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FINITE ELEMENT INVESTIGATION OF THE EFFECT OF FRICTION CONDITIONS AND CUTTING ENVIRONMENT IN TURNING OF AISI H13 HARDENED STEEL

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Abstract: *Friction and cutting environment represent critical factors in machining processes, where intense thermo-mechanical interactions govern tool-workpiece behavior and affect tool performance and workpiece integrity. Despite their significance, the effect of these parameters remains insufficiently understood due to experimental challenges. Thus, it is necessary to perform simulations of these conditions in order to better understand their impact on various aspects of machining processes. This study aims to address the knowledge gap through systematic finite element (FE) simulations investigating the effect of friction and environmental conditions during the turning of AISI H13 hardened steel. By using a numerical framework, the influence of various values of friction coefficient under ambient and cryogenic environments is studied. In the parametric studies, cutting force, temperature profiles, and chip morphology across these conditions are systematically analyzed providing important insights for optimizing machining conditions during processing of hard materials. The findings indicated a non-linear trend of the friction coefficient both with cutting force and cutting temperature, whereas the different cutting environment had a smaller effect on them.*

Keywords: *friction coefficient, cryogenic conditions, FE simulations, thermo-mechanical model, AISI H13 hardened steel*

1. INTRODUCTION

Manufacturing processes have been studied for a long time due to their high importance in industrial practice, including both common and high-end industries, such as the automotive and aerospace ones. A wide range of different processes involving material forming or removal have been developed and optimized to meet the industrial needs. Despite the considerable progress in manufacturing processes with a view to achieve high productivity, the use of novel materials or the need for achieving stricter requirements constitute significant challenges which should be successfully overcome.

In order to optimize the manufacturing processes for extending their capabilities, it is necessary to carry out detailed investigations based on different process conditions. As the experimental investigations often have considerable limitations and it is not always possible to determine every output due to lack of necessary equipment, the use of numerical models can be proven important to better understand the effect of different parameters and determine their optimum values [1].

A considerable amount of research has been already conducted in the field of manufacturing processes simulations. Especially, for machining processes such as turning, a wide range of models has been proposed, starting from simple models based on the orthogonal cutting model to more complex models taking into account the 3D geometry of the turning setup. Apart from the model characteristics, the workpiece material model and the modeling of friction conditions are two important features of the numerical models which are still a topic of interest due to the difficulties to establish generalized models for a wide range of conditions [2,3]. Although friction models are an important part of a FE model of machining, the scarcity of detailed information about the stress conditions in the contact zones, especially for a wide variety of materials renders the modeling procedure of the effect of friction challenging [3]. A notable approach was to employ a corrected friction coefficient value by the experimentally measured cutting forces [3]. In this case, the incorporation of non-uniform stress distibution along the tool rake face was able to reflect a more realistic representation of the friction conditions. In the work of Arrazola and Ozel [4], the effect of friction modeling was investigated by two different ALE models with different types of boundaries, incorporating also the limiting shear stress at the tool-chip contact area and sticking and sliding friction which was proven crucial for an accurate simulation. Arrazola et al. [5] also included a variable friction coefficient model in order to be able to predict all force components with high accuracy. Filice et al. [6] evaluated different friction models and noted that the different models had mainly differences in the prediction of the thermal phenomena instead of the mechanical ones. Yang and Liu [7] proposed a stress-based polynomial model for the friction coefficient based on experimental data and compared this model to two other models, noting that the stress-based model was superior to the force-based one. Franchi et al. [8] presented an inverse methodology for the determination of friction coefficient and material constants based on forces and temperature data.

Shi and Liu [9] used a friction model taking into account both sticking and sliding friction and compared the use of different material models during machining simulations. Banerjee and Sharma [10] developed a friction model for the case of MQL in machining by an inverse methodology. Afrasiabi et al. [11] developed a SPH-FEM model for orthogonal cutting using temperature and velocity-dependent values of friction coefficient. Priest et al. [12] adopted a deformation dependent stick-slip friction model, focusing on the more accurate representation of the friction conditions in the secondary shear zone. Their findings indicated the necessity of variable friction coefficient in order to accurate predict the different force components. Abouridouane et al [13] developed a simple model for the appraent friction coefficient based on experimental data and were able to better explain the effect of friction in various cases. Yi et al. [14] carried out a comparative study of different friction models such as Zorev model, velocity dependent or temperature-dependent model, indicating their advantages and limitations. These models mostly affected the temperature distribution rather than chip formation. Storchak et al. [15] created a friction model taking into account the local forces in each contact zone by decomposing the total forces. Moreover, the investigation of friction has been also extended to special types of materials such as composite materials [16] or in the case of high cutting speeds [17], as well as for other processes such as grinding [18].

As in most of the relevant studies on friction during machining, the possible effect of a different cutting environment conditions is not investigated, in the present study an investigation of the effect of the cutting environment temperature under two different conditions, namely ambient and cryogenic conditions is conducted in order to determine the effect of these conditions on the machinability of AISI H13 hardened steel. Based on the simulation results, the correlation between friction coefficient, cutting forces and temperature can be determined under two different environmental conditions and also the impact of these conditions on chip morphology can also be evaluated.

2. MATERIALS AND METHODS

In this study, the aim is to determine the effect of different friction conditions, represented by different values of the friction coefficient, on the outcome of the turning process under ambient and cryogenic conditions. As the friction coefficient is usually a parameter which is not directly determined by experiments at least at the same conditions as the ones occurring during machining, it is important to determine its effect on the results within a wide range. More specifically, five different values of the friction coefficient, namely shear friction factor in the range of 0.1-0.9 were tested for two cutting environment temperature values, namely 20 and -196^{o}C. The first value corresponds to machining in ambient temperature, whereas in the second case the conditions represent machining in a special chamber under cryogenic e.g. liquid nitrogen environment.

For the simulations a 3D model was adopted, taking into account the exact cutting insert geometry and a 3D representation of the workpiece. The cutting insert is positioned at the right depth of cut and orientation according to the tool holder specifications and moves in a straight path, with a sufficient length to achieve stable machining conditions without high computational cost, according to the cutting speed. Contrary to models which used a simplistic block shaped workpiece, in this work, the model takes into account the material removed from the workpiece in adjacent areas, the feed, as well as the real contact geometry between the insert and the workpiece and although the cutting length represents only a small part of the workpiece diameter, this model setup represents the actual turning process more realistically. These models are expected to perform better than the models related to orthogonal cutting, as the positioning and the exact geometry of the cutting insert may have a considerable effect on the outcome of the machining process.

The workpiece has the geometry depicted in Figure 1 and is composed of AISI H13 hardened steel (X40CrMoV5-1). The workpiece material is considered isotropic but it is represented by a constitutive low that takes into account the variation of flow stress depending also on strain rate and temperature as the machining simulations should include the thermo-mechanical behavior of the workpieces, especially because of strain hardening and thermal softening phenomena. For this material, damage is also considered in order to be able to determine the creation of the chip. The cutting insert which was chosen is a CCMT09T308 carbide turning insert, appropriate for machining steel belonging to the P8 category and is supposed to be rigidly fixed on a toolholder, whereas it is modeled according to its exact geometry. For the correct positioning of the insert relative to the workpiece, it is assumed that the corresponding tool holder is DCLCL2525X09JETI. The process conditions which were adopted and kept constant for the simulation are the following: cutting speed of 150 m/min, depth of cut of 0.3 mm and feed rate of 0.5 mm/rev. The cutting length was also constant at 3 mm.

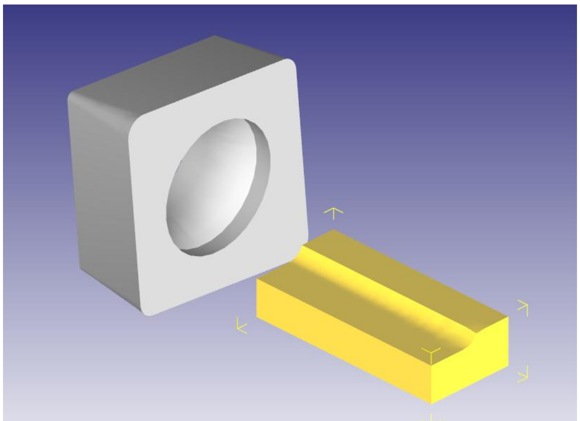


Figure 1. Model setup.

The initial mesh for the cutting tool is composed of 10000 elements, whereas the initial mesh for the workpiece includes 60000 elements with a particular focus on specific areas such as curved regions or the initial cutting surface where higher deformation is expected to occur, whereas the elements are initially larger in regions far from the cutting tool. As the stresses and strain rate are high in the cutting zone, when the deformation exceeds certain limits, the mesh is separated from its initial position, creating the chip. During the simulations, an automatic adaptive remeshing technique is employed to refine the mesh in areas with high deformation, something that is essential due to the large distortion of the elements in these areas.

The simulations were carried out by developing a coupled thermo-mechanical model in a finite element code using an updated Lagrangian formulation. All common boundary conditions regarding displacement and temperature are applied with the workpiece being fixed in space and the cutting tool moving in one direction. Heat is allowed to be transferred from the cutting zone to the tool, workpiece and chip, and also heat generated due to plastic deformation and friction is taken into account. After the simulations are carried out, the value of the main force component, i.e. the cutting force is calculated, as well as the maximum cutting temperature and chip morphology is also observed to serve also as a machinability indicator.

3. RESULTS AND DISCUSSION

After the simulations were carried out, the results regarding cutting force, cutting temperature and chip morphology were analyzed.

In Figure 2, the variation of cutting force in respect to friction coefficient values and cutting environment temperature is depicted. As can be seen, the cutting force has a monotonous correlation with the friction coefficient with the cutting force values gradually increasing as the friction conditions in the tool-workpiece contact zone are more intense. As the friction coefficient increases from 0.1 to 0.9, the cutting force increases almost by 120 N. This observation indicates that the leads to a non-linear, non-proportional increase of force, in contrast to the effect of process parameters e.g. feed or depth of cut. The increase of cutting force in respect to higher friction coefficient can be attributed to the greater resistance occurring at the tool-chip interface, opposing the free chip flow and leading to larger developed shear stresses.

Moreover, the cutting environment temperature also affects the cutting force, as can be seen in Figure 2. In every case, machining the workpiece in a low temperature environment leads to higher cutting force, although the effect of the cutting environment is lower than the effect of the friction coefficient.

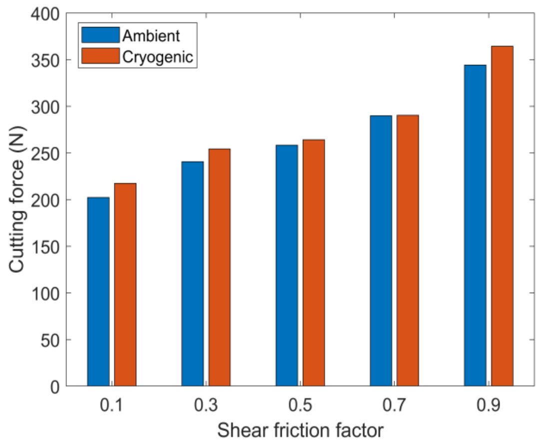


Figure 2. Cutting force values in respect to friction coefficient and cutting environment.

In general, the effect of lower temperature can be material and process-dependent. In the case of some steel types a similar result can be observed, which can attributed to the behavior of metals under low temperatures, which is considerably brittle with higher strength and limited ductility due to cold strengthening which in these cases is superior to any thermal softening effect. Thus, although the cooling effect could be beneficial due to decreased adhesion, the increased resistance to plastic deformation due to restricted atomic mobility. Moreover, the combination of high strain rates during machining and the lower temperature can further facilitate the transition from ductile to brittle behavior. Thus, higher forces are required for the material removal process.

Apart from the investigation regarding cutting force, the variation of cutting temperature is also important for the understanding of the implications of the different friction and environmental conditions on the other results. In Figure 3, the maximum temperature for each case is depicted.

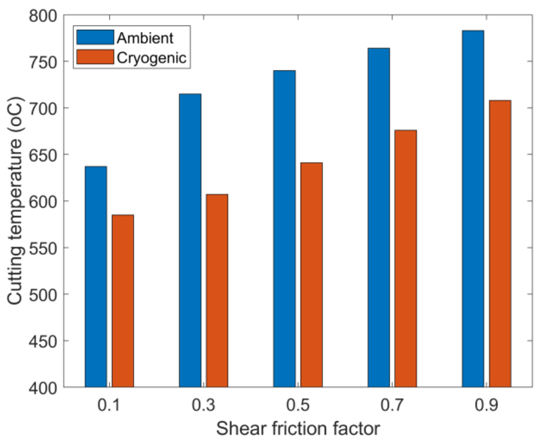
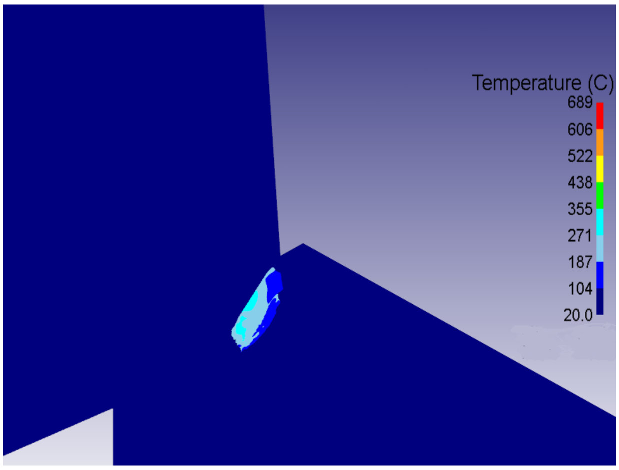
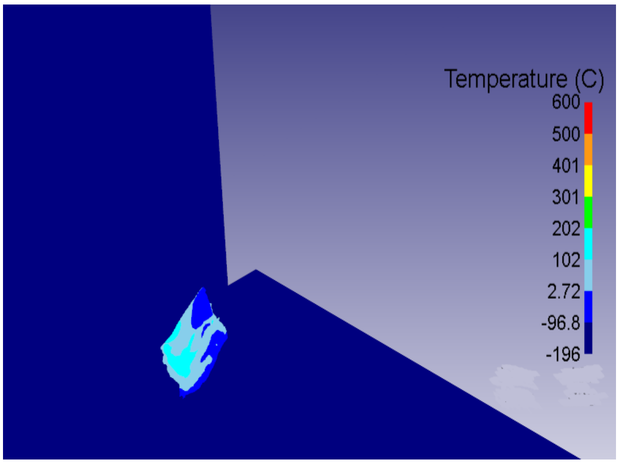


Figure 3. Cutting temperature values in respect to friction coefficient and cutting environment.

From these results it can be confirmed that the increase of friction can lead to a noticeable increase of the cutting temperature. Similarly to the increase of the cutting force, this increase is gradual and non-linear, as the increase of friction coefficient from 0.1 to 0.9 leads to an increase of almost 150°C, indicating the increase of friction work. In the case of cryogenic conditions, the cutting temperature is constantly lower but not considerably lower. The cutting temperature also in this case follows an increasing trend but the highest values are several tens of degrees lower due to the low initial temperature and the heat exchange with the cooler parts of the workpiece and the cutting insert. Despite the lowest initial temperature, the high amount of heat produced during cutting still increases the cutting temperature to a considerable degree, something that could be avoided if only local cryogenic cooling was applied. Although the highest values of temperature are not considerably different, the temperature distribution is considerably different, as can be seen in Figure 4 due to the larger difference between the cutting zone and uncut workpiece areas. Thus, in the case of machining under cryogenic conditions, the quality of the produced part is expected to be different than in the case of ambient temperature, something that should be considered during the planning of the fabrication of the parts.



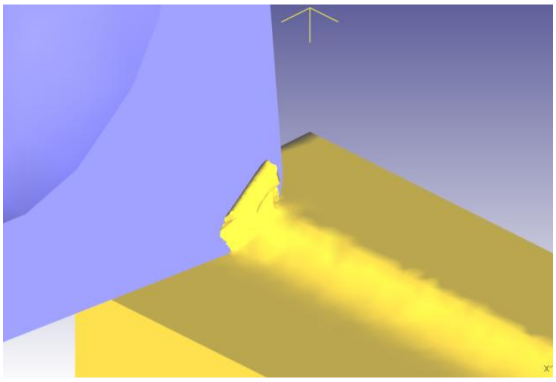
(a)



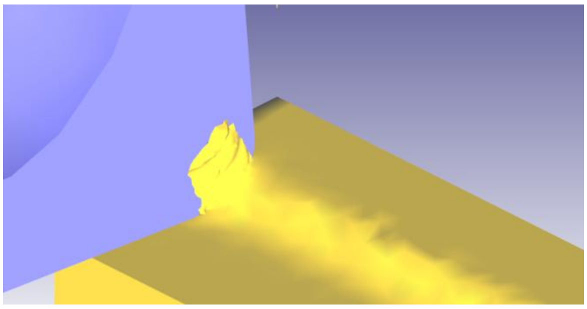
(b)

Figure 4. Cutting temperature distribution: (a) under ambient environment, (b) under cryogenic environment.

Finally, the chip morphology was also observed during the simulations. As can be seen in the indicative graphs of Figure 5, when the friction coefficient value was low, the chip exhibited a tendency to bend after a certain cutting length, whereas the chip was developing in an upwards direction for a longer time when the friction coefficient was higher. The different cutting environment did not alter the shape of the chip noticeably, apart from the anticipated changes in its strength due to its embrittlement.



(a)



(b)

Figure 5. Chip morphology: (a) under low friction conditions (b) under moderate friction conditions.

4. CONCLUSION

In this work, a FE model was developed for carrying out an investigation on the effect of friction coefficient and cutting environment on the turning process outcome for a hardened steel workpiece. Simulations were carried out for five different friction coefficient values and two different cutting environments, namely ambient and cryogenic conditions. Several conclusions were drawn from these investigations:

- The friction coefficient values exhibit the anticipated positive correlation with the cutting force. However, this correlation is non-linear, as the values of cutting force gradually increase when the friction coefficient increase within a wide range, due to subsequent increase of the resistance in the tool-workpiece interface. Similarly, the cutting temperature is also increased due to the increased friction work, up to 150^{o}C. The chip morphology changes for moderate and high friction coefficient values as the chip is flowing upwards for a longer time than bending.
- The cutting environment plays a less important but noticeable role during machining. Machining under cryogenic conditions leads to slightly higher forces as the workpiece material becomes more brittle and strengthens in low temperatures. Moreover, the cutting temperature is affected by the environmental conditions, with relatively lower temperatures observed during cryogenic conditions due to the much intense heat transfer between the cutting zone and the cooler workpiece areas. Finally, chip morphology was not severely affected under different cutting environment despite the alterations on its mechanical behavior.

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