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A full factorial numerical investigation and validation of precision end milling process for hardened tool steel

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Abstract
Tool steel materials have poor machinability, as the high hardness of the material will cause high cutting forces, premature failure of the cutting tools, and is also associated with machining induced tensile stresses within the work piece. Due to high experimental costs, there is no recent research on end milling tool steel, using full factorial experimental or numerical design. A 3D FE-model of a precision end milling process with a two flute ball nose cutter were established in this paper. The FE-Model used a subroutine to model hardening realised through the Johnson-Cook model, additionally were a material removal criteria developed and implemented. Through full factorial numerical simulations the influence of cutting parameters on cutting force of H13 tool steel was studied. Depth of cut was found to be the most influential machining parameter on cutting forces followed by feed rate and surface speed. Four milling experiments were carried out to validate the simulation results. It was found that the simulation and the experiments had a good agreement on the cutting forces. The validated FEA model can be used for further studies on residual stress or temperatures and to optimise the cutting process.

Keywords: FEM, End Milling, hardening, tool steel, HSM

1. Introduction

Machining hard material in a high speed machining process has economic and technology benefits such as reduced process time and higher accuracy, compared to conventional machining. Often tool steel such as AISI H13 is used to produce forming tools in a broad range of industries, such as aerospace, automotive, end-consumer goods etc. This hardened steel can be cut in a high speed cutting machine with a high rigidity. Adiabatic heating takes place during high speed milling, which causes non-favourable tensile stresses on the work piece surface and subsurface. [1] Therefore is the aim of the project to develop a framework and prediction model for the remaining stresses in work pieces to increase its fatigue resistance. This here represented work is the first stage of this project, to validate the 3D-FEM model. Consequently, it is important to investigate the theory and behaviour to optimise the process and enhance the fatigue resistance of the machined work pieces. The recent research has published work on H13 and milling hard / difficult to cut material. However, the published work did not exceed more than 21 physically or simulated experiments. Particularly, there are limited published 3D finite element (FE) models, due to its complexity and high CPU time. Previously published FE models were dominated on a 2D-model, due to its simplification of one dimension and therefore reduced calculation time and costs. This work has realised a 3D-FE-Model including a subroutine, for a more comprehensive material model. The advantage is that the 3D model is able to represent a multi cutting edge engagement during the cutting process, which has a major impact on stress as well as temperature behaviour and consequently on the cutting force. The amount of factors and their levels of a full factorial experimental design lead to sixty realised FE-simulations. Four strategies were physically machined, while cutting force was recorded to validate the FEM simulation.

2. FEM Model

The general setup of the milling FE-model in ABAQUS 6-14 is shown in Figure 1. The work piece was meshed in an explicit environment by using C3D8RT elements, which are 8-node thermally coupled brick with trilinear displacement, temperature, reduced integration and hourglass control elements. It contains a fine mesh and coarse mesh area. Fine mesh with around 13000 elements was used for the material removal during the cutting process. The cutting tool was also meshed but kept rigid, to reduce the calculation time.

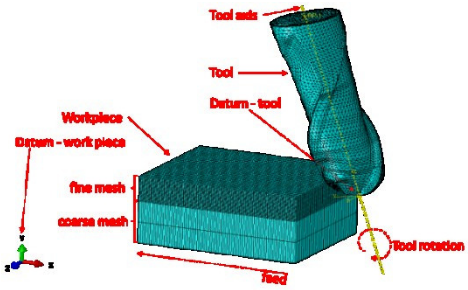

Figure 1. FEM milling model setup

Each cutting strategy run simultaneously on a 16-core high performance computer with a calculation time of 24 h – 48 h, depending on the cutting speed.

AISI H13 was chosen with 45 Rockwell Hardness (HRC). The extended model of Johnson-Cook (JC), described in equation (1), was used to characterise the material of the work piece. The flow stress $\bar{\sigma}$ can be combined with the Von-Mises yield criterion and describes an isotropic hardening, where T is the temperature, $\bar{\varepsilon}$ is the proportional strain and $\dot{\bar{\varepsilon}}$ is the proportional strain rate. A, B, C, m, n, T_0, T_m are material parameters, ε_0 is the reference strain and ε the current strain [2]. These parameters used in the FE-model were mainly taken from literatures [2-4]. The parameters *D* and *E* were determined by a 2^{nd} and 3^{rd} grade of polynomial regression. The material hardening model written in a subroutine

"VUHARD" (an ABAQUS specific subroutine connection for hardening) was similar written to Umbrello et al. [2, 3], however an additional material removal criterion was added.

$$\bar{\sigma}(\bar{\varepsilon},\dot{\bar{\varepsilon}},T) = (A + B(\bar{\varepsilon})^n + D\ln(\varepsilon_0 + \varepsilon) + E) \cdot \left(1 + C\,\ln\frac{\dot{\bar{\varepsilon}}}{\dot{\bar{\varepsilon}}_0}\right)\cdot\left[1-\left(\frac{T-T_0}{T_m-T_0}\right)^m\right] \quad \textbf{(1)}$$

The additional removal criterion is based on the ultimate tensile strength (UTS). The UTS changes with the temperature, therefore was the current temperature in the FEM initialised. The current UTS criteria is calculated by a 3rd grade polynomial regression of tensile stress at different temperatures. If the flow stress exceeds the UTS elements are forced to be deleted, otherwise it remains for further calculation. The surface speed (VEL) with 4 levels, depth of cut (DOC) with 5 levels and the feed rate (FR) with 3 levels were investigated, which can be seen in Table 1. This full factorial variable follows respectively the sequence of surface speed, depth of cut and feed rate (VEL-DOC-FR –> 1-1-1, … , 4-5-3)

Table 1. Factors and their levels

Factor | Level	1	2	3	4	5
DOC/mm	0.2	0.3	0.4	0.5	0.6
VEL/m min^{-1}	150	200	250	300	
FR/mm tooth^{-1}	0.05	0.1	0.15		

3. Experimental Work

In order to validate the simulation results, four physical experiments were carried out under the same setup condition as the FEM. The setup condition of each experiment can be seen in Table 1. A 6 mm two-flute ball nose cutter with a lead angle of 15° was used. A DMG HSC 75 machine for the machining experiment and a Kistler 9257BA dynamometer to record the cutting forces were used.

4. Results and Discussion

4.1 Simulation

The behaviour of cutting forces influenced by the different cutting strategies can be seen in Figure 2. The cutting force increases with increasing the depth of cut or feed rate.

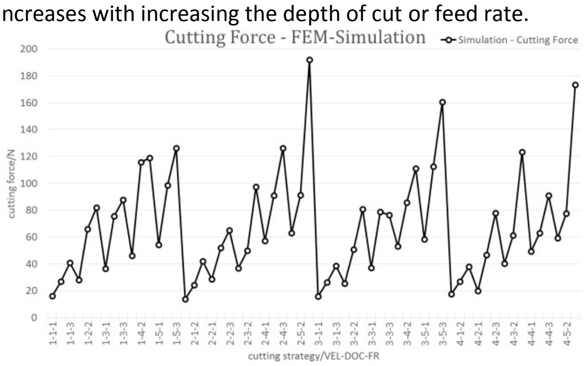

Figure 2. Cutting force behaviour with different settings

The highest cutting force for each surface speed was observed, when the feed rate and the depth of cut are at their highest level, i.e. in 1-5-3, 2-5-3, 3-5-3, 4-5-3. The significance for machining parameters was calculated through a regression analysis. The statistical significance factor (p-value), as smaller the value as more important is the factor, are $1.21{\cdot}10^{-15}$ for DOC, $1.11{\cdot}10^{-4}$ for FR and $5.73{\cdot}10^{-2}$ for VEL. From this it can be seen that the depth of cut has the most significant influence on cutting force, followed by the feed rate and surface speed.

An applied linear regression showed that the surface speed reduces cutting force. In contrast, the feed rate and depth of cut increases cutting force. But surface speed has no significant impact on the cutting force, if the depth of cut or feed rate increases, cutting force increases faster than a higher surface speed can decrease it.

4.2 Comparison

A comparison between the simulation and experiment is shown in Figure 3.

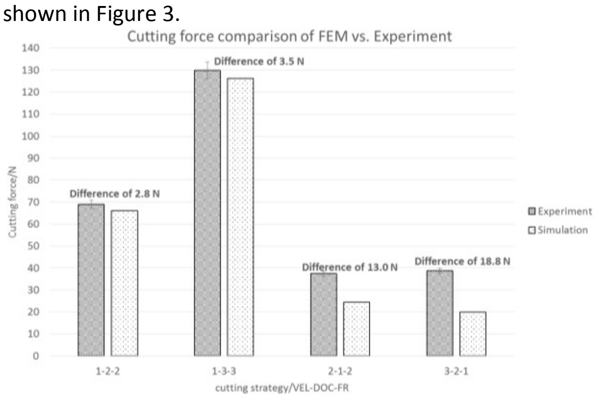

Figure 3. Cutting force comparison between FEM and experiment

It can be seen, that the simulation results agree well with experiment. However, the simulation result is lower than the experimental results. The bigger difference in experiment 2-1-2 and 3-2-1 is possible caused by the inconsistency of work materials used in the experiment as well as wear on the cutter which is neglected in the FE model.

5. Concluding remarks

The FE simulation of end milling of H13 shows the depth of cut has the most significant influence on cutting force. The simulated and measured cutting forces show good correlation. The proposed 3D FE model, therefore, proofs to be an effective means in the prediction of the cutting force, which is known as a key influence on surface integrity. The additional material removal function in the subroutine proofs to be a good solution to the 3D model. Furthermore, the 3D model allows a cost effective solution to a full parametric experimental setup. The full factorial results are used to determine a more accurate prediction of the cutting force and its effects. This dataset can be used for process optimisation. Hence, this is the first stage of this project. In the future, more physical experiments will be realised to confirm the simulation validation. Additionally, analysis and prediction of residual stress after machining will be realised, as well as soft prediction models will be developed.

Acknowledgement

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