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Experimental study of Built-Up Layer formation during machining of high strength free-cutting steel

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ABSTRACT

Machinability of high-strength steels can be improved without degrading the mechanical properties using metallurgical solutions to create or retain non-metallic inclusions. Such a metallurgical treatment usually leads, during machining, to the appearance of so-called Built-Up Layers (BULs) or transfer layers on the cutting tool. These BULs protect the tool against wear, and longer tool life or better productivity is achieved. Formation of such BULs on the cutting tool depends on many parameters i.e. tool geometry, tool material, cutting conditions. This paper proposes an experimental methodology to identify and describe BUL occurring on the tool rake face. Machining tests were carried out with a high strength free-cutting steel using an untested AlSiTiN coated carbide tool. BULs morphology and composition were determined for various cutting conditions. Temperature distributions at the tool-chip interface were measured during the cutting tests using an infrared camera. BUL appearance was then linked to the thermo-mechanical conditions at the tool-chip interface.

1. Introduction

Machining often accounts for a substantial percentage of the cost of mechanical parts and up to 65% for automotive steel parts (Kirsch-Racine et al., 2007). This is why machinability is thoroughly investigated by steelmakers. Machinability is currently defined as the ability of a material to be formed by cutting processes. It is usually assessed through four main parameters: cutting forces, tool life, surface finish and chip control (Chandrasekaran, 1988) or (Klocke, 2001). Steelmakers have specifically developed steels with high machinability: the free-cutting steels which allow reaching high removal rates as well as longer tool lives. They are mainly low carbon steels with high sulphur contents but unfortunately poor mechanical performances. Downsizing is a current trend in mechanical industry especially in automotive industry and requires steel grades with higher mechanical performances and acceptable machinability. This is the reason why high strength free-cutting steels are developed.

Steel machinability depends on steel composition, microstructure and inclusions (Stahl, 2012). Composition and microstructure are defined according to mechanical properties specifications. The most relevant way to enhance machinability is to custom metallic and non-metallic inclusions. Two main solutions are currently used: increase sulphur content and/or promote some oxide types. However high sulphur content decreases some steel properties such as notch toughness or fatigue resistance and makes forging operations more difficult. This is why steelmakers also focus on oxide inclusions trying to produce ductile oxide types with low abrasiveness.

In a first part, this paper presents a brief review about steel inclusions influence on machinability, and it focuses especially on the formation of Built-Up Layers (BUL) which are well-known to enhance the chip flow at the tool-chip interface and to reduce the tool wear. In a second part, an experimental approach of machinability is performed on high strength free-cutting steel highlighting the benefits of inclusions. The high MnS (Manganese Sulphide) content of this steel is assumed to bring a very good chip breakage, and combined with the oxides, the non-metallic inclusions may contribute to the formation of Built-Up Layers. The main objective of this study was thus to investigate the conditions of BUL appearance

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and its effect on cutting forces, temperatures and more generally on steel machinability.

2. Influence of inclusions on steel machinability

Kiessling proposes an important work (Kiessling and Lange, 1990) about steel inclusions and discusses the influence of non-metallic inclusions on steel machinability. He gives an interesting review of the early works. He also refers to the excellent summary of metallurgical aspects of cutting given by Trent and Wright now gathered in (Trent and Wright, 2000).

The inclusions affect all the factors defining the machinability, i.e. tool life, surface quality, cutting force level, and chip formation. In an elementary cutting process, the chip is formed by intense shearing in the *primary shear zone*, PSZ; a *secondary shear zone* SSZ appears along the tool-chip interface, also called *flow zone*. In this zone the chip adheres to the tool rake face (seized region) and then slides (sliding region) and finally breaks contact with tool. The flow zone plays an important role in the cutting process; plastic deformations, stresses and temperatures are there pretty high. Non-metallic inclusions affect the shear process in both primary shear zone and flow zone. In the PSZ, inclusions act as stress-raisers initiating crack formation and then embrittling the chip (Bernsmann et al., 2001). In the flow zone, inclusions are also strongly bonded to the rake face and plastically deformed in the chip flow direction. They also act there as stress raisers and may form a thin layer i.e. a Built-Up Layer which mainly protects the tool rake face and increases tool life. The overall influence of inclusions on machinability depends on their quantity, size, shape, distribution, physical and mechanical properties (Gladman and Pickering, 1962). In the following, effects of sulphides and oxides inclusions are described first then the formation of a Built-Up Layer is detailed.

2.1. Sulphides inclusions

Sulphur is the most important non-metallic element present in the composition of free-cutting steel. The main part of sulphur is combined with manganese, forming manganese sulphide inclusions. According to Kiessling and Lange (1990), the other main sulphide inclusions types are iron sulphide FeS and (Mn,Me)S (Me as metal). The first detailed studies on the positive effect of sulphides on steel machinability were performed during the sixties and were continued in the following decades until today.

In their study, Naylor et al. (1976) observed that an increase in sulphur content results in shorter chips; and Trent and Wright (2000) noted that this reduces the tool-chip contact length and decreases cutting forces. Unfortunately it affects mechanical properties such as notch toughness.

Three different types of manganese sulphide inclusions are to be distinguished according to Sims and Dahle (1938), each having its particular shape and characteristics:

- Type 1 sulphides are spheroidal due to their solidification in the liquid metal. They are found regularly distributed in steel. The melting point of pure MnS is about 1600 °C. Sulphides in steel are not pure and contain oxides (FeO, MnO, SiO_2) and FeS which decrease the melting temperature under the liquidus of steel (around 1500 °C).
- Type 2 sulphides were first observed on final products having concentrations of about 0.002 wt%. Al and about 0.008 wt%. active oxygen. These sulphides are usually found in killed steel when a too strong deoxidization leads to a too low level of oxygen (lower than 0.01%). They segregate in a eutectic like MnS-phase at 1180 °C. Type 2 sulphides are not supposed to be found in closed segments but rather as fine sulphides in a fan or chain like pattern, actually precipitated as interconnected branched rods. These sulphide inclusions can be considered as detrimental to the machinability.
- Type 3 sulphides appear at very low oxygen contents in iron melts with low melting temperature. They are randomly dispersed. Their shape is angular or faceted. These sulphides only occur when an excessive amount of deoxidizer is used; this should be avoided by the steelmaker. This type of sulphide should not be found in steel.

The most common solution adopted by steelmakers consists in limiting the sulphur content and promoting type 1 sulphides which are softer and less abrasive than types 2 and 3. During the cutting process, sulphide inclusions are elongated in the primary shear zone, and more extensively in the flow zone adjacent to the tool-chip interface where additional shearing occurs. As noted by (Kiessling and Lange, 1990), sulphide inclusions act as stress raisers in the shear zones and then facilitate chip formation and chip flow. This stress raising effect depends on inclusions shape and size. At the tool-chip interface low concentration of elongated sulphide inclusions is more efficient than a high concentration of small spheroid inclusions. Gladman and Pickering (1962) compared the friction force at the tool-chip interface and the number of sulphide inclusions. Machinability is improved by an increasing size of sulphide particles and a decreasing number.

Finally, it was experimentally verified that sulphide inclusions can be continuously deposited on rake and flank faces of the tool and deformed to form thin layers. These thin layers act as diffusion protective barriers (Bittes, 1993). The formation of these transfer or Built-Up Layers is examined in the following.

2.2. Oxides inclusions

Steelmaking processes produce oxide inclusions: endogenous inclusions provided by steel deoxidation and exogenous inclusions due to slag or refractories. Oxide inclusions fall into two main categories: hard and brittle inclusions on the one hand and malleable ones on the other. Hard and brittle inclusions never deform plastically at any temperature encountered in steel cutting process and have thus a detrimental effect on steel machinability. They are often sharp-edged and induce a high tool wear rate. Corundum, escolaite or spinels belong to this category (Kiessling and Lange, 1990). Some other oxide inclusions can deform plastically in the primary and/or the secondary shear zone and are gathered in the second category. Inclusions within particular composition ranges in the $MnO\text{-}SiO_2\text{-}Al_2O_3$ and $CaO\text{-}SiO_2\text{-}Al_2O_3$ systems belong to this category. Specific metallurgical treatments such as calcium treatment have been developed to preferentially form these types of oxide inclusion phases. Kiessling and Lange describe their effects on Al and Si-deoxidized steels (Kiessling and Lange, 1990). After Ca-treatment, manganese sulphide inclusions composition can be also modified leading to less malleable inclusions. Aluminium oxides are transformed to complex $CaO\text{-}Al_2O_3$ or $CaO\text{-}Al_2O_3\text{-}SiO_2$, depending on the initial deoxidation process. The new complex oxides have a smoother geometry reducing their abrasiveness. Silicates are also transformed into complex $CaO\text{-}Al_2O_3\text{-}SiO_2$ inclusions. When sulphur content is high, calcium treatment can modify the sharp-edged Al_2O_3 inclusions into globular calcium-aluminates surrounded by soft rims of (Ca,Mn)S (Ruppi et al., 1998). During cutting of Ca-treated steels, adhering layers with compositions similar to that of the inclusions in steel are often formed on the tool. These Built-Up Layers reduce tool wear, especially crater wear (Larsson and Ruppi, 2001).

As for the sulphide inclusions, the oxide inclusions which deform plastically have a positive influence in the shear zones of the cutting process. Chip breakage is favoured. The inclusions layers or