Friction - wear modeling in drilling process of H-13 tool steel

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Abstract. Simulation of metal cutting is complex both from numerical and physical perspective. The scope of this work is to elaborate on the process and physics of metal cutting, and more specifically drilling. The description of H-13 steel dry drilling with the use of a single-layer TiN coated carbide twist drill is presented. H-13 is a high strength alloy steel used in demanding applications and elevated temperatures. A simulation model was developed with use of Deform-3D software, and an experiment was conducted in order to evaluate the acquired simulation results, meaning the wear mechanisms and thermal loads implemented during the process of drilling. The Usui wear model was used for the calculation of the wear rate of the drill. Regarding the experiment, a thermal camera was used in order to record the temperature of the drill after the process. The comparative analysis of the simulation models and the experiment showed that adhesion is the dominant wear mechanism. Higher wear values were observed in the rake faces of the drill, where the coating starts to fade, due to built-up edges (BUE). The tool and workpiece temperatures reach near steady state conditions during process. Elevated temperatures are applied on the removed material. Good chip evacuation and chip length indicate that coated drills with optimized geometry are suitable for drilling tough materials.

1. Introduction

Drilling or hole production is a major material removal process and is one of the most common machining processes in the manufacturing industry for the production of holes in components. In [1], Horvat et al. investigated the influence the drill point geometry has on the life of the tool. The research included experiments of coated and uncoated twist drills on drilling Hardox 500 specimens. The results showed that under the same conditions the TiN coated drills outperformed the other types. Most of the wear was observed on the flank faces and the margins of the drills.

Sharif et al. got involved with drilling of Ti6Al14V with TiAlN-PVD coated and uncoated carbide drills [2]. Ti6Al14V is a titanium alloy with poor thermal properties which determines the plastic deformation at the cutting point. Also, titanium alloys are known to be quite reactive with most of the tool materials, and their elasticity module reduces at moderate temperatures leading to bending, considering that the temperatures in the tool-workpiece contact area are very high during machining. The tools used were all made from similar substrate, meaning WC-CO and their grades were K30/40. The results showed that coated drills on low cutting velocities (25-35 m/min) indicated gradual flank wear, while on higher speeds (45-55 m/min) the wear was increased rapidly. Later, the same authors tested the effect of cutting geometry of the drills on the same material in [3]. For their research they used...
two different kinds of split point uncoated WC-CO solid drills. The main wear mechanism that occurred was adhesion wear on the tools’ cutting edges.

The beneficial effects of lubrication during drilling have been already described by Grzesik et al., however it is also acknowledged that lubricants bring oxygen in the tool-chip interface, leading to oxidation of the material [4,5].

Prior knowledge suggests that TiN coating is generally considered to be prone to oxidation, as the gas oxygen molecules have the tendency to replace nitrogen on the coating, leading to the formation of a layer of oxidized titanium, in a process which is thermodynamically favoured at temperatures higher than 500°C. The oxidized titanium has reduced hardness and can be removed during drilling exposing a fresh layer of TiN available for oxidation, leading to repeated cycles of corrosion of the tool according to Chauhan and his colleagues in [6] and Knotek et al. in [7]. On the other hand, it has been shown that although TiN coating offers relatively poor performance when pure water is used for lubrication, it can exhibit better tribological behaviour under sea water, as it has corrosion-resistant properties, suggesting its suitability for marine applications as seen in the work of Matei and colleagues in [8] and in [9] by Wang et al.

On the above studies, the main wear mechanism is adhesion. Also, what is more interesting is the fact that despite changes in the cutting lips’ geometry of the drill, flank faces tend to be prone to wear, determining the drills’ life. In addition, flaking is very typical in most of the drills’ periphery due to the high rake angle they are grinded with.

1.1. Wear mechanisms

Wear is the gradual removal of material at contacting surfaces in relative motion. While friction results in energy losses, wear correlates to increased maintenance costs as well as energy loss. Wear phenomena are linked closely to frictional process. Friction forces are generally the result of shearing and ploughing. Moreover, wear is heavily influenced by the fact that most surfaces are rough at some point, no matter the preceded treatments they have.

There are many types of wear, classified according their influence on the cutting tool. The performance of a cutting tool relies on its ability to endure the loads applied during metal cutting. The main categories of wear mechanisms that occur are thermal and mechanical wear, chemical (oxidation and diffusion), abrasive and adhesive wear. In the present work the adhesive wear mechanism will be examined thoroughly. In addition, the wear mechanisms are mostly dependent on temperature generated during cutting as seen on the following illustration (Figure 1). On lower temperatures, abrasive and adhesive wear mostly affect the tool, while on higher ones, diffusion has a major role, and adhesive wear is reduced significantly.

Adhesive wear mechanism is the most common wear type that is presented in machining. It is characterized by two surfaces under plastic contact that have sufficient bonding strength in between them preventing them from sliding. This results in deformation due to compression and shearing, and crack propagation usually initiates. When the crack reaches their interface then a wear particle is created and is ripped off. In machining of ductile materials, adhesive wear is found either on the tool workpiece
interface, or in the tool chip interface. Another phenomenon of adhesion in machining is the built-up edge (BUE), where the parts of the material to be processed are again adhered on the cutting edges of the tool. The severity of adhesion wear depends on temperature as show in Figure 1, where after a specific value it starts to decline. Also, below this specific temperature there is a lower tendency for material to adhere on the tool’s surfaces.

Many models have been designed to estimate adhesive wear. In 1953 Holm and Archard presented an equation for the calculation of adhesive wear. Based on Archard’s law, a number of general models around the hardness of the adhered material have been created. In machining, the workpiece hardness is essential to be known, and this is the one that adheres on the tool. Moreover, the sliding velocity has to be known, as well, which is the length of the cut, and in drilling is the hole depth. Finally, the normal contact pressure at plastic deformation has to be of a known value. The worn volume in its simplest form can be expressed as:

\[ V = \frac{1}{3} WL \]  

where \( V \) is the volume that is worn, \( W \) is the normal load applied, \( L \) is the sliding distance and \( H \) is the hardness of the material that is worn. In this form of equation, the worn volume is increased when normal load and sliding distance are also increased and inversely proportional to the hardness of the material. Also, the tougher the drill’s coating the less wear will occur [10].

With the use of Archard’s law as a fundamental equation of wear calculation, Usui and colleagues resulted in the following equation in [11]:

\[ \frac{dW}{dt} = C_1 \sigma_s V_c \exp \left( -\frac{C_2}{\theta} \right) \]  

This equation refers to the wear rate, meaning the fraction \( \frac{dW}{dt} \), and is known as Usui’s Wear model.

In the present study it will be used for the calculation of adhesive wear in carbide drilling tools [11]. The parameters \( C_1 \) and \( C_2 \) are experimentally calculated, \( \sigma_s \) is the normal stress between the friction couple, \( \theta \) is the temperature of the chip surface and \( V_c \) is the cutting speed.

1.2. Drilling wear

In general, there are many different wear types in machining. Most of them are easily explained for turning based on their appearance, but can also be applied in drilling, with slight modifications. The most common one is flank wear.

Flank wear is the type of wear that occurs on the flank face of the tool due to shear stress from normal pressure while the tool slides over the machined surface. It firstly develops close to the cutting edge, and then grows away from it evenly distributed on the remaining flank face. It is the most typical type of wear that appears during machining. Variations can be found on this which depend on the material that is processed, cutting data and tool shape. For example, smaller lip relief angle on a drill bit is more prone to flank wear due to the higher contact with the machined surface of the material.

Flank wear is usually measured according to ISO 3685 standard which is also used by Grzesik [4], where a \( VB_x \) or \( VB_{max} \) value is produced, which is the distance measured from the cutting-edge perpendicular to lowest worn area of the tool. Tool life limits often range at about 0.3 mm for flank wear, and average value for the \( VB \) parameter.

2. Design of experiment

In order to study the adhesive wear mechanism and wear characteristics during the process of drilling, a friction couple model is determined. This means that a specific type of metal with known geometry and mechanical properties is used as the workpiece material and also a drill with known geometry and
material characteristics is used as the tool. The friction couple is designed in the 3D CAD system and it is simulated with use of the Deform-3D software. Moreover, in order to validate the data collected after the finite element analysis, experiments will be conducted under the same cutting conditions.

Regarding the material that is used as a specimen, this is H-13 steel, also known as Orvar [23]. This material is used as a tool in quite demanding applications where high thermal loads are applied such as extrusion, plastic molds or die castings. Also, the yield strength $R_p$ of Orvar is 880 MPa and tensile strength $R_m$ is 550 MPa in soft annealed condition.

The tool that is used plays a major role on the system that is studied. The most common style of drills are the broadly known twist drills, and this is the drill which is implemented in this work. The drill is made out of tungsten carbide (WC) with a single layer coating. A commercial drill which meets the above requirements was found. It is TiN coated via the PVD process with a layer thickness of 1.5 - 4 mm at 500°C. Also, the coating’s hardness reaches 2400 HV and more importantly, its friction coefficient $\mu$ is measured at 0.5 according to the manufacturer.

The friction couple generated is the specimen to be processed and the drill. The specimen is H-13 steel which was secured on the CNC machine’s table in an appropriate way in order to provide the best possible rigidity. The cutting conditions that were used during the process were chosen according to the manufacturer’s recommendations for the specified drill series. Also, the cutting process was dry, which means that no cutting oil or emulsion was used. Table 1 shows the cutting feeds and speeds that were used both for the simulation and the experiment. The holes produced were of 20 mm depth.

Table 1. Cutting speeds and feeds for the simulations.

| Parameters                  | Parameters’ variables | Values |
|-----------------------------|-----------------------|--------|
| Cutting speed (m/min)       | $V_c$                 | 40     |
| Spindle speed (rpm)         | $N$                   | 1270   |
| Feed per revolution (mm/rev)| $f_{rev}$             | 0.1    |
| Feed per minute (mm/min)    | $f$                   | 127    |

3. Results
What is interesting about the split point geometry is the fact that the temperature plots on both the tool and the workpiece tend to get a shallow slope. This means that the system starts to reach a steady state condition in machining. However, as there is no coolant during process except air, and knowing that the tool wear is gradually increasing, it is reasonable that the temperature plots will always show elevating temperatures Figure 2.
Figure 2. Temperatures generated on the workpiece (a), and temperature on the tool (b) during process.

When the whole cutting edge of the drill is cutting material, the wear rate increases, and the areas that tend to be subject to high friction and stresses, and wear faster, are the ones in the periphery of the drill due to their highly positive rake angle and the higher amount of material they have to remove.

Figure 3. H-13 specimen of experiment, chips produced and simulation temperatures.

Figure 4. Temperatures of the high performance drill.

Regarding the temperatures, the drill showed results pretty close to the simulations. In Figure 4, the temperatures are illustrated. More specifically, the thermal camera used to record the temperature during machining showed the following results:

- 120 °C on the third hole and
- 135 °C on the fifth hole.

Finally, after inspecting the chips’ microstructure on SEM, the abrasive and adhesive wear in the tool-workpiece interface is presented (Figure 5). In this figure, it can be seen that abrasion takes place on the workpiece, leading to the creation of chips. In addition, adhered masses can be seen, which are probably fragments of the drill’s coating.
4. Conclusions and future work
The temperatures calculated from the model ranged approximately around 140 °C. The differences on the model and the thermal camera were caused by the thermal camera’s calibration, and the difficulty in recording the exact tip of the tool. The optimization of geometry in twist drills is critical in order to make them more efficient and productive during drilling, especially in cases where tough materials are machined. Also, the coating used is an important factor which is responsible for low friction and wear on the tool. Nevertheless, the experiment comes to good agreement with the simulations.

Taking the results of this paper a step further, future work can focus on the chemical properties of the materials during drilling such as the oxidation and the effects of lubrication/cooling in elevated temperatures. Assessing the performance of the tool under altered tribological conditions (i.e. upon the addition of lubricant) can provide a better understanding of the suitability of each tool material for different applications. In other words, it is important to carefully select the appropriate combinations of metals and coatings for the drill and the specimen in order to achieve more efficient drilling with reduced tool wear due to high temperature and oxidation.

Based on the previous findings of other researchers, our future work will therefore elaborate on the effects of different lubricating materials in the level of oxidation and consequently, endurance of the drill.

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