A detailed description of the used numerical model, where no friction is taken into account can be found in [2, 3]. The aim of this paper is to qualitatively study the influence of friction using the following Tresca friction model:

$$\tau = -\bar{m}\frac{\bar{\sigma}}{\sqrt{3}}\frac{\Delta V}{\left\|\Delta V\right\|} \quad (2)$$

Where $\bar{m}$ is the Tresca coefficient which will either be equal to 0.4 or 0.8, ΔV is the difference in velocity between the two solids in contact and $\left\|\Delta V\right\|$ its norm.

2.2 *Orthogonal Cutting Configuration*

The present problem consists in a high speed orthogonal cutting operation first presented by Bäker [6] and described in Figure 1. The dimensions are summarized in Table 1.

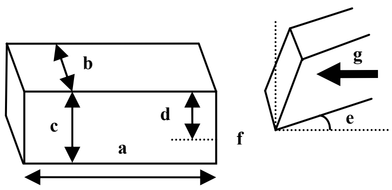

Figure 1: High speed orthogonal cutting test configuration.

In order to model plane strains, symmetry planes have been added on both lateral faces of the 3D mesh, which reaches a maximum of 29,000 nodes and 140,000 elements during the numerous remeshing operations.

Table 1. Orthogonal cutting test values described in Figure 1

Value description	Numerical value
Length (a)	0.28 mm
Width (b)	0.04 mm
Height (c)	0.15 mm
Cutting depth (d)	0.04 mm
Cutting angle (e)	10°
Roundness of the tool (f)	3 µm
Cutting speed (g)	50 m/s

3 RESULTS

3.1 *Comparison with Baker's results*

In order to evaluate our numerical model based on an adaptive ALE formulation using error estimation [2], the results have first been compared to Bäker's [6]. Figure 2 shows that they are very similar in terms of strain distribution, which has also been confirmed by analyzing the cutting force evolution in [4]. The difference between chip curvatures is explained by the different tool edge radii used in both models, the one utilized here being more realistic. A numerical investigation, detailed in [2], has shown that these results, obtained after four days on a PC Pentium IV, 3.20 GHz with 2Go of RAM, are mesh independent. It can therefore be concluded that the developed model is capable of simulating ASB in 3D orthogonal cutting without any preliminarily information to guide the numerical model.

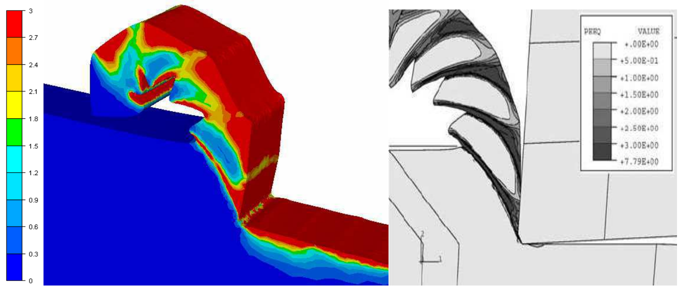

Figure 2: Left: strain distribution in a 3D segmented chip of Ti6Al4V at t = 178.2 µs. Right: 2D Bäker's model [6].

3.2 *Description of the ASB formation process*

In [2, 3, 4], it has been shown that without friction, the ASB formation process strongly depends on the interaction of two distinct bands: the temperature and strain rate ones (Figure 3). Because the initiation point of the temperature band is located at the top of the tool tip, while the one of the strain rate band is at the tool tip, the hot temperature point makes the strain rate band bend upward. When both bands overlay, then the ASB actually initiates.

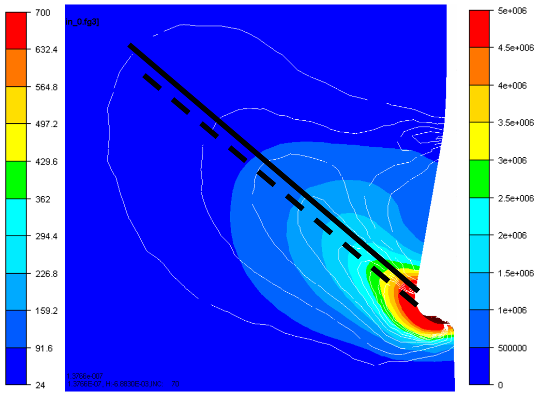

Figure 3: Temperature (left scale) and strain rate (contour plot, right scale) at t = 137.7 ns, with approximate directions of temperature (full line) and strain rate (dashed line) bands.

3.3 *Friction effect in orthogonal cutting*

Taking friction into account has two main consequences in an orthogonal cutting. First, the material at the tool tip is less easily convected, because of the difficulty for it to slide along the cutting edge. Consequently, the temperature is more localized there (Figure 4), the contact tool length is larger, and the temperature is higher.

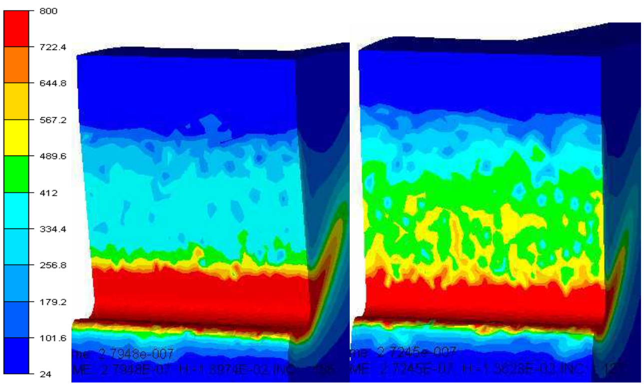

Figure 4: Temperature (°C) distributions for $\bar{m}$ = 0.4 (left) and $\bar{m}$ = 0.8 (right) at t = 273 ns.

3.4 *Friction effect on the ASB formation*

At the beginning of cutting, the temperature is localized at the tool tip. The increase of friction leads to a localization of the temperature closer to the middle of the tool edge radius, where the material separates. This makes the initiation point of the temperature band take place closer to the middle of the tool tip. Because the hottest point is no longer located at the top of the tool tip, it does not influence the ASB by making the temperature band bend upward. Consequently, the ASB angle decreases when friction increases (Figure 5).

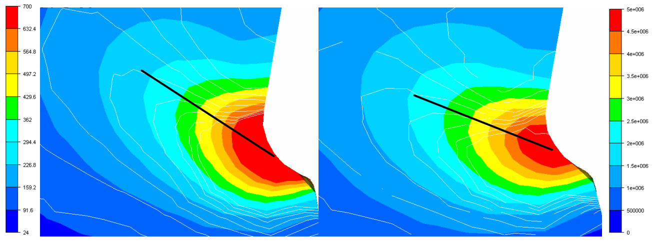

Figure 5: Temperature (left scale) and strain rate (right scale, contour plot) for $\bar{m}$ = 0.4 (left) and $\bar{m}$ = 0.8 (right) at t =142 ns

Because the ASB angle is lower at the band initiation with higher friction, the band has to cover a larger distance to reach the free surface. As a consequence, the ASB will need more time to establish (about 450 ns with $\bar{m}$ = 0.4 and 500 ns with $\bar{m}$ = 0.8). During the ASB formation, it can be observed that its angle increases, making the band bend upward, and consequently establish more rapidly. This can be explained by analyzing the influence of the temperature at tool edge (Figure 6). Because of friction, the temperature is higher in this region, making the band to bend upward and consequently the ASB angle increase throughout the formation process.

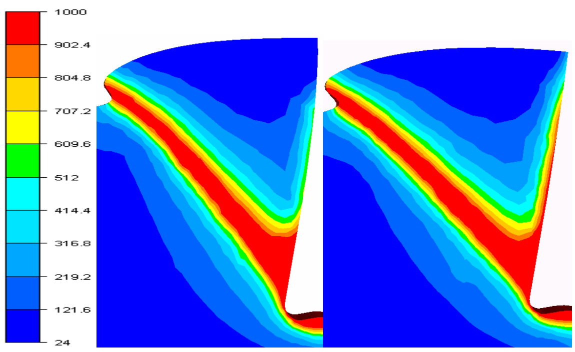

Figure 6: Temperature distribution (°C) for $\bar{m}$ = 0.4 at t =448 ns (left) and $\bar{m}$ = 0.8at t =502 ns (right)

3.5 *Influence of friction on the chip geometry*

After the setting up of the first ASB, the temperature distributions are very close in both models, with low and high friction coefficients. As the ASBs are almost subjected to the same influence, it makes the ASB angles similar. It can therefore be concluded that the influence of friction is lower on the second ASB formation.

In Figure 7, it can be observed that the chip geometry is largely dependent upon the friction phenomenon. When looking at the free surface, it can be seen that even if the ASB angle is lower with higher friction, it does not really influence the material flow there. Consequently, the difference in chip geometry is only governed by the phenomenon which takes place at the tool edge region. This is confirmed by noticing that stronger friction forces the material to stay longer in contact with the tool. Consequently, the stuck material does not curve down before a larger amount of material has been cut, but when it does, it does it more rapidly (Figure 7).

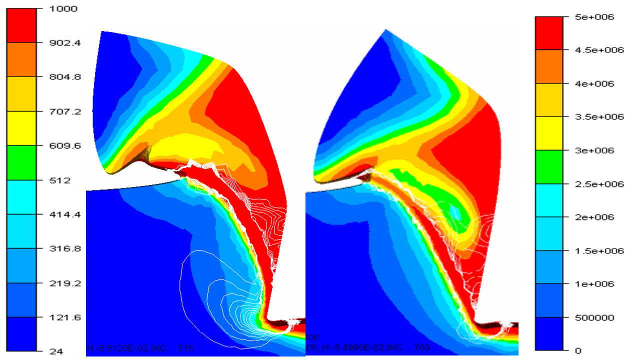

Figure 7: Temperature (left scale) and strain rate (right scale) for $\bar{m}$ = 0.4 (left) and $\bar{m}$ = 0.8 (right) at t = 1192 ns

4 CONCLUSIONS

This numerical study provides a better understanding of the friction influence on the ASB formation process. It shows that it only strongly influences the angle of the first ASB, leading to the formation of a different chip. Further experiments should be welcome to confirm or contradict these numerical observations.

ACKNOWLEDGEMENTS

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