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In-Process measurement of friction coefficient in orthogonal cutting

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In order to represent actual cutting process conditions, an in-process tribometer is examined to measure friction during orthogonal turning process at cutting speeds up to 300m/min. The tribometer consists of a spring preloaded tungsten carbide pin with spherical tip mounted behind the cutting edge and rubbing on the freshly generated workpiece surface. The pin preload is set according to feed force. A 3D-force measuring device in the fixation of the pin allows evaluating friction coefficient from tangential and normal forces. Experiments show strongly different results when contacting fresh and oxidized surfaces and decreasing friction coefficient with increasing cutting speed.

Friction, Cutting, Tribometer

1. Introduction

The friction between tool, chip and work piece directly affects the chip formation and therefore the tool life, the work piece surface quality and the energy consumption of the metal cutting process. Thus, in-depth knowledge of tribology in metal cutting is crucial for progress in metal cutting and especially for modelling of the process [1 – 4]. In order to investigate the tribological phenomena at these interfaces, researchers use mainly two approaches. The first approach, used by several researchers consists of using the cutting process itself. The second approach proposed by [5 - 12] uses frictional laboratory tests, where the investigations are usually based on turning tests of a tube made of the investigated material, with a cutting tool made of the relevant substrate and coating. In the past, pin-on-disc tribometer were used, where a pin rubs repeatedly over a rotating disc to obtain the coefficient of friction and the worn volume. However, as pointed out by Puls [2], the pin rubs over the same track and neither fulfils the required contact conditions nor uses a refreshed surface as generated during metal cutting. A better understanding of the frictional phenomena at the tool-work piece interface can be achieved by using dedicated tribometers, which are able to simulate similar tribological conditions (pressure, temperature, and velocity) as those occurring along the tool-work material interface in cutting, as concluded by Neugebauer [1] and Rech [4].

Olsson [5] modified the pin-on-disc system with a refreshing tool and was able to reach the relevant sliding velocity and contact temperatures. However, low contact pressures of around 15MPa are realised compared to some GPa existing during the machining process. Zemzemi [6] worked with a refreshed surface of a tubular workpiece and was able to reach the required contact conditions. However, this experiment does not ensure chemical purity of the contact surface because the machined surface is still able to react with the environment before the friction measurement is performed, as commented by Puls [2].

Other approaches are modified pin-on-ring systems by Hedenqvist [7] or Bonnet et al [8 – 11], where a pin rubs over a cylindrical surface in a helical movement. While both designs cannot completely avoid oxidized surfaces, the design of Bonnet is able to create the required contact pressures. Recently, Puls [2] presented an experimental setup, which can be seen as an orthogonal cutting operation on a disc with an extreme negative rake angle. However, seen by Rech [4] only a single rotation of the work piece is possible before rubbing against the already deformed surface, thus limiting the time span of friction measurements.

Owing to the lack of real process conditions in existing friction coefficient measurement methods, an in-process tribometer is conceptualised which can measure friction of the newly generated non-oxidized surfaces of orthogonal cut over longer sample durations.

2. Experimental setup

The in-process tribometer is examined to measure friction during orthogonal turning process on a lathe as shown in Figure 1. The tribometer consists of a spring preloaded tungsten carbide pin with a 3mm spherical tip mounted behind the cutting edge and rubbing on the freshly generated work piece surface. As shown by Courbon [13] and Zhao [14], titanium alloys for instance are known for their strong chemical reactivity with surrounding gas due to their high chemical affinity, especially in dry machining. After Astakhov [16] it is a strong belief among the metal cutting researchers that the formation of oxidized, nitrogenized and oxi-nitrogenized films on the contact surfaces is the result of such reactions. Therefore, the distance between the cutting edge and pin must be kept as low as possible. The pin is placed 14mm behind the orthogonal cutting contact zone in the measuring setup as depicted in Figure 2. This ensures that the time interval between the surface generation by the cutting tool and the measurement of the friction coefficient is kept low. For example, for $v_c = 20\text{m/min}$, the interval is of 42ms and for $v_c = 300\text{m/min}$ it is only 3ms. A later figure of this paper will show that this time interval was sufficient to prevent the oxidation of

the freshly generated surface. The tungsten carbide structure and the TiAlN+TiN coating of the pin are same as the cutting insert proposed in Wyen [17].

Previous cutting force measurements are used to set the pin preload F_n by a spring, which corresponds to the feed force at same cutting conditions. The friction forces on the pin are measured by a 3D-Dynamometer Kistler 9047C.

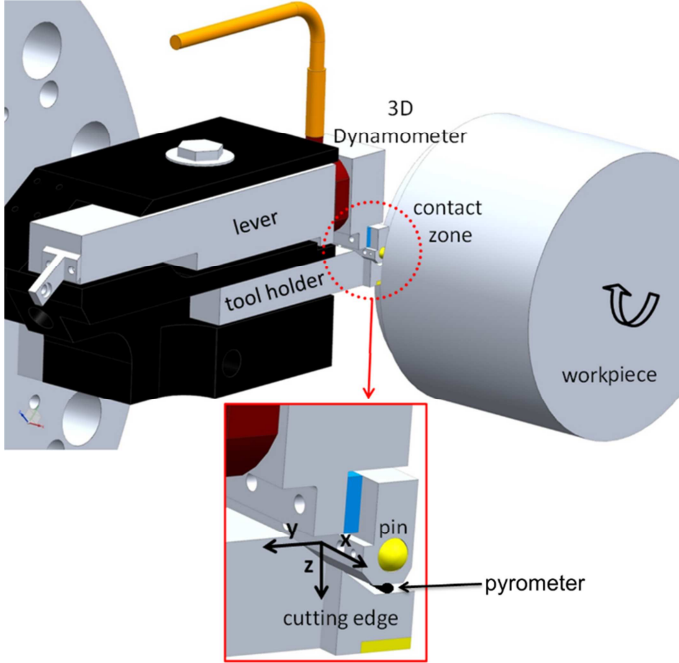


Figure 1 In-process tribometer setup orthogonal cut on lathe

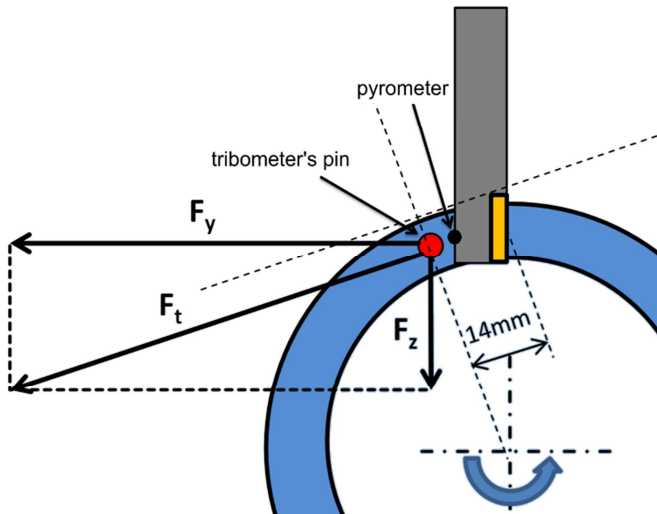


Figure 2 Tangential friction force

To realize equivalent preload contact pressures “p” a worn surface is defined for both situations cutting and tribometer. For cutting the estimated contact area is

$$A_{cc} = b a_{VB} \quad (1)$$

where b is the width of cut, a_{VB} is the length of the flank face wear, assumed to be 0.1 mm. For the pin the contact area is

$$A_{cp} = \pi R^2 (1 - \cos \theta) \quad (2)$$

$$\theta = \sin^{-1} \left(\frac{l}{2R} \right) \quad (3)$$

where R is the radius of the spherical tip, l is the width of flat worn contact surface radius which is assumed to be 0.1 mm as suggested by Abdelali et al. [15]. Contact pressures of 1 – 3GPa are applied during measurements, calculated as

$$p = \frac{F_n}{A_{ci}} \quad (4)$$

Then friction coefficient is calculated from:

$$\mu = \frac{F_t}{F_n} \quad (5)$$

with

$$F_t = \sqrt{F_y^2 + F_z^2} \quad (6)$$

Experiments are carried out at cutting speeds between 50 and 300m/min with a feed rate of 0.1mm/rev and a 3mm depth of cut. Although the tribometer has the option of supplying lubrication, dry cutting conditions are used.

2.1. Investigated Materials

Two in the last year developed steels, G1 and G2, which contain graphite inclusions in their ferritic matrix are investigated regarding friction coefficient measurement in cutting. G1 and G2 differ in the silicon content with 1% and 3% Si respectively. The graphite inclusions grow with increasing annealing time and substitute lead in free cutting steels. The influence of graphite on the tribological properties is yet to be examined. Graphite is generally regarded as a solid lubricant. To check its validity, the friction coefficient is measured on graphite steel at different cutting speeds. As reference, leaded 11SMnPb30 free-cutting steel is taken. Additional investigations are performed on leaded steel 16MnCrS5Pb and normalized C45E. In order to understand the influence of surface oxidation on friction behaviour, further measurements are carried out with Ti6Al4V. To compare an oxidized surface with a fresh non-oxidized one measurements are made without cutting operation. In this case, the pin rubs along a helical track on the front face of the work piece. For each test, after two repetitions a new pin is used in order to estimate the uncertainty.

3. Results

3.1. Friction coefficient

Figure 3 gives an overview on the frictional behaviour of the investigated materials at different cutting speeds on freshly generated metallic surfaces. The preload F_n was set by a spring at 430N for all experiments. Previous examinations show that F_n has a negligible influence on the friction coefficient. It is seen that sliding velocity has a high influence on the friction coefficient compared to the contact pressure. As three experiment repetitions were performed, the average uncertainty in friction measurements was found to be lower than $\pm 4\%$. At lower cutting velocities, friction coefficients μ can vary significantly (i.e. from 0.2 to about 0.6) between the different materials. Increasing the cutting speed these differences are getting smaller and the curves approach a value of 0.2 in dry conditions, which corresponds to a semi-solid frictional regime as assumed by Neugebauer [1] and Rech [4].

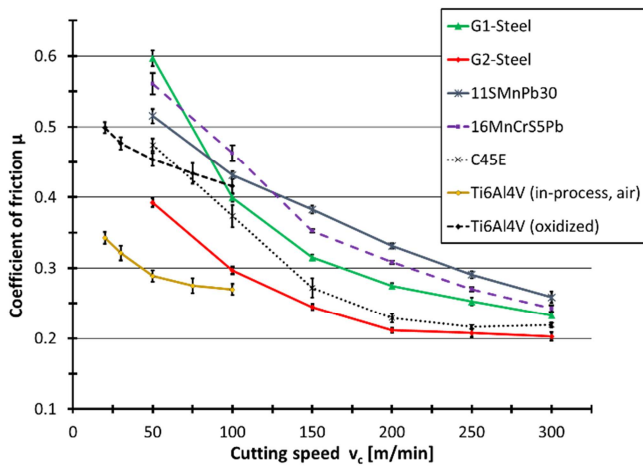


Figure 3 Measured friction coefficient at different cutting speeds

Among all tested conditions graphitic steel G1 with low silicon content exhibits the highest friction coefficient at 50m/min followed by 16MnCrS5Pb and 11SMnPb30 at the same speed. For all tested materials, the friction coefficient decreases with increasing cutting speed. The lowest values were measured for graphitic steel G2 with high silicon content at cutting speeds above 150 m/min. For higher cutting velocities at about 300m/min, the friction coefficients for all the steel types were in similar order of magnitude between 0.2 – 0.25. The friction coefficient can be modelled as identified by least mean squares in Table 1, which can in turning be used for numerical simulation of metal cutting processes. These models derived from the measurements are based on power functions and are valid within the tested range of sliding velocities.

Table 1 In-process friction models at dry conditions for investigated materials, where the normal force against the surface is $F_n = 430N$

Work material against tungsten carbide pin with TiAlN+TiN coating	Friction model
Graphite steel G1	$\mu = 4.60(v_c)^{-0.528}$
Graphite steel G2	$\mu = 1.76(v_c)^{-0.389}$
11SMnPb30	$\mu = 2.37(v_c)^{-0.378}$
16MnCrS5Pb	$\mu = 3.87(v_c)^{-0.48}$
C45E_dry	$\mu = 3.15(v_c)^{-0.481}$
TiAl6V4	$\mu = 0.54(v_c)^{-0.156}$

While some researchers as Rech [4] measure the heat flux in the pin, for this paper, the temperature is measured on freshly generated workpiece surface. A two-colour-pyrometer, type Fire 3 WSA RWTH Aachen, is used to observe the surface temperature between cutting edge and pin. An optic quartz-fibre with a spot size of 0.5 mm was applied. A slight increase of surface temperatures with increasing cutting speed was observed, but the correlation between these parameters was found to be negligible and therefore was not further investigated.

Another aspect to be considered is the relation of surface roughness to friction coefficient. Thus, roughness of the processed surfaces was measured with a surface profiler and is shown in Figure 4. Free cutting steels like 11SMnPb30 are known for their ability to achieve good quality surfaces. This characteristic is attributed to the phases with low melting temperature. Graphite steel G1 shows the highest surface roughness, which could be due to graphite inclusions. Graphite steel G2 has a harder ferritic matrix resulting in a better surface quality. Surface roughness R_a decreases with increasing cutting velocity. Although a similar trend can be seen in friction coefficient measurements, no direct relation has been established.

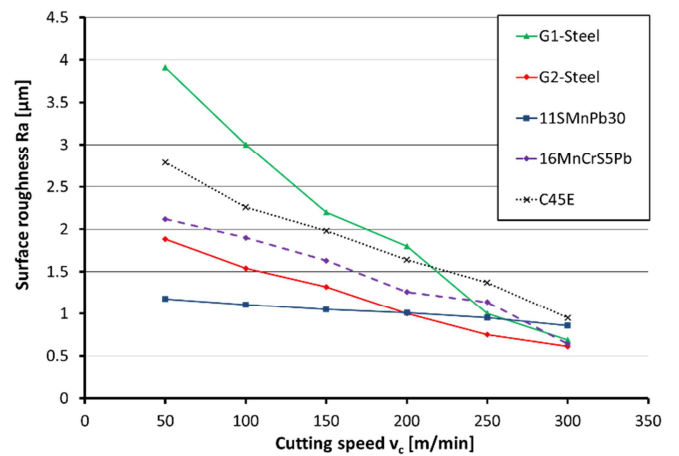


Figure 4 Surface roughness R_a as function of cutting speed for different steels

Figure 5 shows the measured friction coefficient of Ti6Al4V at cutting velocities of 20 – 100m/min with a feed rate of 0.1mm/rev. Given by the distance of 14mm from pin to cutting edge, there is a time delay of 42ms at 20m/min and 8ms at 100m/min between the real cutting process and measurements. The initial oxidation of this highly reactive material is minimized as far as possible by this short time delay. Additionally, measurements are performed during cutting with argon gas flushing. It can be seen in Figure 5 that the measured in-process friction coefficients are very similar for cutting in air and in argon, which proves that the construction of the tribometer ensures the measurement of a non-oxidized surface, even at lower cutting speeds for a very reactive material. The friction coefficients of oxidized surfaces in comparison to fresh titanium surfaces is up to 40% higher as shown in Figure 5.

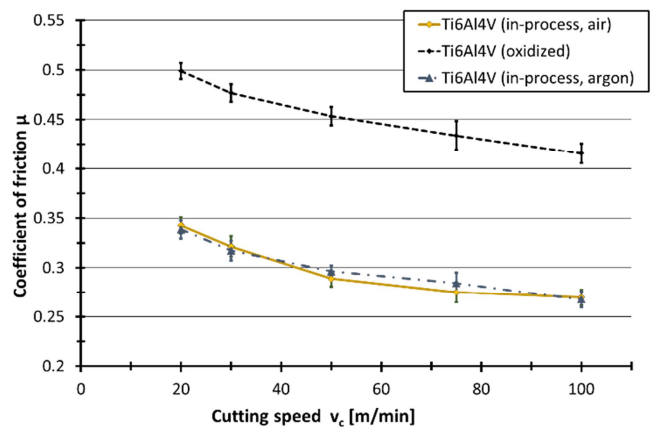


Figure 5 Coefficient of friction for Ti6Al4V in cutting process in air, with argon flushing and on oxidized surface

3.2. Microscopy of contact zone

As the tribometer pin rubs over the workpiece during friction measurements, an imprint having width of about $l=770\mu m$, similar to the contact width l of the pin is generated, as shown in Figure 6. On the other hand, material transfer from workpiece to pin contact area takes place, which is analysed using scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX). Figure 7a shows an example of the analysis of pin after 36s sliding contact with graphite steel G1. Although the coating is not damaged, there is some debris on the contact area of the pin. Figure 7b contains a short summary of EDX analysis. Apart from clearly visible TiAlN+TiN coating, various elements from the workpiece alloy are detected. The distribution

of the adhered elements is visualised by colours. Graphite can be seen as a red stripe on the edge of contact zone. Further detected adhesions are manganese, sulphur and silicon.

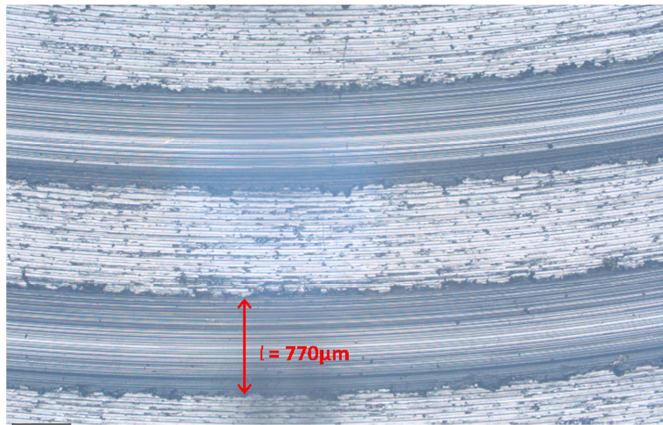


Figure 6 Imprint track left by tribometer pin on the workpiece surface

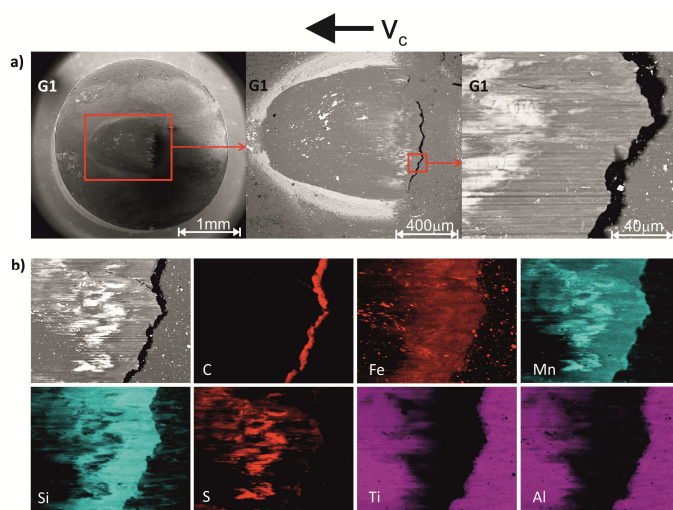


Figure 7 Pin contact area, a) SEM micrographs b) EDX analysis of debris

4. Conclusion

A newly developed in-process tribometer is utilized for quick characterisation of friction coefficient in orthogonal cutting. The friction measurement method is shown to be reliable and repeatable in actual metal cutting process, where two graphite steels are compared to 11SMnPb30, 16MnCrS5Pb and C45E. It has been observed that for all investigated materials, the friction coefficient decreases with increasing cutting speed. The obtained results are consistent with the aforementioned publications. A strong influence of oxidation on the friction coefficients has been verified by comparing the freshly generated and oxidized surfaces of Ti6Al4V. This has been further validated by measurements performed during cutting with argon flushing between cutting region and pin contact region. Thus, the conceptualised tribometer offers the ability to make in-process friction measurements on freshly generated non-oxidized surfaces for longer sample times. The ability to apply a wide range of cutting speeds and variety of materials facilitates measurements in actual process conditions such as contact pressure, cutting speed and temperature. It also allows comparison of friction properties of different coatings or lubrications in quasi-real process conditions. Further investigations on the influence of temperature are planned in order to estimate the real friction temperature of the contact

zone, which might be higher than actual measurements. In a next step the pin contact area can be varied from spherical to flat in order to obtain line contact, which may depict the real contact condition of cutting edge more accurately. In addition studies are required to examine the influence of wear on friction process.

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