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NUMERICAL INVESTIGATION OF HEAT-INDUCED EFFECTS ON STEEL WORKPIECES DURING HARD TURNING MACHINING PROCESS

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ABSTRACT

Hard turning is a machining process intended for significantly hard materials such as steel workpieces with hardness more than 45 HRC. Hard turning constitutes also a promising cost-efficient alternative of grinding regarding surface finishing operations. However, the large amount of heat produced during this process primarily by friction work in the tool-chip interface, affects significantly the workpiece surface and subsurface layers as well. In order to investigate thoroughly the heat-induced effects on machined workpiece, finite elements models are developed to simulate hard turning for various cases with variable depth of cut and feed values. In each case, temperature profiles are analyzed to determine heat-induced effects on subsurface layers such as heat affected zone and thermally induced stresses in the workpiece and desirable set of machining parameters for the reduction of heat-induced effects is determined.

Keywords: *hard turning, Finite Element Method (FEM), thermal phenomena, thermal stresses.*

INTRODUCTION

Finishing operations constitute usually the final step after machining operations with a view to render a better surface quality of workpieces and comply with the requirements set. Careful choice of machining parameters needs to be performed before machining operations occur, so as to ensure that they are effectively conducted. However, in industrial scale, the financial factors should also be taken into account, as processing time and equipment cost should be reduced. Furthermore, it should not be underestimated, that machining operations can induce significant undesired residual stresses beneath the surface (apart from alterations in roughness profile) both due to mechanical and thermal loads and thus shorten life and undermine quality of machined components. As far as finishing of cylindrical parts is concerned, two main alternatives are often considered: cylindrical grinding and hard turning (or a combination of the two).

Hard turning evolved essentially as a sub-category of turning operations during the 90s. The term hard turning refers to turning of considerably hard steel specimens, over 45 HRC, often in the range 45-68 HRC [1], with special types of cutting tools [2]. The set-up for this machining process has some particularities due to increased workpiece material hardness and low feed, often in the range of 0.04 - 0.25 mm/rev and small depths of cut, often between 0.1 - 0.3 mm [3, 4], as well as specific tool types, i.e. ceramics such as PCBN, CBN and carbides are often employed [2, 5] and no cutting fluid is usually applied, resulting in excessive heat generation [5]. Cutting speed is often moderate or high, in the range 100 - 250 m/min [1, 4] and sometimes up to 300 m/min [3]. Problems occurring during high speed machining processes, such as excessive tool wear, lead to geometric and dimensional errors [1, 6]. Furthermore, high rigidity of machine tool is required due to high machining forces, as only hardened materials are processed. Two theories are proposed to explain the phenomena occurring during hard turning; the most widely accepted is that a high temperature zone is developed in front of the cutting tool, leading to material softening in this area, as a process similar to annealing occurs [1], thus enabling cutting to be easier performed [5]. However, other researchers have proposed that the plastic deformation through high compressive stresses is the dominant factor in this process [5]. Two phenomena that are present in the workpiece after hard turning is performed are residual stresses and white layer formation [1, 2, 4].

Important characteristics of hard turning, specifically thermal and thermo-mechanical phenomena occurring during this process have been studied in the relevant literature. Kountanya et al. [7] studied the effect of tool edge geometry and cutting conditions in orthogonal hard turning of steel with a view to determine mechanisms that contribute to chip formation and machining forces. It was found that surface shear-cracking was a predominant mechanism in the majority of cases, that thermoplastic softening was also present and that segmented chip formation is related mainly to length scale in the work material and not time-scale. Cakir and Sik [8] studied the cutting tool condition before fracture during hard turning of steel occurs. Data from an actual tool breakage monitoring system were acquired and both static and dynamic FEM analyses were conducted. Angular velocities that can source resonance and natural frequencies that cause breakage were determined and high stress regions were also detected. Sukaylo et al. [9] presented a FEM model of hard turning concerning thermal distortions caused by this process. This model aimed to determine thermal deformation of the workpiece during multi-pass turning and was validated by comparison with experimental findings. Yan et al. [10] employed a coupled thermo-mechanical model for the orthogonal cutting of AISI H13 hardened steel. In contrast to other models, they used modified models to account for the relatively high hardness of materials machined during hard turning. Higher cutting speed, smaller depth of cut and larger tool tip radius were found to lead to an improvement of the surface integrity of the workpiece. Useful conclusions concerning machining forces and temperatures in respect to machining parameters were also drawn. Poulachon et al. [11] focused their study on the conflicting effect of work hardening and thermal softening processes during hard turning using a thermo-mechanical model along with experimental work. For this reason a new shear instability criterion was proposed. Hua et al. [12] highlighted the importance of simulation model regarding the accuracy of residual stress profile prediction. Thus, they employed a revised elastic-viscoplastic FEM formulation, taking into consideration material hardening and cutting tool tip geometry. This model was validated by comparison with experimental results.

In the current paper, an investigation of thermal phenomena during hard turning is attempted with the use of a 3D thermal model of a steel workpiece machined at various machining conditions with a view to determine thermal profile in the workpiece, heat affected zone and thermally induced stresses.

MODEL DESCRIPTION

Thermal phenomena within solids such as machined workpieces can be studied by the use of 3D time-dependent heat transfer equation:

$$\frac{\partial(\rho h)}{\partial t} + \nabla \cdot (\vec{v} \rho h) = \nabla \cdot (k \nabla T) + S_h \qquad (1)$$

where ρ denotes material density, h denotes specific enthalpy, $\vec{v}$ denotes heat source velocity, which is the combination of the circumferential and feed speeds, described in detail in the following paragraph, k denotes thermal conductivity, and S_h denotes volume heat sources. The numerical model is solved in COMSOL software.

In order to improve the accuracy of the numerical model, the thermal conductivity, specific heat and density are considered as functions of temperature in this study and are inserted into software library for AISI H13 steel. As it is desired to focus primarily on thermal phenomena during hard turning, the effect of the interaction between cutting tool and workpiece is simulated via a heat source, deriving from analysis conducted in [13], taking into consideration process parameters such as: cutting forces, feed, cutting speed and cutting tool geometry. The heat source is moving realistically around the external surface of the workpiece, conducting a spiral movement which consists of a movement along workpiece length at feed speed and a rotational movement at circumferential velocity v_c, thus simulating the contact between workpiece and cutting tool. This simplification can be considered valid as depth of cut is usually in the range of a few μm. The workpiece is considered homogeneous medium and has a cylindrical geometry with a diameter of 100 mm and length of 300 mm. Initial temperature is set at 300 K. The regions far from the cutting tool can exchange heat with the environment (assumed air) by convection. Numerical timestep is chosen each time according to the time scales involved in the study, i.e. feed and cutting speed, in order to accurately observe phenomena during hard turning simulation. As for the calculation of thermally induced stresses, a structural mechanics model is also included in the study, as a second step, receiving data from thermal analysis.

In the current paper, two different values of cutting speed, namely 100 and 200 m/min, and three different values of feed rate, i.e. 0.1, 0.15 and 0.25 mm/rev, are considered and the effect of these conditions in the temperature profile of the workpiece, heat affected zone, and thermally induced stresses is investigated.

RESULTS AND DISCUSSION

After the aforementioned simulations are conducted, the results are analyzed in order to investigate thermo-mechanical phenomena present during hard turning. At first, results concerning one particular case will be presented in detail, namely the case with parameters: f = 0.1 mm/rev and v_c = 100 m/min, to determine the basic features of the process and then results concerning all cases will be discussed.

In Fig. 1, three snapshots of the temperature field on the workpiece at the first, intermediate and final stages of the process are presented, see Figs. 1a-c, respectively. A zone with elevated temperatures is developing as the cutting tool tip travels over the workpiece. As feed values for hard turning are relatively small, overlapping phenomenon occurs and heat produced at each timestep is added to previously produced heat, thus intensifying the thermal effects. Furthermore, cooling of workpiece regions that are behind and far away from the cutting tool position occurs but temperatures remain relatively high even after some time has elapsed. The time evolution of temperature profile along the workpiece length can be seen by comparing Figs. 2a-c, which represent the temperature profile along the workpiece at the initial, intermediate and final stages of the process, respectively. From these figures it can be clearly seen that temperature drops abruptly a few mm below surface and the same temperature profile is "moving" along the workpiece at feed speed, causing significant temperature rise at a small distance of about 50 mm near the tool tip. From these figures, it can be also deduced that the temperature peak in this case is about 1100 K, clearly above austenitization temperature for this type of steel. This indicates that significant alterations in the microstructure of a thin layer above the surface are taking place during hard turning.

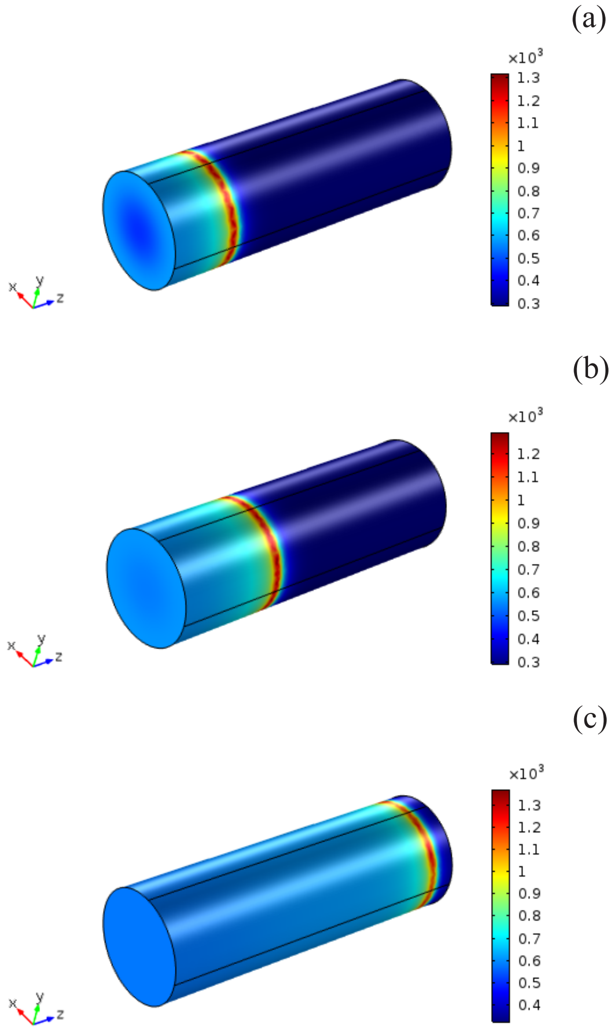

Fig. 1. Snapshots of hard turning process during: (a) initial, (b) intermediate and (c) final stages of the process.

Finally, the stresses due to thermal phenomena were calculated and maximum von Mises stress is shown to be 310 MPa in this case, indicating that due to the increased temperatures developing during hard turning, the effect of thermally induced stresses is significant.

After initial discussion of results concerning a specific case, the results concerning all the cases are presented. In Figs. 3 and 4, the maximum temperature and von Mises stress at various simulation cases are

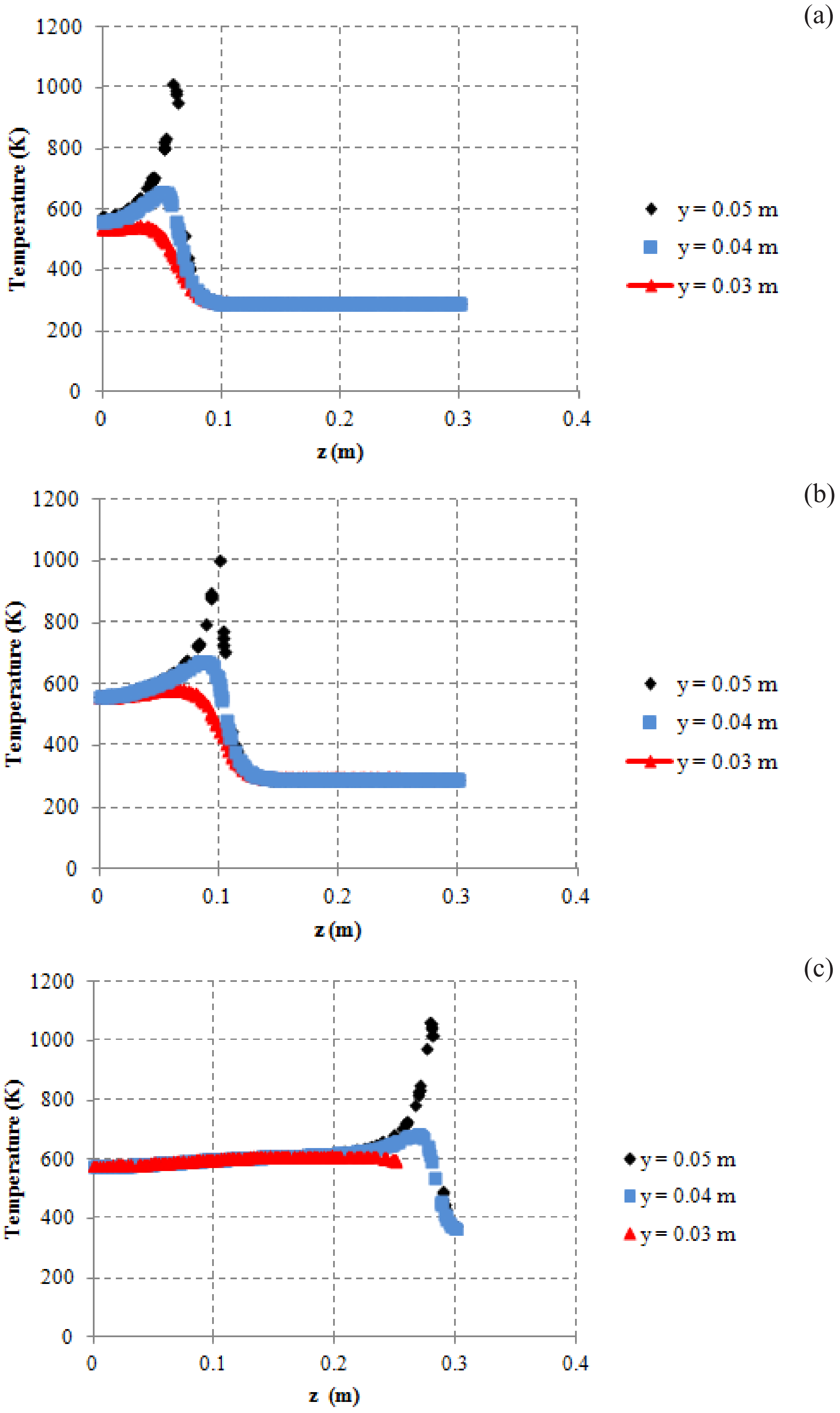

Fig. 2. Temperature field along the workpiece at three different depths during: (a) initial, (b) in-termediate and (c) final stages of the process.

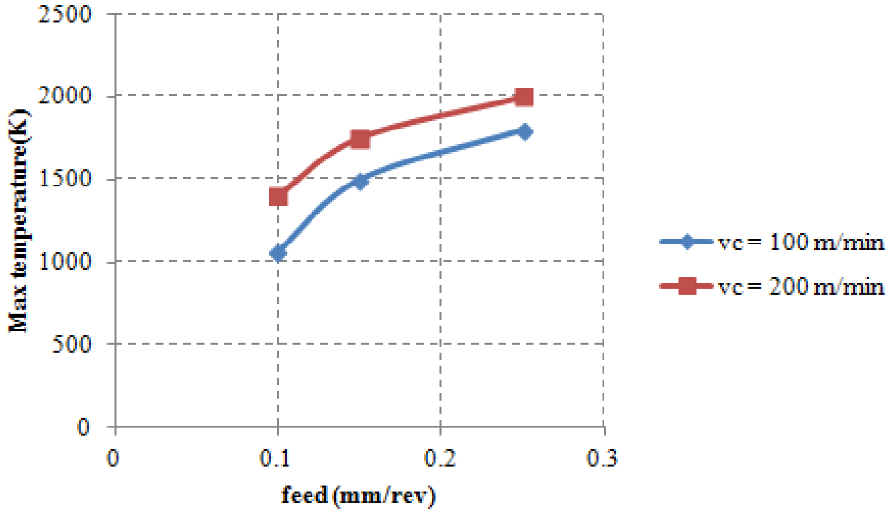

Fig. 3. Maximum temperature in respect to feed and cutting speed values.

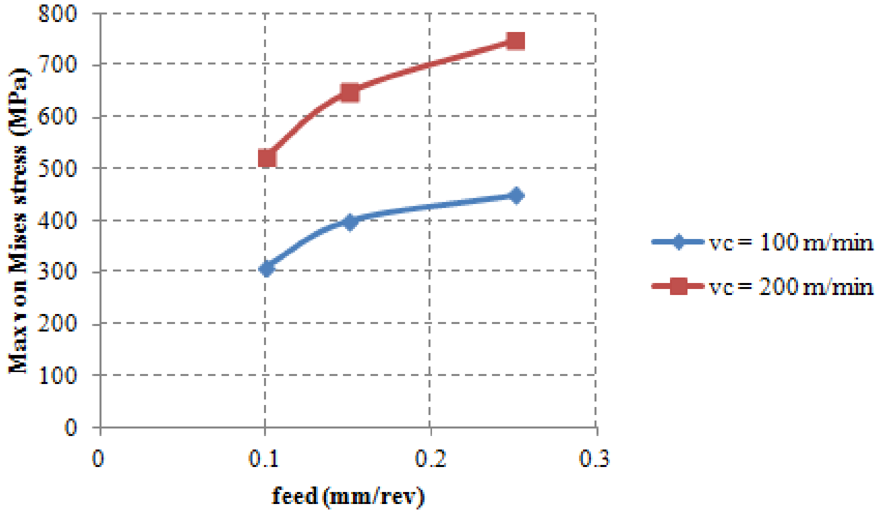

Fig. 4. Maximum von Mises stress in respect to feed and cutting speed values.

presented, respectively.

At first, it can be seen that the maximum temperature varies in a non-linear way in respect to feed speed. Increased feed and cutting speed values give rise to larger temperature values and more intense thermal phenomena on the workpiece. However, temperature increase is not linear as an increase in feed results also to less time for heat to be transferred into the bulk material. The increase of von Mises stress with increase of feed at cutting speed is justified, as it is anticipated that it will follow the trend of temperature increase in the workpiece.

These results are in accordance to the findings of previous works in the literature. More specifically, Hua et al. [12] conducted numerical investigations and found that with an increase of feed, a non-linear increase of both axial and circumferential stress is observed. Bapat et al. [14] observed increase of temperature with increased cutting speed both experimentally and numericaly. The same conclusion was also drawn by Yan et al. [10] who conducted numerical simulations for hard turning of AISI H13 steel. Finally, Chou et al. [13] determined that increase of feed and cutting speed and decrease of depth of cut result to increased temperature in the workpiece during hard turning.

From the aforementioned results, smaller values of feed and cutting speed can lead to mild thermal phenomena and subsequently variations in stress field within the workpiece. However, in industrial practice, a compromise between the outcome of the process and processing time should be determined in order to ensure productivity.

CONCLUSIONS

Several simulation cases of hard turning for various feed rates and cutting speeds are conducted using a 3D thermal model with a realistically moving heat source simulating cutting tool tip contact with the workpiece. The results confirm the significant effect of thermally induced phenomena during hard turning of steel components, which give rise to microstructural alterations and significant thermal stresses. It was observed that, an increase of feed and cutting speed leads to increased maximum temperature and von Mises stress in the workpiece. The results of this preliminary study are considered satisfying and further studies should be conducted to determine residual stress profile during hard turning and process characteristics in a wide range of parameters.

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