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Further insight into the chip formation of ferritic-pearlitic steels: Microstructural evolutions and associated thermo-mechanical loadings

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ABSTRACT

The main objective of this paper is to clarify the deformation mechanisms of ferritic-pearlitic steels in metal cutting and correlate them to the associated thermo-mechanical loadings. Dry orthogonal cutting tests have been performed on a normalised AISI 1045 steel with coated carbide tools. Experimental evidences of a drastic grain refinement process in the main deformation zones are advanced on the basis of optical microscope, Field Emission Scanning Electron Microscope (FESEM) and Electron BackScattered Diffraction (EBSD). Microstructural evolutions leading to a grain size down to 200 nm and fragmented cementite are especially emphasized. A numerical approach is further employed to target and quantify the loadings applied to the machined material and extract further information on the Secondary Shear Zone (SSZ). Strains amplitude appears to be the driving parameter of these evolutions via a dynamic recrystallisation process promoted by an intense and localised heat generation. The present contribution highlights that in-depth and microscale investigations of chip formation including microstructural aspects are still required.

1. Introduction

Due to an increasing demand for process control and cost reductions, a need for flexible and predictive cutting models is clearly rising in order to limit the experimental campaigns, optimise the use of existing materials and also help toolmakers in designing new grades and geometries. However, achieving predictive numerical models in machining is only possible if material constitutive equations and tribological interactions between workmaterials and tools are known and properly implemented.

An extensive work is in progress to gain a better understanding of material behaviour in metal cutting. Many research groups have endeavoured to assess the thermo-mechanical loadings, reproduce them as closely as possible to finally identify a constitutive model. The intense conditions under which deformation occurs still make the comparison between the observed behaviour in conventional testing methods and the one encountered in the process relatively complicated. However, prior to the characterisation of the rheology of a material, a proper understanding of the deformation mechanisms involved in the chip formation process as well as the conditions under which the machine material is actually loaded, can be seen as essential. Only then the advanced constitutive models based not only on empirical fitting but also on strong physical basis can be proposed.

In this framework, the main objective of this paper is to investigate the deformation mechanisms of ferritic-pearlitic steels in metal cutting, to emphasise the microstructural evolution taking place in the main deformation zones and correlate them to a range of thermo-mechanical loadings. The first part of this work aims at highlighting that chip formation mechanisms are still not fully understood from a microstructural point of view, especially in the SSZ. A systematic quantification of the local thermo-mechanical loadings in the different shear zones, as well as investigations covering the microstructural phenomena occurring on a microscale, is of vital importance in order to enhance the understanding of the process. Another insight into the process is thus provided on a microscopic scale by a detailed metallurgical study based on optical microscope, Field Emission Scanning Electron Microscope (FESEM) and Electron BackScattered Diffraction (EBSD). A numerical approach is further employed in order to target and quantify more effectively the loadings applied to the machined material and extract additional information on the Secondary Shear Zone (SSZ).

2. Background of the study

2.1. Study of the cutting mechanisms

Investigating cutting mechanisms can be based on a simple model describing the mechanics but also the kinematics aspects of

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metal cutting. Single shear-plane model, upper-bound theory, slip-line theory or many other approaches reviewed by Astakhov et al. [1] have been developed to this end. From an experimental point of view, it mainly rests on a thorough analysis of the collected chips or chip root specimens obtained with the so-called quick-stop method. As far as steels are concerned, such studies have been mostly conducted on hardened steels to understand the mechanisms leading to the specific serrated shape of the chips. Transition from continuous to serrated chips has been observed depending on the cutting conditions [2] and has been attributed to a catastrophic shear instability [3] or even the initiation and propagation of cracks [4] depending on the initial hardness of the workmaterial. The previously cited works were focused on martensitic steels and highlighted the high deformations existing in the shear regions. They, however, limited their observations to a macroscopic level and did not really explain how the microstructure was actually affected.

Microstructural analyses have been mainly performed when the machined surface was of interest, especially regarding the formation of “white layers”, well known in hard turning. SEM images from Poulachon et al. [5] first showed that they present a featureless microstructure after etching with Nital. Nevertheless, the in-depth investigation carried out by Ramesh et al. [6] on a similar bearing steel emphasised that they are in fact made of refined grains and also suggested the occurrence of a martensitic phase transformation. These findings were in agreement with those reported by Barry and Byrne [7] some years before. The studies initiated by Duan and Wang [8] on a high strength low alloy steel and more recently by Duan and Zhang [9] on a hardened AISI 1045 steel proved that a better understanding of the cutting mechanisms could also be reached by using advanced analysis techniques (TEM, X-ray diffraction, etc.) and considering the phenomena occurring on a lower scale. The extensive work conducted in the latter [9] but again, applied to a martensitic steel, clearly showed how the martensite laths are deformed and broken in the deformed bands and how a dynamic rotational recrystallisation process can lead to fine equiaxed grains.

Carbon steels in a ferritic-pearlitic state are intensively used in many applications especially transmission shafts, camshafts, gear wheels, pinions and gear shafts or wheel hubs. Their structure mainly consists of a ferritic matrix with embedded islands of a hard second phase and thus can be seen as multiphase materials. Controlling this combination enables to reach higher ultimate tensile strengths and workhardening rates than conventional steels of a similar yield strength. This appears as a growth way to develop new cost-effective grades with improved mechanical properties and/or forming capabilities compared with quenched and tempered steels. It can be noted though that little attention has been given to how these microstructures behave when submitted to the loadings encountered in cutting.

Komanduri and Brown [10] mainly focused their work on the mechanisms governing the chip geometry. Authors showed that chip segmentation when machining a low carbon steel at low cutting speed (55 m/min) results from the combination of micro-cracks and voids formation around second phase particles (pearlite) and stick-slip friction on the tool rake face. However, this study did not investigate thoroughly the possibility of microstructural evolution and skated around the particular case of the SSZ. M'Saoubi and Ryde [11] tried to reach a lower scale in the deformation zones by applying the EBSD technique but faced limitations in resolving the EBSD patterns in materials with continuous chip such as carbon steels. This has been successfully provided by Trent and Wright [12] who presented an interesting transmission electron micrograph of the structure of the SSZ (figure 3.20 in the cited reference). In a 0.19%C steel machined at 70 m/min, they demonstrated that a microstructural evolution occurred and that refined equiaxed grains can be formed in the SSZ. Unfortunately it has neither been further investigated nor really considered in the literature but it undeniably attests that the phenomena related to chip formation are still not perfectly understood.

2.2. Assessment of thermo-mechanical loadings in cutting

The previous paragraphs confirmed that the mechanisms are complex from a material point of view but it did not mention the loadings the material is subjected to.

An extensive work has been carried out over the years and provides more information about the temperature field within the chip mainly by infrared and near infrared imaging techniques [13,14]. Jaspers and Dautzenberg [13] extracted an average value close to 300 °C when measuring the shear plane temperature at the chip's free side, which could be compared to the temperature of the Primary Shear Zone (PSZ). Similar results between 300 °C and 400 °C have been reported by Davies et al. [15] depending on the cutting conditions; furthermore, they also measured temperatures in the range of 600 to 1000 °C in the SSZ. M'Saoubi and Chandrasekaran [14] also recorded temperatures up to 1000 °C on the lateral tool face in 2D cutting of a quenched and tempered martensitic steel. It has especially been shown that the generated heat is impaired by the cutting edge micro-geometry or tool coating. A recent study conducted by Arrazola et al. [16] on a AISI 4140 steel under realistic cutting conditions (V_c=300 and 400 m/min, f=0.2 mm/rev with coated tools) reported a difference of nearly 300 °C between the maximum temperatures reached in the tool and in the chip. This has not been observed before. Besides the questions related to the actual contact conditions [17], the limitations in spatial and temporal resolution of these optical methods can be raised [15]. Heat generation at the tool-chip interface occurs indeed in such a confined area that most of the previous studies could have underestimated the temperature in the SSZ due to an averaging effect.

As far as strain and strain rates are concerned, their assessment can be done following two main methods:

- a metallurgical analysis of post-mortem collected chips or chip roots obtained from the already mentioned “Quick-Stop” tests [4,13];
- the deformation of a fine grid pattern, laid on the surface of the sample to be machined and observed with a microscope as in the works of Oxley [18] and Childs [19], or more recently in-situ with a high speed imaging technique [20].

As an example, Jaspers and Dautzenberg [13] extracted in the PSZ when machining AISI 1045 steel, equivalent plastic strains between 1 and 2 as well as strain rates from 15 to $20 \times 10^3\ s^{-1}$. When machining AISI 4140 steel, values of strains reported by Pujana et al. [20] were in the range 0.5–1 and strain rates between 10 and $30 \times 10^3\ s^{-1}$. In their latest study conducted on a low carbon steel AISI 1018 under severe cutting conditions, i.e. 1020 m/min and feed of 0.84 mm, List et al. [21] computed strain and strain rates based on the analysis of streamlines experimentally recorded by means of an ultra-rapid intensified CCD camera. They reported strains from 0 to 1.2 in the PSZ and maximum strain rates from $40 \times 10^3\ s^{-1}$ to $1.6 \times 10^5\ s^{-1}$ depending on the distance to the cutting edge. It was seen that these values are significantly varying from the entrance to the exit of the deformation region. Experimental values were also in good agreement with those extracted from a finite element model, showing the ability of numerical approaches to extract relevant local information.

The previously mentioned methods are known for providing a good order of magnitude but they hardly enable the extraction of