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Research on the Test Method of Machining Stress Based on the Instrumented Indentation Test

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Abstract. The main objective of this study is to measure the distribution of machining stress by the instrumented indentation test (IIT). Finite element method (FEM) was performed to investigate the influences of tensile stress and compression stress on the indentation response (Load-displacement curves, average contact pressure and contact area). The thicknesses of machining stress layer under turning and grinding processing ways were obtained by layer stripping method based on instrumented indentation technique. Results indicate that the machining stress brings complex stress state. Under the same load, the corresponding indentation displacement increases while the indentation plastic work, contact area and average contact pressure decrease with the increases of machining stress (from compressive stress to tensile stress). Tensile stress does just the opposite. In addition, the layer thicknesses of the machining stress for turning and grinding members were measured by instrumented indentation method, results agree with X-ray method and demonstrate the effectiveness of the proposed approach.

1 Introduction

Metal cutting process is very complicated, the residual stress will produce inside workpiece during the turning, grinding and other different cutting processes, which affects the mechanical properties of materials. The interior or exterior residual stress of metal components has importance effect on mechanic performance [1]. A quantity of friction heat generates instantaneously in the cutting process, few of the heat passes workpiece interior and almost all heat gathers at the surface of workpiece. The difference of temperature distribution makes the metal surface produce tensile stress or compressive stress. That is the reason of residual stress caused by mechanical processing [2, 3]. A series of domestic and overseas research have been conducted to investigate the effects of machining parameters on working stress [4]. Lots of residual stress measurement methods have been developed at present, familiar ones are hole drilling method and X-ray diffraction method [5]. But these methods have certain damages to the specimen and they are relatively difficult to implement.

Some scholars have developed a new method for measuring machining stress by using micro hardness test [6-8]. Tsui and Oliver conducted a series of nano indentation experiments on AL 8009 alloy under uniaxial and biaxial stress conditions and calculated the indentation hardness by using Oliver-Pharr method [9]. Bolshakov investigated the influence of maching stress on the indentation surrounding material's pile-up using FEM analysis [10]. Cheng introduced the dimensional method into the indentation analysis, which provieded a new idea to establish the relation between indentation response and material properties [11]. Xu et al studied the effect of residual stress on the unloading behaviors for indentation samples [12]. 2012, Jin researched the relation between residual stress and indentation hardness based on energy method [6]. The instrumented indentation test (IIT) can characterize materials' micro mechanical properties and it is used more and more widely due to its high precision, easy operation and non-damage detection.

This study proposes a new method to measure the machining stress distribution based on FEM and IIT. For turning and grinding specimens, the machining stress states (tensile stress or compressive stress) and machining stress distribution along the strip layer depth are measured respectively. This study provides the reference and guides for the engineering application of the machining stress's measurment.

2 Materials and methods

2.1 FEM model

Figure 1 shows the finite element model of ABAQUS/Standard used in the present study. The spherical indenter was modeled as an analytic rigid surface with radius R=1mm in cylindrical coordinates, while the metal material was a half-space axisymmetric model with radius r=5mm and height h=15mm. According to the principle of Saint Venant, the effect of boundary on the stress distribution of the indentation area can be eliminated. Contact status between the rigid sphere and the deformable medium was assumed to be frictionless. Element type is the explicit linear model CAX4R quadrilateral element. And the local refined mesh size is 0.003mm.

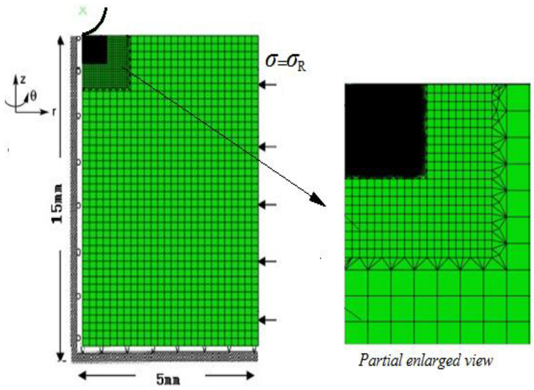


Figure 1. FEM model

The constitutive material model was assumed as elastic-perfectly plastic, its property parameters were expressed as E=200GPa, υ=0.3, yield strength σy=350MPa. Yielding is determined by the von Mises yield criterion [13], expressed as:

$$\sigma_{eq} = \sqrt{\frac{3}{2} S_{ij} S_{ij}} = \sigma_Y \tag{1}$$

Where σeq is the von Mises equivalent stress and Sij represents components of the deviatoric stress tensor. The evolution of plasticity in the indented half-space is tracked by the equivalent plastic strain $\bar{\varepsilon}_p$, defined as:

$$\bar{\varepsilon}_p = \int_{\Omega} \sqrt{\frac{2}{3} d\varepsilon_{ij}^p d\varepsilon_{ij}^p} \tag{2}$$

Where Ω is the strain path used to track the accumulation of plasticity and $d\varepsilon_{ij}^p$ denotes increments of plastic strain.

The load and displacement boundary conditions are as shown in Figure 1, σR is defined as the uniaxial machining stress, its negative value presents compressive stress and positive value presents tensile stress. According to the values of σR, the calculations were divided into five groups, which represented compressive stress state, unstressed state and tensile stress state (Table 1). Besides, the rigid indenter load F=-20N.

Table 1. The machining stress state σ_R (MPa).

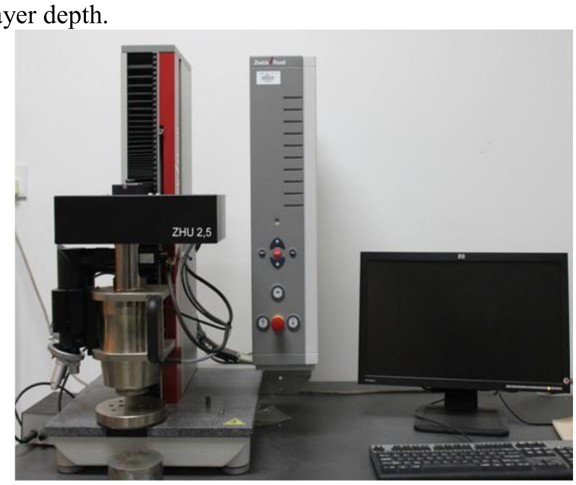
No.	1	2	3	4	5
Values	-300	-150	0	150	300
Stress state	compressive stress		unstressed	tensile stress	

2.2 Experiment

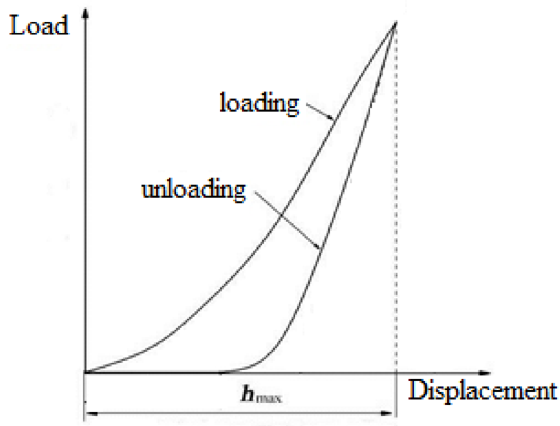
To measure the thickness of surface machining stress layer, the IIT was conducted based on layer stripping method.

Figure 2 shows the instrumented indentation testing machine Germany's Zwick ZHU 2.5 system. It works by measuring the load-displacement curves continuously in loading and unloading processes to calculate material's mechanical parameters. The resolution of the displacement measurement system is 0.02μm. A spherical indenter with diameter *D*=1mm was used, and the level of the loading force was HBW2.5: *F*=24.52N [14].

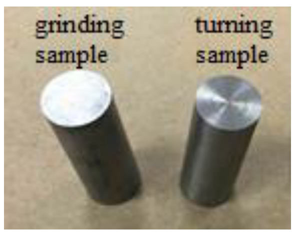
The experiment was divided into two groups: turning group and grinding group, each group included three specimens. The specimens were cylinders with diameter *d*=10mm and height *h*=25mm. Their material was 45 steel with *E*=200GPa, *υ*=0.3 and yield strength σ_y=350MPa. The distribution law of the max. Indentation depth h_m with the layer depth *d* was measured based on layer stripping. Each layer included 3-5 testing data, the 2000cc sandpaper was used to strip layer and the digital dial gauge with resolution 0.001mm was used to control layer depth.



(a) Zwick ZHU 2.5 machine



(b) Principle of the instrumented indentation test



(c) samples

Figure 2. Experimental facility

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3 Results and discussions

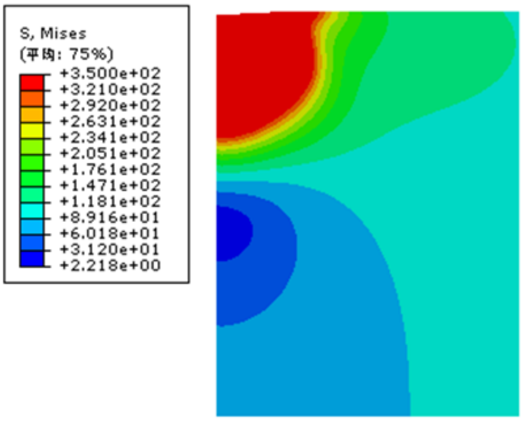
3.1. Equivalent stress distribution

For spherical indenter presses into the bulking materials with elastic-plastic hardening characteristics in loading process, the load and mechanical parameters have the following relation [9]:

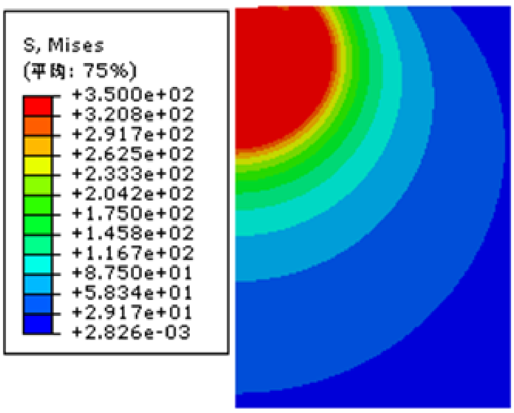
$$F = f_L(E, \nu, E_i, \nu_i, \sigma_y, \sigma_R, n, h, R) \quad (3)$$

Where E, ν, E_i, ν_i are the elastic modulus and possion's ratio of tested material and indenter; σ_y, σ_R are the yield strength and machining stress; n, h, R are the material's hardening exponent, indenter displacement and indenter radius.

Figure 3 shows the equivalent stress distribution in tensile stress state with σ_R=300MPa and unstress state respectively. It is obvious that the equivalent stress distribution is more complicated compared with unstress state when the machining stress exists. Besides, the plastic zone increases with the increase of indentation depth.



(a) Tensile stress state



(b) Unstressed state

Figure 3. Equivalent stress distribution

3.2 Load-displacement curves

According to Table 1, the load-displacement curves (*F-h* curves) in different cases are calculated, their results are shown in Figure 4.

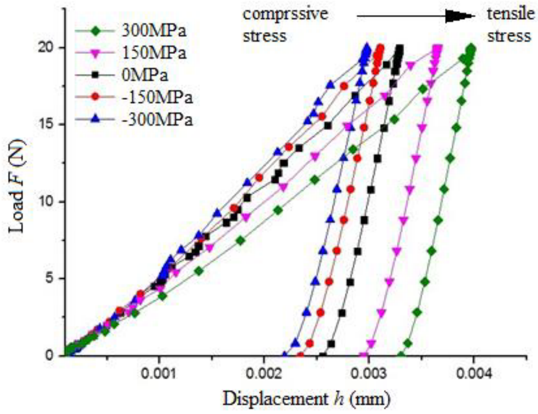


Figure 4. Load-displacement curves with different machining stresses

It is observed that the indentation depth h_m increases when machining stress turns from compressive stress to tensile stress. Under a constant load, compressive stress will make the *F-h* curve move towards a lower h_m while tensile stress will make the *F-h* curve go towards a higher h_m. Besides, h_m decreases with the increase of compressive stress and increases with the increase of tensile stress. In addition, by comparing the slopes of loading and unloading, it is discovered that the loading process is more sensitive to machining stress. Also, tensile stress effect on the *F-h* curve is larger than compressive stress.

3.3 Average contact pressure and contact area

By assuming that the pressure distribution on contact area is parabolic shape, then the expressions of contact pressure and contact radius are [13]:

$$p = p_0\sqrt{1-(r/a)^2}\,, \quad a = \left(\frac{3FR}{4E^*}\right)^{\frac{1}{3}} \quad (4)$$

Where p_0 is the max. the contact pressure in the center of contact area and r is the radial distance, E^* is reduced elastic modulus that defined as $1/E^* = (1-\nu^2)/E + (1-\nu_i^2)/E_i$, where E, E_i, ν and ν_i are elastic modulus and possion's ratio of two contact bodies.

In indentation process, the loading curve integral area is the *total* work W_t [14] while the unloading curve integral area is the elastic work W_e, then the plastic work W_p is:

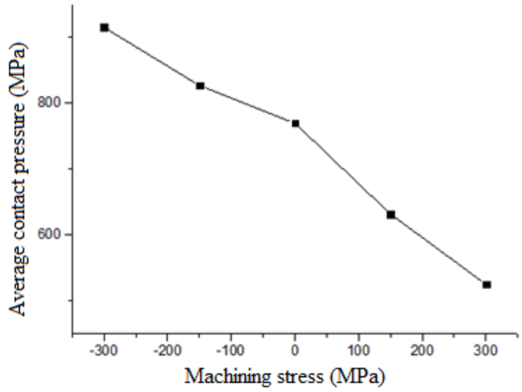
$$W_p = W_t - W_e \quad (5)$$

Table 2. Relationship between the plastic work and the machining stress

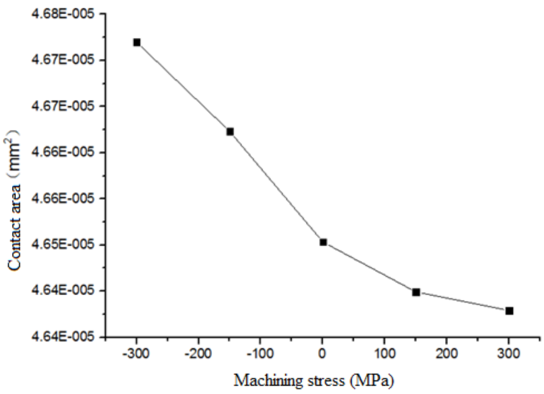
Machining stress (MPa)	-300	-150	0	150	300
Plastic work (10^{-5}J)	2.02	2.16	2.34	2.94	3.01

According to Eq. (5), the plastic works with different machining stresses are calculated (Table 2). It shows that W_p increases gradually when machining stress turns from compressive stress to tensile stress, which because of the integral path $h_c > h_t$.

Figure 5 shows the effect of machining stress on average contact pressure and contact area. The average contact pressure and contact area decrease with the increase of machining stress. That is because the plastic deformation increases with σ_R increasing (Table 2). Under the same load, material is prone to sink-in with displacement increases [6], therefore the contact area decreases. Besides, as the slope $k_c > k_t$, so the effect of compressive stress on the contact area is larger than tensile stress.



(a) Average contact pressure



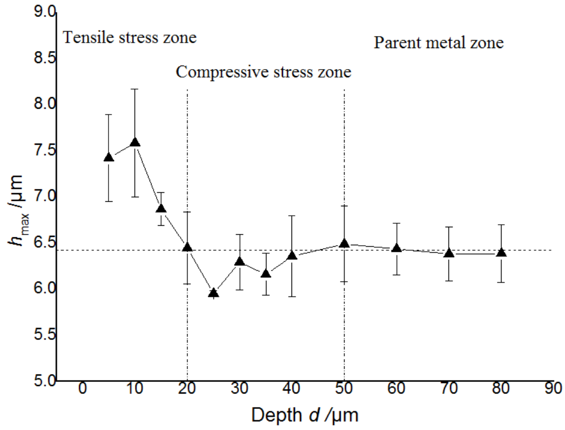
(b) Contact area

Figure 5. Effect of machining stress on average contact pressure and contact area.

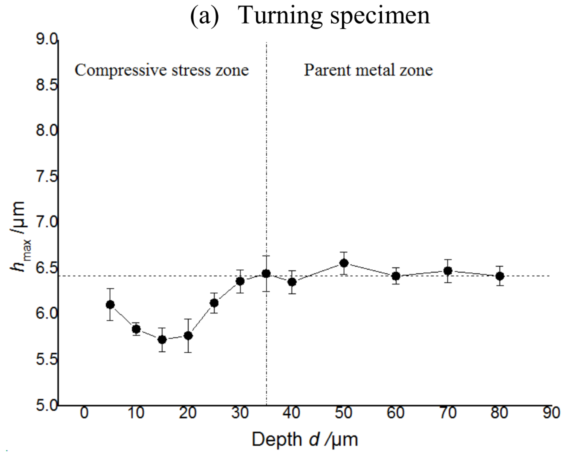
3.4 Machining stress thickness

Figure 6 indicates the relationship between layer depth d and the indentation depth h_m, Fig 6a shows the turing specimen with real surface roughness Ra=3.27 while Figure 6b shows the grinding one with Ra=0.31.

The max. indentation depth of parent metal h_0=6.42μm. Figure 6a shows that h_m decreases at first, increases subsequently and tends to be stable finally. $h_m > h_0$ when stripping depth d<20μm, $h_m < h_0$ when 20μm<d<50μm and $h_m = h_0$ when d>50μm.The change rule of h_m reflects the specimen's machining stress thickness. The initial range with $h_m > h_0$ is tensile stress zone; h_m decreases with depth increasing and when $h_m < h_0$, material gets into compressive zone; and when there's no significant difference between h_m and h_0 means that the machining stress disappears and material becomes parent metal.



(a) Turning specimen



(b) Grinding specimen

Figure 6. Machining stress layer thickness based on layer stripping method

These results presented here are identical with the values obtained by X-ray method in reference [4]. Similarly, in Figure 6b, the ranges of d<35μm and d>35μm represent cmpressive stress zone and parent metal respectively. In conclusion, the measured truning machining stress layer based on IIT consists of tensile stress and compressive stress and its stress layer thickness is about 50μm. The measured grinding machining stress layer is characterized by compressive stress and its thickness is about 35μm.

4 Conclusions

In this work, the test method of machining stress based on the instrumented indentation test is investigated. The influences of tensile stress and compression stress on the indentation response are studied by FEM. Under the same indentation load, the indentation displacement increases with the increasing of machining stress (from compressive stress to tensile stress). The stress state with machining stress is more complex. Compressive stress reduces the contact area, average contact pressure and plastic work, tensile stress will do just the opposite. Additionally, the machining stress layer thickness under turning and grinding processing ways are obtained by layer stripping method based on instrumented indentation technique, these results demonstrate the effectiveness of the proposed approach.

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