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6th CIRP Conference on Surface Integrity

Influence of lubrication mode onto residual stress generation in turning

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Abstract

Residual stresses in the surface layer have a significant impact on the fatigue resistance of machined surfaces. This paper investigates the influence of lubrication mode (flood cooling ⇔ micro quantity lubrication) and of cutting fluid composition (emulsion ⇔ vegetable oil) on the generation of residual stresses in finish turning. First an experimental campaign quantifies the sensitivity of both parameters when turning an austenitic stainless steel 316L, then a numerical model provides some physical explanations on the results. It is shown that the application of a cutting fluid for this application does not influence significantly the residual stress generation.

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Keywords: Turning; numerical modelling; lubrication;

1. Introduction

Fatigue resistance of critical components is correlated to the surface integrity of highly stressed areas [1]. Surface integrity is characterized by several elements: residual stress profiles, microstructure and surface roughness. The finishing process plays a dominant role in surface integrity. For cylindrical surfaces, the longitudinal turning process (Fig. 1) is the preferred solution because this process is productive and easy to handle on any lathe.

The surface integrity induced by turning operations is governed by several parameters:

- the cutting tool geometry and its composition (substrate, coating)
- the cutting parameters (cutting speed, depth of cut, feed, ...)
- the cutting fluid (composition of the cutting fluid, flow rate, orientation...).

This paper focuses on the influence of cutting fluids in turning. While a huge number of publications have investigated the influence of cutting fluids on criteria such as tool wear, surface roughness, cutting forces [2-4], ... The influence of cutting fluids on residual stresses has gained little attention from the scientific community. Few works were concerned with specific case studies, i.e. hard turning of an AISI52100 steel [5], or cryogenic assisted turning of Inconel718 [6].

This, this paper focuses on the influence of cutting fluids on surface residual stresses generated by longitudinal finish turning of an austenitic stainless steel AISI316L. From a theoretical point of view, it is expected that cutting fluids influence cutting by three ways:

-Heat transfer: the cutting fluid evacuates heat from the cutting zone and especially from the machined surface. This rapid decrease of temperature on the machined surface may influence the residual stress generation as shown by [1].

-Tribological mechanisms: the cutting fluid may induce a decrease of friction at the tool-workmaterial interface and may

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lead to a reduction of mechanical stresses applied on the machined surface, as well as a reduction of heat generation [7] at the tool-workmaterial interface, that influence residual stress generation [8].

While the composition of cutting fluids has a clear influence on heat transfer (heat conduction) and tribological mechanisms (friction coefficient), the application mode (flow rate, pressure, orientation of nozzles,...) has also an influence on heat exchanges (convection) [9] and tribological mechanisms (thickness of lubrication films) [10].

Few works aimed at modeling the influence of cooling and reduction of friction on residual stresses. It is only possible to report the work of [11] that proposes qualitative conclusions thanks to an analytical model.

The purpose of this paper is to study the influence of the composition of two cutting fluids (emulsion ↔ vegetal oil) and three modes of application (flood cooling ↔ MQL ↔ dry) on the residual stresses induced by a longitudinal turning operation of an austenitic 316L stainless steel. The paper will start by studying this effect through an experimental work. Then, a numerical model will aim at predicting the influence of the lubrication mode on the generation of residual stresses.

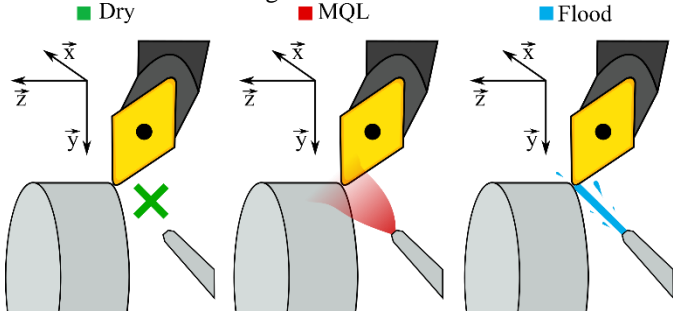


Fig. 1. Three lubrication modes

2. Experimental setup

Longitudinal turning tests have been performed on 316L samples as shown in Figure 2. The cutting insert (DNMG 15 06 08-PM1525 from Sandvik) was mounted on an insert holder (PNJNL2020K15). A dynamometer was used to measure cutting forces. Three types of tests have been done and replicated at least 5 times: flood cooling with emulsion, MQL cutting with a vegetal oil and dry turning.

Turning tests under flood cooling (emulsion) were performed with a concentration of 8% of Betronol EP V 1664-2. The application conditions were as follows: flow rate 40 l/min and pressure 4 bars.

Turning tests under MQL were performed with a vegetal oil named Ecocut MPF 245. A Vogel VarioSuper set-up was used to apply an oil mist with a flow rate of approximately 50 ml/h.

The residual stress state after turning was estimated by X-Ray diffraction thanks to an iXRD system from the proto company. A MG40 head having a 2 mm diameter collimator was used with conditions listed in [12].

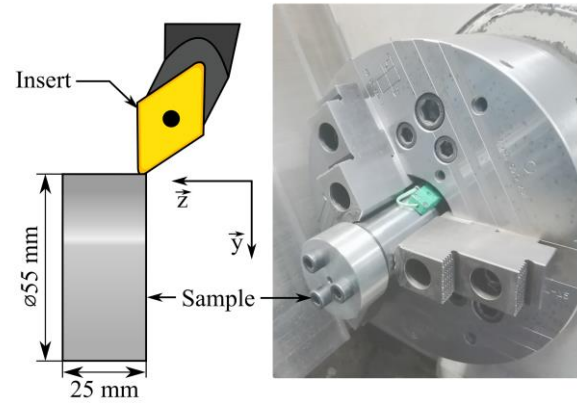


Figure 2: Configuration of longitudinal turning tests

3. Experimental results and discussions

3.1. Forces measurements

Figure 3 reveals very limited differences among the three testing conditions. The vegetable oil is supposed to decrease friction coefficient at the tool-workmaterial interface. However this theoretical behaviour is not visible on forces. So it can be assumed that oil is not able to penetrate at the interface between the cutting tool and the workmaterial. This is a common observation made in continuous cutting processes. The high contact pressure and the sliding movement of the workmaterial evacuates oil from the interface with few milliseconds as shown by [7]. Without any variation of friction coefficients, it is not possible to expect any variation of penetration F_p and feed F_f forces as shown by [13].

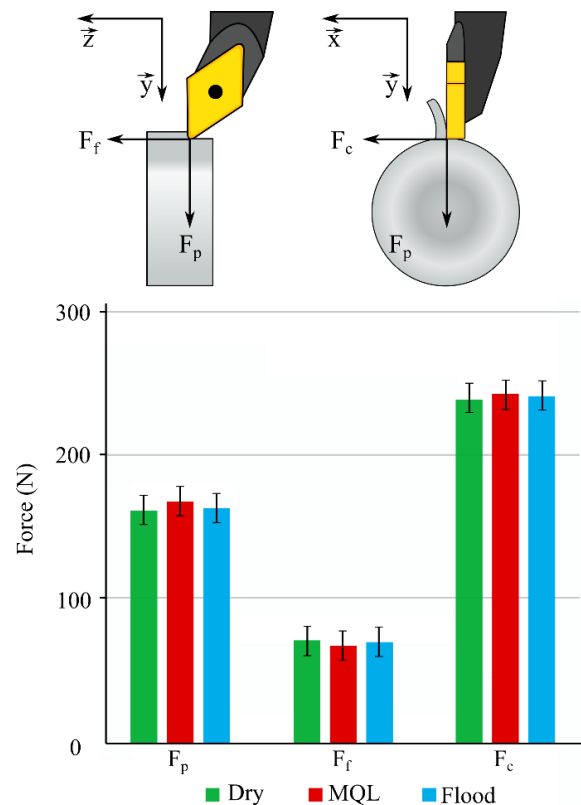


Fig. 3. Force measurements

3.2. Residual stress characterization

The residual stress states of 6 samples (2 for each lubrication conditions) have been characterized by X-Ray diffraction. Figure 4 plots the residual stress profiles obtained. Typical hooked shape profiles are obtained, with tensile stresses on the external surfaces. These results are in accordance with previous observations made by [14] on a 304L stainless steel.

However, Figure 3 reveals there is no significant influence of the lubrication mode on residual stress profiles. Even if section 3.1 has shown that there is almost no effect on friction at the interface, the cooling effect exists. It is well known that emulsion (mainly composed of water) has a much higher heat transfer coefficient, compared to oil mist and of course, compared to dry cutting (convection with air). Since [15], the exchange coefficient is respectively around $10 \text{ W.kg}^{-1}.\text{K}^{-1}$ for dry turning, $100 \text{ W.kg}^{-1}.\text{K}^{-1}$ for MQL, and $5000 \text{ W.kg}^{-1}.\text{K}^{-1}$ for emulsion. From a theoretical point a view, it is expected to modify the cooling rate on the machined surface and consequently the residual stress state. So as to investigate the sensitivity of the heat exchange coefficient on the residual stress state, a numerical investigation is of interest.

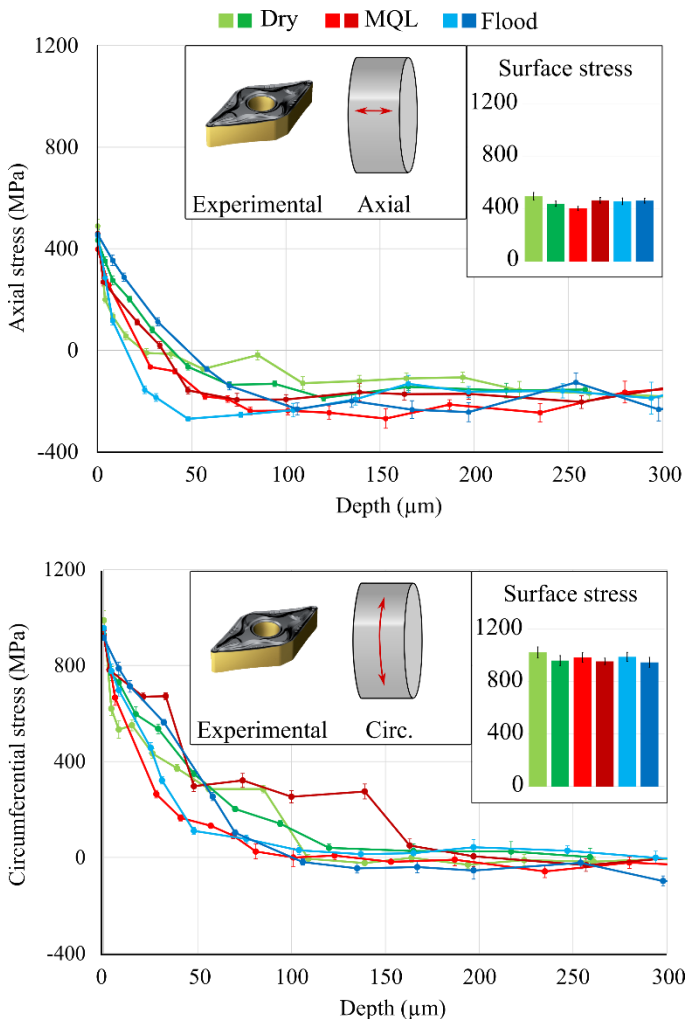


Fig. 4. Experimental residual stress profiles

4. Numerical design

Residual stresses are generated by the thermal and mechanical loadings induced by turning. Whereas thermal sources are more prone to induce tensile stresses in the external layer, mechanical loadings tend to induce compressive stresses [1]. Valiorgue et al. have shown that the most efficient way to predict residual stresses in longitudinal turning of an austenitic stainless steel is to use the so-called “hybrid model” [14]. It consists in replacing the tool and chip modeling by equivalent thermo-mechanical loadings (Fig. 5). These equivalent loadings are moved onto the machined surface with a velocity equal to the cutting speed. After the cooling phase, this model makes it possible to predict residual stresses. This hybrid model for residual stress prediction presents advantages like the removal of highly distorted mesh and contact modeling and the possibility of 3D multi-revolution simulations.

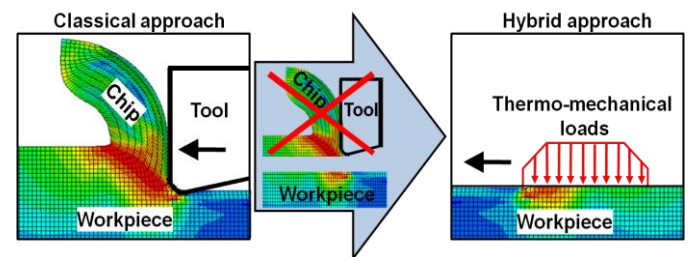


Fig. 5. Principle of the hybrid model

This model [14] has been used to evaluate the sensitivity of the heat exchange coefficient for each cutting fluid composition and for each application mode. It has been assumed that the material properties of the 316L are very close to the one of the 304L. As shown by [14], the intensity of the thermal and mechanical loadings generated by cutting around the cutting tool can be estimated thanks to the force measurements presented in section 3.1. As a consequence, a variation of force is required to expect a variation of the thermal and mechanical loadings applied on the surface. As almost no difference among the three lubrication modes have been observed, no variation of the thermo-mechanical loadings may exist. The unique variation comes from the heat exchange coefficient with the environment. It has been assumed that the exchange coefficients are respectively $10 \text{ W.kg}^{-1}.\text{K}^{-1}$ for dry turning, $100 \text{ W.kg}^{-1}.\text{K}^{-1}$ for MQL, and $5000 \text{ W.kg}^{-1}.\text{K}^{-1}$ for emulsion.

Figure 6 plots the 3 numerical residual stress profiles obtained in axial and circumferential directions. It can be seen that the overall shapes of the profiles are similar to the ones measured experimentally. Tensile stresses are induced in the external layer, then a peak of compression is obtained below the surface before going back to the equilibrium in the bulk. It can be stated that there is only slight difference among the three lubrication modes. It is only possible to observe a small decrease of the tensile stress state in the external layer when cutting with an emulsion. However, this variation is much smaller than the natural deviation observed among the experimental stress profiles. So, it can be concluded the heat

exchange coefficient plays a secondary role in residual stress generation.

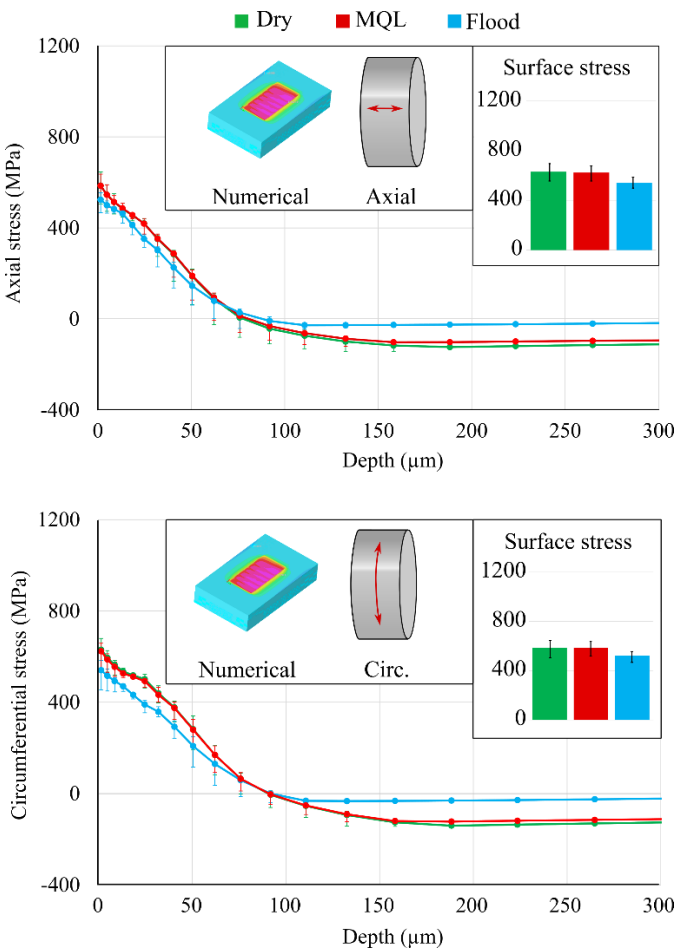


Fig. 6. Numerical stress profiles

5. Conclusions and discussions

This paper has investigated the influence of three lubrication modes on residual stresses induced by a longitudinal turning operation on a 316L stainless steel: dry, MQL with a vegetal oil, flood cooling with an emulsion.

It has been observed that the lubrication mode does not influence significantly residual stress generation in this application. This is explained by the absence of influence on cutting forces, which cannot enable to modify the thermo-mechanical loadings applied by the cutting tool on the surface.

It has also been shown that, despite of significant difference on the heat exchange coefficient for the three lubrication modes, the cooling properties are of secondary importance in residual stress generation.

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