Modeling of surface dynamic recrystallisation during the finish turning of the 15-5PH steel

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Abstract

Modelling surface microstructural changes is a key issue when considering the manufacture of critical metallic parts. During machining, extreme conditions of temperature and deformation appear in the cutting zone. Consequently, surface microstructure is strongly affected with a direct impact on its integrity and the fatigue resistance of the part. Thus, the machining effect on the 15-5PH steel surface has been underlined. To explain and predict the formation of this modified surface layer, the dynamic recrystallization (DRX) has been considered.

Firstly, a DRX model has been identified using dynamic compressive tests. The calibrated DRX model is composed of two parts: a criterion of initiation and an evolution law. EBSD maps obtained from compressed samples show recrystallized microstructures comparable with micrographs of machined surface.

Then, the DRX model has been implemented in an ALE orthogonal cutting model. Numerical simulation results predict the recrystallized layer at the machined surface. The DRX proportion rapidly decreases from 100% at the surface to 0% at few micrometers depth. So, experimental observations are successfully reproduced.

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1. Introduction

Precipitated hardening (PH) stainless steels show excellent mechanical properties, excellent weldability and good corrosion resistance. That is why they are used in aerospace and nuclear industries. Predicting the surface integrity of mechanical parts is crucial for these industries [1]. This paper focuses on the surface microstructure modifications generated by finish longitudinal turning of the 15-5PH steel.

Recently, a number of studies have reported the apparition of a white layer on the surface of turned steel. Ramesh et al. [2]’s study presents white layers formed during machining of hardened AISI 52100 steel (62 HRC). TEM results suggest that white layers produced at low-to-moderate cutting speeds are in large part due to grain refinement induced by severe plastic deformation, whereas white layer formation at high cutting speeds is mainly due to thermally-driven phase transformation (austenite transformation). Umbrello et al. [3] study residual stresses induced by hard machining of AISI 52100 steel. It is shown that white and dark surface layers formation influences the residual stress distribution. Two simple thermal models based on the hardness modification were considered to predict phase transformation.

Nevertheless, the formation mechanisms and nature of white layers produced in machining are not clearly understood to date. On one hand, phase transformation (rapid heating, austenite formation and quenching) due to purely thermal effects is considered [4]. The white layer is described as untempered martensite and is accompanied by a dark layer (overtempered martensite).
On the other hand, some authors present the white layer as an ultrafine structure layer generated by a large strain gradient and high strain rate (dynamic phase transformation, [5]). The mechanical aspect is clearly dominant.

In the present work, after the finish turning operation, a white surface layer is revealed (Figure 2). To explain and predict the formation of this modified surface layer, two metallurgical transformations may be evoked: the possible austenitization of the initial martensitic structure of the 15-5PH steel or the the dynamic recrystallization. Concerning the possibility of an austenite transformation of the machined surface, Mondelin et al. [6] have shown that austenitization doesn’t occur during the finish turning of 15-5PH (due to very high thermal kinetics) and so it is not the explanation of the modified surface microstructure. So, this study focuses on the dynamic recrystallization (DRX). A DRX metallurgical model is calibrated using compression test and then is implemented in a 2D orthogonal cutting simulation.

2. Surface modified microstructure

The present study considers a classical orthogonal cutting test of discs (Figure 1) with standard cutting conditions. TNMG 16 T3 08 carbide inserts are used with 0.02mm cutting edge radius. The material studied is the 15-5PH steel (a martensitic precipitation-hardening stainless steel) in H1025 (40HRC) condition.

The following cutting parameters have been used:
- Cutting speed $V_c = 250 \text{ m.min}^{-1}$
- Feed $f: 0.18 \text{ mm.rev}^{-1}$
- Lubrication condition: flow with an emulsion (15% of mineral oil)
- Insert: Al$_2$O$_3$/TiCN coating

After machining, surface samples have been coated in resin, mechanically polished and etched. A white layer is then revealed with a microstructure totally different compared with the 15-5PH original one (Figure 2). Its average thickness is around 3 $\mu m$.

3. Dynamic recrystallization modeling

3.1. Surface observations

SEM/EBSD observations reveal a submicronic structure (Figure 3) and suggest that white layer is in large part due to grain refinement induced by severe plastic deformation. Indeed, the surface layer is composed of small equiaxed grains (characteristic of dynamic recrystallization (DRX) phenomenon [7]) and different from sub-surface deformed microstructure. So, a DRX model should be calibrated in order to predict surface transformation during machining of 15-5PH.
5.2. DRX model

The DRX model is composed of two parts: a criterion of initiation and an evolution law (kinetic). Following the methodologies developed by Poliak et al. [8] and Mirzadeh et al. [7], the two parts of the model are extracted from compression tests. A range of three strain rates (0.01, 1 and 80 s\(^{-1}\)) and six temperatures (20, 100, 200, 400, 500, 600 °C) has been tested up to a minimum plastic strain of 100%. This level of strain hardening is commonly encountered in processes like machining. The capacities of the thermo-mechanical power-controlled simulator Gleeble® were used for these experiments. Heating is produced by Joule effect. Figure 4 presents microstructure before and after compression tests.

![Figure 4: Comparison between original microstructure and microstructure after a compressive test (T=600°C; dc/dt=80 s\(^{-1}\)).](image)

After some corrections due to friction, self-heating and machine rigidity, isothermal ‘stress-plastic strain’ curves are obtained (Figure 5, a). DRX critical condition of deformation is determined from the inflection point of the curve ‘hardening rate- stress’ curve according to Poliak et al. [8] (Figure 5, b). Then, plotting the evolution of the DRX critical strain \(\varepsilon_c\) as a function of the Zener-Hollomon parameter for all the tested conditions (temperature and strain rate), it appears a linear relationship (Figure 6).

Following the approach of Mirzadeh et al. [7], the progress of DRX is modelled by a Jonhson-Mehl-Avrami-Kolmogorov (JMAK) kinetic equation (Equation 1). The flow softening of the material (Figure 5, a) is directly related to the proportion of DRX (X: proportion of material recrystalized). Plotting \(\log(\ln(1/(1-X)))\) as a function of \(\log(t)\) (Figure 6) for all the tested conditions, it is possible to calibrate parameters \(k\) and \(n\) of JMAK kinetic equation.

\[
X = 1 - \exp\left( -k \cdot t^n \right)
\]

Finally, the following model of DRX is obtained (Equation 1):

- If \(\varepsilon_p < \varepsilon_c\) then \(X = 0\)
- If \(\varepsilon_p > \varepsilon_c\) then \(X = 1 - \exp\left( -\dot{\varepsilon}_p \cdot t_{RD}^{1.1} \varepsilon_c \right)\)

With
- \(t_{RD} = (\dot{\varepsilon}_p \cdot t_{RD})\): DRX time
- \(\varepsilon_p\): plastic strain
- \(\dot{\varepsilon}_p\): plastic strain rate
- \(\varepsilon_c\): critical strain \((\varepsilon_c=0.0012\ln(Z)+0.013)\)
- \(X\): proportion of recrystalized material
- \(Z\): Zener hollomon parameter

![Figure 5: Compression test: flow curve and work hardening curve for T=500 °C and dc/dt=0.01 s\(^{-1}\).](image)

![Figure 6: Example of Avrami constant determination for T=500°C and \(\varepsilon = 0.01\ s^{-1}\).](image)
4. Application of the DRX model in machining simulation

4.1. Orthogonal cutting model description

The 2D orthogonal cutting model based on the A.L.E approach (Figure 7) has been developed and wholly described by Courbon et al. [9]. The simulated machining time is equal to 10 ms for the following simulations. Coupled thermo-mechanical simulations are conducted in the commercial code Abaqus/Explicit. The model consists of a deformable workpiece and rigid cutting tool. In this Eulerian-based A.L.E model, Eulerian boundaries, such as input and output surfaces, have to be defined to permit the flow of the workpiece material (Figure 7). The nodes at the bottom of the workpiece are fixed vertically via symmetry conditions whereas the tool is completely embedded. As for the interface, a master slave penalty contact method was used. The frictional behavior of the interface is modeled according to the identification performed using the friction tests and results described in [10]. So the friction coefficient is set as dependent on the local sliding velocity. Regarding thermal modeling of the interface, thermal contact conductance $k$ is fixed to $104 \text{ W.m}^{-2}.\text{K}^{-1}$ to be consistent with the identification of Courbon et al. [11].

A Johnson-Cook-Flow stress model has been used to model the 15-5PH steel mechanical behavior. The model parameters have been calibrated using experimental compression and traction tests from 20°C to 1100°C ([13], [14]).

The important thermo-mechanical interactions existing in machining are considered by the Quinney-Taylor coefficient which indicates the fraction of plastic work converted into heat. A constant value of 0.9 has been set as it is usually considered in the machining literature [15].

The previously calibrated metallurgical model (dynamic recrystallization model) has been implemented in the 2D orthogonal model using user-programmed subroutine (VUMAT in Abaqus/explicit).

4.2. Dynamic recrystallization results

Prediction of dynamic recrystallization induced by an operation of orthogonal cutting leads to the DRX mapping presented in Figure 8.

The physical properties of the WC-Co cutting tool substrate can be found respectively in [12] and will not be recalled here. The Al203-TiCN coating has not been directly represented in the numerical model but its tribological influence at the interface has been taken into account with the friction model (friction and heat partition coefficients).

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Numerical results show that the DRX appears in the primary shear zone (chip formation zone). Nevertheless, the proportion of recrystallized material $X$ after the primary shear zone (and so in the chip) remains very low (about 20%). Conversely, the proportion of
recrystallized material X reaches 100% after a passage through the second and the tertiary shear zone (contact zones between the tool, the chip and the machined surface). This result is directly related to extreme temperature and deformation conditions which occur in these friction zones.

It could be noted that the DRX proportion drastically goes down after the first five microns in depth (that corresponds to experimental observations).

5. Conclusion

After an operation of finish turning on 15-5PH martensitic steel, an affected surface layer (= white layer) consistently appears. To justify and predict the formation of the surface layer, the dynamic recrystallization has been taken into account.

Using compression tests, a DRX model (based on a criterion of initiation and an evolution law) has been calibrated. Then, the calibrated metallurgical model has been implemented in an orthogonal cutting model using a user subroutine.

The calibrated DRX model coupled with the 2D cutting model provides DRX mapping of the machining surface. The DRX phenomenon is condensed at the surface level since the DRX proportion considerably goes down after the five first microns in depth (that corresponds to experimental observations). Supported by SEM/EBSD observations of the machined 15-5PH microstructure, these simulations results can confirm that the modified surface layer is due to dynamic recrystallization phenomenon.

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