Numerical simulation of finish hard turning for AISI H13 die steel

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Abstract

A coupled thermo-mechanical model of plane-strain orthogonal turning of hardened steel was presented. In general, the flow stress models used in computer simulation of machining processes are a function of effective strain, effective strain rate and temperature developed during the cutting process. However, these models do not adequately describe the material behavior in hard machining, where the workpiece material is machined in its hardened condition. This hardness modifies the strength and work hardening characteristics of the material being cut. So, the flow stress of the work-material was taken with literature [H. Yan, J. Hua, R. Shivpuri, Development of flow stress model for hard machining of AISI H13 work tool steel. The Fourth International Conference on Physical and Numerical Simulation of Materials Processing, Shanghui in China, 2004, p. 5] in order to take into account the effect of the large strain, strain-rate, temperature and initial workpiece hardness. Then a series of numerical simulations had been done to investigate the effect of machining parameters on the machinability of hardened steel AISI H13 in finish turning process. The results obtained are helpful for optimizing process parameters and improving the design of cutting inserts in finish turning of hardened steel AISI H13.

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1. Introduction

Hardened steel parts are widely used in the automotive, gear, bearing, tool, and die industry. By eliminating the need to finish grind parts, the automotive industry reduced capital outlays by as much as 40% and increased production by approximately 30%. So, hard turning of machine parts is a production process that holds considerable promise for the future since it is an effective means of increasing productivity.

AISI H13 die steel possesses good resistance to thermal softening and heat checking, high hardenability, high strength and high toughness. So, this steel has been applied widely to produce many kinds of hot work dies, such as forging dies, extrusion dies, die-casting dies and so on. The benefits for the manufacture of dies/molds in their hardened state are substantial in terms of reduced machining costs and lead times, in comparison to the more traditional route which involves machining in the annealed state, heat treatment, grinding/electrical discharge machining (EDM), and manual finishing. In addition, improved quality/workpiece surface integrity (SI) leading to longer component life is also reported [2].

In order to gain acceptance as an equivalent of the grinding process, finish hard turning must be able to satisfy the high quality requirements of the workpiece concerning form and size accuracy, surface finish, and surface integrity. However, machining conditions in finish hard turning are different from conventional turning, the former chip formation occurs only in tool-tip radius because of the relative small depth of cut (less than 0.1 mm) and the large tool-tip radius. In general, the depth of cut (cutting thickness, undeformed chip thickness) is smaller than the tool-tip radius. A thorough analysis of this novel technology will improve the process capability greatly. An extensive body of the literature on hard turning is limited to experiment work [3–9], while few FEM analysis of this promising machining process are reported. Ng et al. [10] simulated cutting forces and temperature distributions when orthogonal turning a hardened hot work die steel AISI H13 (HRC 52) with FORGE 2, then simulated continuous
and segmental chip formation when machining AISI H13 tool/die steel treated to HRC 49 with ABAQUS/Explicit [11]. However, the influence of an initial workpiece hardness on flow stress in the former FEM model was not taken into account, the latter model made the assumption that the tool was perfectly sharp, which restricted their analysis within the depth of cut of 0.25 mm. Therefore, in order to understand the process better and improve the performance of cutting tools, this study tries to include the above ignored factors in our developed FEM model and does a series of numerical simulations to investigate the effect of machining parameters on the machinability of hardened steel AISI H13 in finish turning.

2. Thermo-rigid-plastic finite element method formulation

2.1. Basic equations of rigid-plastic finite element method

With the rigid-plastic finite element method [12], the basic equations are required to be satisfied once the rigid-plastic body takes place of plastic deformation.

(a) Equilibrium condition
\[ \sigma_{ij} = 0 \]  

(b) Compatibility condition
\[ \dot{e}_{ij} = \frac{1}{2} (v_i + v_j) \]  

(c) Constitutive relation
\[ \sigma'_{ij} = \frac{2}{3} \frac{s}{s} \dot{e}_{ij} \]  

(d) Incompressibility condition
\[ \dot{e}_{kk} = 0 \]  

(e) Boundary conditions
\[ \sigma_{ij} n_i = \bar{F}_j \quad \text{(on } S_r) \]  
\[ v_i = \bar{v}_i \quad \text{(on } S_s) \]  

The field equations given above can be solved by a variational principle expressed as follows
\[ \delta \phi = \int_{V} \bar{\sigma} \delta \epsilon \, dV + \int_{V} K \dot{e}_{kk} \delta \dot{e}_{mn} \, dV + \int_{S_r} F_i \delta v_i \, dS = 0 \]  

where \( \sigma_{ij}, \dot{e}_{ij} \) and \( v_i \) are the stress, strain rate and the velocity components, respectively, and \( \sigma'_{ij} \) is deviatoric stress component, \( V \) the volume of deformed body, \( S_r \) the force surface, \( S_v \) the velocity surface, \( \bar{F}_j \) the traction (frictional) stress and \( K \) a large positive constant to penalize volume change. The solution of non-linear simulation equations can be obtained by the Newton–Raphson method.

2.2. Heat transfer equation

This rigid-plastic material model is coupled with a heat transfer model (the heat exchange between the workpiece, tooling and ambient surrounding), expressed by the following equation
\[ (kT_{ij}) + \dot{r} - (\rho c_p \dot{T}) = 0 \]  

where \( k \) denotes thermal conductivity, \( \dot{r} \) the heat generation rate, \( T \) the temperature, \( \rho \) the specific density and \( C_p \) the specific heat. The first term \( (kT_{ij}) \) and the third term \( \rho c_p \dot{T} \) represent the heat transfer rate and the internal heat energy generation rate (e.g. latent heat), respectively. The rate of the heat generation in the deforming body due to plastic deformation is given as follows
\[ \dot{r} = \alpha \rho e \]  

where \( \dot{r} \) is the heat generation efficiency, \( \alpha \) represents the fraction of mechanical energy converted to heat and is as usual assumed to be 0.9. The fraction of the remainder of the plastic deformation energy is associated with causing changes in dislocation density, grain boundary generation and migration, and phase transformation and evolution. Along the boundary of the workpiece, either the temperature \( T \) is prescribed or a heat flux is given. The energy balance equation can be rewritten by the weighted residual method as follows
\[ \int_{V} k T_{ij} \partial T_{ij} \, dV + \int_{V} \rho c_p \dot{T} \partial T \, dV - \int_{S_r} \alpha \dot{\epsilon} \partial T \, dV \]  
\[ + \int_{S_s} q_n \partial T \, dS = 0 \]  

where \( q_n \) is the heat flux normal to the boundary surface. In general, \( q_n \) includes the friction heat flux (\( q_1 \)) due to the relative movement between the tool and the workpiece, the heat flux through contact with other hotter or colder objects and the convection heat loss (\( q_2 \)), and the radiation heat loss to the environment (\( q_3 \))
\[ q_n = q_1 + q_2 + q_3 \]  
\[ q_1 = F_i v_i \]  

where \( F_i \) is the contact friction force and \( v_i \) the relative sliding velocity between the chip and the tool rake face. This flux is split into two equal parts, assigned to each of the contacting parts, i.e. the chip and the tool.

Machining is performed at ambient temperature (i.e. the initial temperature of both the workpiece and the tool is
20 °C), while the heat losses to the environment from the free surface of the workpiece, due to convection heat transfer, are determined by the distributed heat flux

\[ q_2 = h(T_w - T_0) \]  

(13)

where \( h \) is the convection heat-transfer coefficient of the workpiece material, \( T_w \) the temperature of the workpiece, to the ambient temperature, taken as 20 °C.

Heat transfer by radiation \( q_3 \) is considered insignificant and is not therefore taken into account. The temperature distribution of both the workpiece and the tool can be obtained readily by solving the above energy balance equation.

### 3. Finite element model

The machining of hardened steel AISI H13 is modeled as an orthogonal cutting process assuming plane strain conditions. A schematic of the finite element model is shown in Fig. 1.

#### 3.1. Workpiece and tool material modeling

We developed the flow stress model of AISI H13 work tool steel at the different hardness [1], which is used for this modeling case

\[ \sigma(\dot{\varepsilon}, \dot{\varepsilon}, T, HRC = \text{const}) = (A + B\dot{\varepsilon}^m + C \ln(\varepsilon_0 + \varepsilon) + D)(1 + E \ln \dot{\varepsilon}^*) (1 - (T^*)^m) \]  

(14a)

where \( \varepsilon_0 \) presents the reference strain and is taken to be \( 10^{-3} \), \( \dot{\varepsilon}^* = \dot{\varepsilon}/\dot{\varepsilon}_0 \) is the dimensionless strain rate for \( \dot{\varepsilon}_0 = 1.0 \) s\(^{-1} \) and \( A, B, E, n, \) and \( m \) are considered to be material constants and are taken with Table 1. \( T^* \) the homologous temperature \( T^* = (T - T_0)/(T_{\text{melting}} - T_0) \), \( T \) the workpiece temperature, and \( T_{\text{melting}} \) and \( T_0 \) are, respectively, the material melting temperature and the reference ambient temperature. The \( C \) and \( D \) are the function of the initial workpiece hardness and taken as follows:

#### 4. FEM simulation analysis

#### 4.1. Effect of cutting speed

The parameters for the study of effects of cutting speed are: depth of cut = 5 \( \mu \)m, rake angle = \( -10^\circ \), flank angle = \( 8^\circ \) and tool-tip radius = 20 \( \mu \)m. Fig. 2 shows the chip geometries at the two different speeds. The transition from continuous chip to segmented chip takes place with increasing cutting speed from 150 to 750 m/min. The similar observation was presented by Tonshoff et al. [13]. Fig. 3 illustrates the distributions of hydrostatic stresses at two different cutting speeds. The distribution of hydrostatic stress in the cutting zones is similar for two different cutting speeds, but its magnitude is significantly affected by the cutting speed. The maximum tensile hydrostatic stress

### Table 1

Parameters in Eq. (14a) \((E, m, \) and \( n \) are dimensionless)

|   |   |   |   |   |
|---|---|---|---|---|
|   |   |   |   |   |

Table 2

The mechanical and physical properties of the workpiece and tool material

|                  | AISI H13 | PCBN       |
|------------------|----------|------------|
| Young’s modulus  | 211,000  | 652,000    |
| Poisson’s ratio   | 0.28     | 0.128      |
| Density (kg/m\(^3\)) | 7800    | 3399.5     |
| Thermal conductivity (W/m K) | 28.4    | 100        |
| Specific heat (J/kg K) | 560     | 960        |

\[ C(HRC) = 0.0576 \times (HRC)^2 - 3.7861 \times HRC \]

+ 52.82 \( \text{MPa} \) \hspace{1cm} (14b)

\[ D(HRC) = 0.6311 \times (HRC)^2 - 12.752 \times HRC \]

− 727.5 \( \text{MPa} \) \hspace{1cm} (14c)

In this case, the initial workpiece hardness is taken to be 52HRC. Based on the above equations, \( C = 11.69 \) MPa; \( D = 315 \) MPa.

Due to the high elastic modulus of the tool material of PCBN, the tool is considered as a perfectly rigid body and only a heat-transfer analysis is conducted on it. Other mechanical and physical properties of hardened AISI H13 steel and PCBN are listed in Table 2.

### 3.2. Process parameters

The tool geometry and the cutting conditions used for the turning simulation are given in Table 3.

### Table 3

The cutting conditions and tool geometries

|                  |   |   |
|------------------|---|---|
| Tool rake angle  |   | −10 |
| Tool clearance angle | 10 |
| Tool-tip radius (mm) | 0.02, 0.04 |
| Cutting speed (m/min) | 150, 450, 750 |
| Feed rate (mm/rev) |   | 0.005, 0.010, 0.020 |
decreases with increasing cutting speed. So, it is helpful for cutting process as the cutting speed increases properly.

Fig. 4 represents the distributions of temperatures at two different cutting speeds. The magnitude and distribution of temperature are affected by the cutting speed. The maximum workpiece temperature increases from around 646 to 922.7°C, the maximum tool temperature increases from 147.6 to 406.7°C when the cutting speed increases from 150 to 750 m/min. The areas of high temperatures are concentrated on the chip–tool interface and the flank of the tool. The comparisons between the cutting and thrust forces decreases with increasing cutting speed. So, it is helpful for cutting process as the cutting speed increases properly. 

Fig. 4. Temperature distributions in two different cutting speeds (Unit: °C).
at two different speeds are shown in Fig. 5. The cutting and thrust forces decrease with increasing cutting speed. The thrust force is larger than the cutting force for the higher cutting speed of 750 m/mm.

4.2. Effect of depth of cut

The effect of feed was studied setting the parameters as: cutting speed = 450 m/min, tool-tip radius = 20 mm, rake angle = −10°, flank angle = 10°, depth of cut = 5 or 20 μm. Fig. 6 shows the chip geometries at two different depths of cut. Fig. 7 illustrates the distributions of hydrostatic stresses at two different depths of cut. As the depth of cut increases, the hydrostatic stress increases. Fig. 8 represents the distributions of temperatures at two different depths of cut. The maximum workpiece temperature increases from around 804.9 to 934.5 °C, the maximum tool temperature increases from 352.2 to 385.2 °C when the depth of cut increases from 5 to 20 μm.
increases from 5 to 20 μm. The comparisons between the cutting and thrust forces at two different depths of cut are shown in Fig. 9. The cutting and thrust force increase as the depth of cut is increased. The thrust force is larger than the cutting force for the lower depth of cut of 5 μm.

### 4.3. Effect of tool-tip radius

The effect of tool-tip radius was studied by cutting speed = 450 m/min, depth of cut = 10 μm, rake angle = −10°, flank angle = 10°, tool-tip radius = 20 or 40 μm. Fig. 10 shows the chip geometries at the two different tool-tip radii. Fig. 11 illustrates the distributions of hydrostatic stresses at two tool-tip radii. As the tool-tip radius increases from 20 to 40 μm, the maximum tensile hydrostatic stress decreases from 670.5 to nearly 0 MPa. These results are helpful for us to understand the function of increasing proper tool-tip radius in the practice hard machining process. Fig. 12 represents the distributions of temperatures at two different tool-tip radii. The maximum workpiece temperature increases from around 876.9 to 1081.9 °C, the maximum tool temperature increases from 378.9 to 551.7 °C as the tool-tip radius increases from 20 to 40 μm. The comparisons between the cutting and thrust forces at the two different tool-tip radii are shown in Fig. 13. The cutting and thrust forces increase with increasing in tool-tip radius. The thrust force is larger than the cutting force for both tool-tip radii.

### 5. Conclusions

The work completed from a parametric study conducted to investigate the effects of cutting speed, depth of cut and tool-tip radius on the finish hard turning of AISI H13 steel can be summarized as following:

1. A couple thermo-mechanical implicit finite element model was developed to simulate chip formation process in finish turning of hardened steel.
The flow stress of the work-material was taken with our previous proposed model in order to take into account the effect of the large strain, strain-rate, temperature and initial workpiece hardness.

From simulation results, higher speed, smaller depth of cut and larger tool-tip radius help to decrease hydrostatic tension in machined layer, which improves the surface integrity of the machined workpiece and eliminate residual stress. It is also helpful to improve the design of cutting inserts, especially to optimize the edge geometry of PCBN inserts for precision machining of hardened steels.

The thrust force is dominant and larger than the cutting force in finish hard machining. As cutting speeds increase, cutting and thrust forces decrease, which helps to improve the surface integrity of the machined workpiece. However, cutting forces, especially in thrust direction, increase with the increase in feed and tool-tip radius. It is observed that the region of high stresses in the thrust direction turns inward as the feed and tool-tip radius increase, which may result in higher residual stresses on the finish surface and more rapid flank wear.

As cutting speed, depth of cut and tool-tip radius increase, the workpiece and tool temperatures increase, which may induce more serious diffusion crater and flank wears in the tool.

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