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Development of Flow Stress of AISI H13 Die Steel in Hard Machining

YAN Hong[1] , QIAN Guohua[2] , HU Qiang[1]
(1.School of Mechanical & Electrical Engineering, Nanchang University, Nanchang 330029, China;
2.School of Shangrao Vocation Technology, Shangrao 334009, China)

Abstract: An approach was presented to characterize the stress response of workpiece in hard machining, accounting for the effect of the initial workpiece hardness in addition to temperature, strain and strain rate on flow stress in this paper. AISI H13 die steel was chosen to verify this methodology. The proposed flow stress model demonstrates a good agreement with experimental data. Therefore, the proposed model can be used to predict the corresponding flow stress-strain response of AISI H13 die steel with variation of the initial workpiece hardness in hard machining.
Key words: flow stress; hard machining; finite element modeling; AISI H13 die steel

1 Introduction

Traditionally, the production of molds/dies generally involves conventional machining in the annealed (soft) state, followed by heat treatment, electrode manufacture, electro-discharge machining (EDM) and manual polish/ finish grinding[1]. A significant portion of the lead-time is spent for finish machining including electrode manufacture, EDM and manual polish/finish grinding, taking approximately two third of total manufacturing costs. As a result of the advances in machine tools and cutting tools technology, high speed hard machining (milling) becomes a cost-effective manufacturing process to produce parts with precision and surface quality. Especially, now it has been applied to the manufacture of moulds and dies where some processes can be eliminated by substituting a single process for two or more such as replacing the slow EDM and manual polish/finish grinding processes in many applications, giving considerable savings in both time and cost. The high flexibility and the ability to manufacture complex workpiece geometry in one set-up represent the main advantages of hard cutting in comparison to grinding[2]. In addition, the improved quality/workpiece surface integrity (SI) leading to longer component life was also reported[1-3].

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YAN Hong (闫洪) : Prof.; Ph D; E-mail: hyan@ncu.edu.cn
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AISI H13 die steel possesses a 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 hardness of AISI H13 die steel varies with its application for the different type of dies. AISI H13 hardness recommended is at 43-52 HRC for extrusion dies, at 44-50 HRC for die-casting dies, at 40-55 for forging dies and so on[4]. However, the effect of variation of the initial hardness on the flow stress can not be taken into account in current material flow stress model. In order to implement FE simulation and theoretical analysis of hard machining of AISI H13 die steel, flow stress data are needed with variation of the initial workpiece hardness. Therefore, the flow stress model with variation of the initial workpiece hardness is first required to be developed.

2 Flow Stress of AISI H13 Die Steel

The parameters in the existing flow stress models[5-10] were determined by tests for the specific initial hardness of material. If the initial workpiece hardness is changed, these parameters need to be redetermined by tests. Therefore, it is not convenient to use these models for characterizing the corresponding stress response with variation of the initial workpiece hardness in hard machining. A reasonable material model should meet two basic requirements: high accuracy and mathematical simplicity. A new approach was presented in this study to characterize the stress response of a workpiece in hard machining for taking into account the effect of the initial workpiece hardness on the flow stress.

2.1 Procedure for establishing flow stress model in hard machining

The construction of the material model accounting for the influence of the initial workpiece hardness is considered as follows. First, the reference flow stress curve at the certain workpiece hardness is chosen. Then, an additional component of stress is included for taking into account the effect of the initial workpiece hardness on the flow stress. The overall material stress response is presented by coupling these two parts as follows:

$$\bar{\sigma}(\bar{\varepsilon},\dot{\bar{\varepsilon}},T,HRC=\text{const})=f(\bar{\sigma}_{\text{Re}}f(\bar{\varepsilon},\dot{\bar{\varepsilon}},T),\Delta\sigma(HRC=\text{const})) \quad (1)$$

where, $\bar{\sigma}_{\text{Re}}f(\bar{\varepsilon},\dot{\bar{\varepsilon}},T)$ presents the reference flow stress curve at the certain workpiece hardness, $\Delta\sigma(HRC)$ denotes an additional component of stress, reflecting the influence of the initial workpiece hardness.

2.2 Determination of the reference flow stress curve

The reference flow stress curve is chosen to be described with Johnson-Cook's model[6] due to its incorporation of strain, strain rate and thermal softening effects, which is suitable for characterizing the stress response of AISI H13 die steel in hard machining[11].

$$\bar{\sigma}_{\text{Re}}f(\bar{\varepsilon},\dot{\bar{\varepsilon}},T)=(A+B\bar{\varepsilon}^{n})(1+E\ln\dot{\bar{\varepsilon}}^{*})(1-(T^{*})^{m}) \quad (2)$$

where, $\dot{\bar{\varepsilon}}_0^{*}=\dot{\bar{\varepsilon}}/\dot{\bar{\varepsilon}}_0$ is the dimensionless strain rate for $\dot{\bar{\varepsilon}}_0$=1.0s^{-1} and A, B, E, n and m are considered to be material constants, T^{*} the homologous temperature $T^{*}=(T-T_0)/(T_{\text{melting}}-T_0)$, T the workpiece temperature, and T_{melting} and T_0 are respectively the material melting temperature and the reference ambient temperature. Strain hardening, strain-rate hardening, and thermal softening are taken into account. The hardness for the reference flow stress curve is chosen as the certain workpiece hardness of HRC46. Based on the experimental data[11], the parameters in the reference flow stress curve can be determined by the regression analysis procedure, the five parameters can be estimated to be A=908.54 MPa, B=321.39 MPa, n=0.278, E=0.028 and m=1.18.

2.3 Determination of an additional component of stress

For a given material, the hardness behaviour varies with different heat treatment. This increase in strength due to hardness is not caused by the mechanical work but by the thermal treatment. Consequently, it can be resumed that the hardness is independent of the mechanical work and does not change with the short time in the high temperature cutting zone (shear zone). Therefore, in this study the initial hardness of the workpiece is incorporated in the flow stress using the following procedure: Take the yield stress and tensile strength as the start and the end points for a specific flow stress curve. If the hardness is higher, then both the yield stress and tensile strength are increasing. The points within this range are obtained by assuming a logarithm behaviour which will be added to the reference work-hardening value; For the given material assume the Young's modulus to be independent of the hardness. This is often the case for most materials.

In order to take into account the influence of the initial workpiece hardness, an additional component of stress is proposed as expressed in the following equation, which is a function of incremental flow stress between the reference flow stress and those having a different hardness with variation of strain.

$$\Delta\sigma(HRC=\text{const})=C\ln(\varepsilon_0+\varepsilon)+D \quad (3)$$

where, ε_0 presents the reference strain and is taken to be 10^{-3}. C and D are the function of the initial workpiece hardness accounting for the influence of hardness. Fig.1 shows the relationships of both the yield stress and tensile strength with variation of the workiece hardness[4]. Following this figure, Table 1 lists the differences of the yield stress and tensile strength between their values at different hardness. Based on Table 2, C and D are determined as follows:

$$C(HRC)=0.0576\times(HRC)^2\text{-}3.7861\times HRC+52.82 \text{ (MPa)}$$
$$D(HRC)=0.6311\times(HRC)^2\text{-}12.752\times HRC\text{-}727.5 \text{ (MPa)} \quad (4)$$

Table 1 The relative yield stress and tensile strength (HRC 46)

Different hardness /HRC	Basic hardness /HRC	$\Delta\sigma_{\text{yield}}$/%	$\Delta\sigma_{\text{strength}}$/%
60	46	4.6	5.2
55	46	3.0	3.3
50	46	1.5	1.5
46	46	0.0	0.0
40	46	–1.5	–1.5
35	46	–2.8	–2.6
30	46	–3.9	–3.6

Table 2 *C* and *D* values at the different hardness

Hardness /HRC	C/MPa	D/MPa
30	–9.87	–544.76
35	–7.89	–395.76
40	–5.92	–221.80
46	0.00	0.00
50	5.92	221.80
55	19.74	489.49
60	32.89	774.26

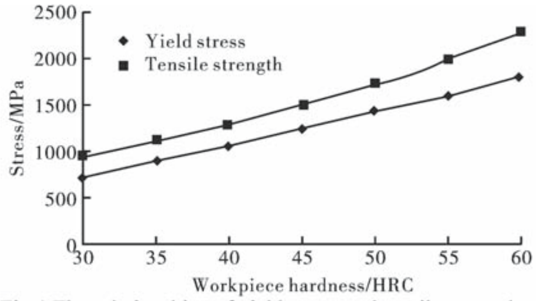


Fig.1 The relationships of yield stress and tensile strength with variation of workpiece hardness

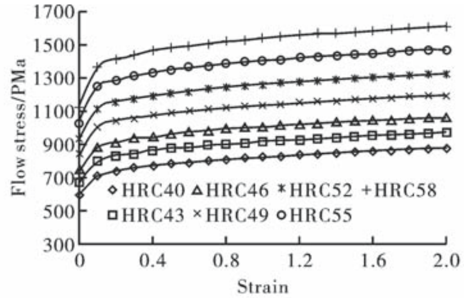


Fig.2 Flow stress data for AISI H13 die steel at its different hardness (T=625 ℃, strain rate=1E4 1/s)

2.4 Proposed flow stress model

Following equation (1) and combining equation (2) and with equation (3), the flow stress model for AISI H13 die steel at the different initial workpiece hardness can be expressed as follows:

$$\bar{\sigma}(\bar{\varepsilon},\dot{\bar{\varepsilon}},T,HRC\text{=const})$$

$$=(A+B\bar{\varepsilon}^{n}+C\ln(\varepsilon_0+\varepsilon)+D)(1+E\ln\dot{\varepsilon}^{*})(1-(T^{*})^{m}) \quad (5)$$

where, ε_0 presents the reference strain and is taken to be 10^{-3}, $\dot{\varepsilon}_0^{*}=\dot{\varepsilon}/\dot{\varepsilon}_0$ 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 given in **2.2**. T^{*} the homologous temperature $T^{*}=(T-T_0)/(T_{melting}-T_0)$, T the workpiece temperature, and $T_{melting}$ and T_0 are, respectively the material melting temperature and the reference ambient temperature. C and D are the function of the initial workpiece hardness as follows:

$C(HRC)=0.0576\times(HRC)^2-3.7861\times HRC+52.82$ (MPa)

$D(HRC)=0.6311\times(HRC)^2-12.752\times HRC-727.5$ (MPa)

Therefore, if the initial workpiece hardness HRC of AISI H13 die steel is given, equation (5) can be used to predict the corresponding flow stress-strain response of this material at its different hardness (Fig. 2).

3 Model Validation

To verify the proposed flow stress model, a FEM procedure was developed, in which this flow stress model was incorporated to simulate the given hard machining process. The predicted FEM results were then validated by comparing predictions with machining experiments, including the comparison of cutting load, chip morphology and temperature at different cutting speeds.

3.1 Finite element modeling

3.1.1 Friction on the tool-chip Interface

The interactions between the tool and the chip were analyzed by considering the contact area behavior, in which the contact area can be treated as sticking zone similar to the upsetting deformation. Therefore, the friction at the chip-tool interface was modeled using shear friction. The shear factor was considered as m=0.5 over the entire chip-tool contact area according to the comparison to experimental results.

Table 3 The cutting conditions and tool geometry

Variables	Value
Tool rake angle /°	– 5
Tool clearance angle /°	– 5
T-land chamfer /mm	–20 ° × 0.2
Cutting speed /(m/min)	75, 150, 200
Undeformed chip thickness /mm	0.25
Width of cut /mm	2.0
Cutting environment	Dry

Table 4 The mechanical and physical properties of the workpiece and tool material

Parameters	Workpiece (AISI H13)	Cutting tool (PCBN)
Young's modulus /MPa	211000	652000
Pisson's ratio	0.28	0.128
Density /(kg/m^3)	7800	3399.5
Thermal conductivity /(W/(m•K))	37	100
Specific heat /(J/(kg•K))	560	960
Hardness /HV	544	4000
Heat transfer coefficient /(N/sec/mm/C)	40	

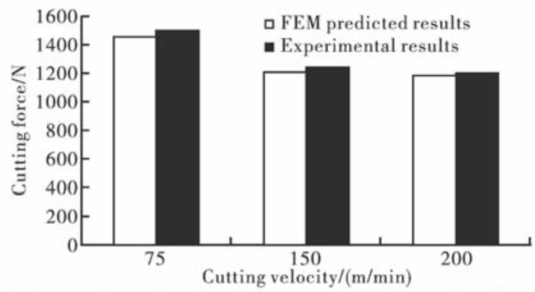
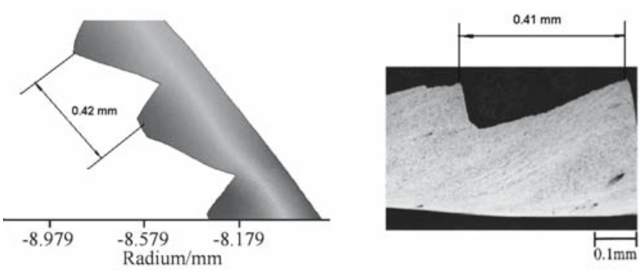


Fig.3 Comparison of cutting forces among FEM predicted results, experimental results during orthogonal turning of AISI H13 die steel (52 HRC)

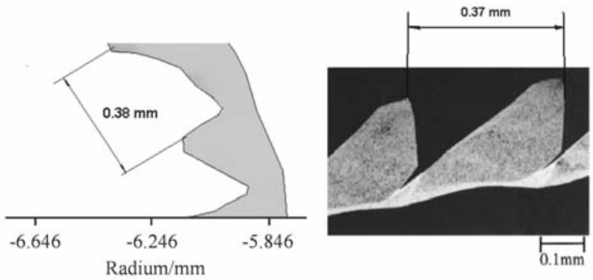
3.1.2 Process parameters

FEM simulations were conducted in this study with the same experimental conditions employed by the Ref.[12]. The tool geometry and the cutting conditions used for this simulation are listed in Table 3. The workpiece material was AISI H13 die steel (52 HRc), the tool was PCBN insert. Other material physical properties for the tool and workpiece are listed in Table 4.



(a) Simulation result (b) Experimental result

Fig.4 Comparison of chip morphologies at cutting speed V=75 m/min between FEM predicted result and published experimental result



(a) Simulation result (b) Experimental result

Fig.5 Comparison of chip morphologies at cutting speed V=200 m/min between FEM predicted result and published experimental result

3.2 Comparison of predictions with experiments

The following section summarizes the comparison of the cutting load, chip morphology and temperature to the experimental and published data.

3.2.1 Cutting force

The forces during the cutting experiments were measured using a Kistler type piezo-electric dynamometer. The charge amplifiers of the force platform were connected to a PC-pentium based data acquisition system. Accordingly, cutting forces were measured. In this study, the cutting forces were predicted by the FEM-based code DEFORM-2D using the proposed flow stress model of AISI H13 die steel. The predicted results from the present study were compared with experimental observations. It can be observed, in Fig.3, that the forces predicted are in reasonable agreement with experimental results.

3.2.2 Chip morphology

The comparisons of the chip morphology from the present FEM simulation to the published experimental results are shown in Fig. 4 and Fig.5[12]. The shape and chip pitch or the saw-tooth chip segments in these figures show a very good agreement with those observed in the published experiment[12].

4 Conclusions

In order to account for the effect of the initial material hardness, an approach was presented in this study to characterize the stress response of a workpiece in hard machining. The presented methodology is expressed by coupling the reference flow stress curve at the certain workpiece hardness and an additional component of stress accounting for the influence of the workpiece hardness. The reference flow stress model takes advantage of the form of the Johnson-Cook model, incorporating strain, strain rate and thermal softening effects. The chosen function of an additional component of stress describes well the variation of incremental flow stress between the reference flow stress and those having a different hardness. The methodology presented was used to establish the flow stress model for hard machining of AISI H13 die steel. The predicted cutting forces, chip morphologies and temperatures with the proposed model are in reasonable agreement with experimental results. Therefore, the proposed model can be used to predict the corresponding flow stress-strain response of AISI H13 die steel at a different hardness in hard machining.

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