Generation Mechanism of Work Hardened Surface Layer in Metal Cutting*

(Study of Mechanical Factors Acting on Depth of Work Hardened Surface Layer Using Calculation Model)

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Finish machining used to be carried out in grinding, but it is being replaced by cutting with very small undeformed chip thickness. In ultra precision process, the effects of the cutting conditions and the complicated factors on the machined surface integrity are the serious problems. In this research, work hardened surface layer was dealt with as an evaluation of the machined surface integrity and the effect of the mechanical factors on work hardening was investigated experimentally in orthogonal cutting. As a result, it was found that work hardened surface layer was affected not only by the shear angle varied under the cutting conditions and the thrust force of cutting resistance, but also by the thrust force acting point, the coefficient of the thrust force and the compressive stress equivalent to the bulk hardness. Furthermore, these mechanical factors acting on the depth of the work hardened surface layer were investigated with the calculation model.

Key Words: Cutting, Hardness, Work Hardening, Work Hardened Surface Layer, Shear Angle, Thrust Force, Mechanical Factors, Surface Integrity

1. Introduction

With the improvement of accuracy in machine tools, ultra precision final machining has more and more come to be carried out by cutting⁽¹⁾. However, the damage done to the surface integrity in machining and the resultant surface roughness affect the fatigue strength⁽²⁾⁻⁽⁵⁾. Thus, in order to obtain high quality

machining, it is important to understand how the work hardened surface layer is generated.

This study aims to clarify the mechanical factors affecting the damaged layer. Focusing on the work hardened surface layer generated by plastic deformation due to mechanical energy in the affected layer, our previous paper⁽⁶⁾ demonstrated empirically, from the distribution of the cross-sectional hardness in the shear deformation zone and in the zone beneath the machined surface in several different work materials, a significant relation between the shear angle and the depth of the work hardened surface layer normalized by the undeformed chip thickness. At present, there have been relatively few theoretical studies of the depth of the work hardened surface layer. Using a theoretical model and observed data, Okushima et al.⁽⁷⁾ clarified the relation between the cutting edge force and the depth of the work hardened surface layer. Shirakashi⁽⁸⁾ used an FEM simulation to investigate the mechanical factors which affect the work

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hardened surface layer. Given this background, the first step of this study is to show a significant relation between the depth of the work hardened surface layer and the shear angle. To achieve this, a theoretical model is suggested here, with a simple theory of the distribution of stress beneath the machined surface. The immediate mechanical factors affecting the depth of the work hardened surface layer were clarified with the help of this theoretical model, and the relation between these mechanical factors and the shear angle was also investigated. Also, the values at different depths of the work hardened surface layer were calculated using that relation, and the effectiveness of this theoretical model using the immediate mechanical factors which affect the depth of the work hardened surface layer was investigated by comparing the calculated values with the observed ones.

2. Theoretical Model for Calculating Depth of Work Hardened Surface Layer

Assuming the work hardened surface layer is generated due to plastic deformation caused by cutting resistance, it is possible to estimate the depth of the work hardened surface layer. Okushima et al.⁽⁷⁾ examined the relation between the cutting force and the depth of the work hardened surface layer, substituting the yield stress and the work hardening exponent as data of material characteristics in Sokolovskii's stress equation for the compression and bending of the equilibrium wedge⁽⁹⁾. In this paper, the calculation method of determining the depth of the work hardened surface layer is considered.

In his stress equation, Sokolovskii defines D as the depth from the surface to the point where the compressive stress value is σ_D ; C is the coefficient of the concentration load in the internal stress equation when the concentration load acts on the surface. Assuming the thrust force F_t acts on the machined surface, the relation between F_t and the compressive stress σ_D is expressed in the following Eq.(1).

$$\sigma_D = \frac{C}{D} F_t \quad (1)$$

In this study, the thrust force F_t is used as the concentration load; thus, C is the coefficient of the thrust force. Assuming that in metal cutting the cutting resistance does not act on the machined surface when the cutting edge is sharp but on D_0 , above the machined surface, as shown in Fig. 1, the denominator of the right side of Eq.(1) is properly shown as $D + D_0$. Therefore, Eq.(2) is obtained as follows:

$$\sigma_D = \frac{C}{D + D_0} F_t \quad (2)$$

The compressive stress distribution beneath the machined surface is shown in Fig.1, although the

Fig. 1 Definition of D and D_0

Fig. 2 Relation between stress and hardness

curve differs under different cutting conditions⁽¹⁰⁾. D_H , the depth of the work hardened surface layer, refers to the distance from the hardest machined surface to the bulk hardness boundary. The compressive stress corresponding to the bulk hardness is shown as σ_e in Fig. 1. This compressive stress σ_e is on the verge of work hardening. If σ_D in Eq. (2) is replaced by σ_e , Eq. (3) is obtained as follows:

$$D_H = C \frac{F_t}{\sigma_e} - D_0 \quad (3)$$

where F_t is obtained by measurement and σ_e by a material test. If C and D_0 are determined according to the cutting conditions of each different work material, D_H is obtained from Eq.(3). Equation (2) can now be re-written as follows:

$$\frac{F_t}{\sigma_D} = \frac{1}{C} D + \frac{D_0}{C} \quad (4)$$

C and D_0 are estimated from the relation between F_t/σ_D and D . The relation between C , D_0 and the cutting conditions of each different work material was investigated. However, it is difficult to measure σ_D directly. In this paper, by using the cross-sectional hardness distribution, the compressive stress σ_D was estimated from hardness Hv .

Table 1 Bulk hardness and compressive stress equivalent to bulk hardness

Work materials	60-40Brass	S25C	SUS304
Bulk hardness Hv_0	98	113	180
σ_e MPa	140	115	181

The stress-hardness diagram (Fig. 2) was obtained by compressing an annealed short rod specimen 10 mm in diameter and 10 mm long using the Amsler universal tester in the axial direction⁽¹¹⁾. Spindle oil was applied on the compressed face of the specimen in order not to make it barrel-like in loading, and the compression was carried out at a low speed to avoid the influence of increasing temperature. The strain rate was about 10^{-3} sec^{-1} . Every time the specimen strain increased by 5%, the compression was stopped and the hardness was measured. Since the lubrication effect of the spindle oil made no difference between the compressed face of the specimen and the hardness of its center, the compressed face hardness was measured by using a micro Vickers hardness measuring instrument (test load: 0.49 N) after the specimen was compressed up to the given strain value.

Ramaekers et al.⁽¹²⁾ obtained the relation between the hardness and the stress in large plastic deformation by punching as shown in Eq. (5).

$$Hv = C_1 \sigma_D + C_2 \quad (5)$$

where C_1 and C_2 are constants. In this experiment, the relation between the hardness and the compressive stress is seen in Eq. (5), as shown in Fig. 2. Therefore, the compressive stress σ_D was obtained from the hardness Hv by using Eq. (5).

Moreover, σ_e was equal to the compressive stress which corresponded to the bulk hardness found by extrapolating the data for every work material in Fig. 2. Table 1 shows the average bulk hardness of each work material Hv_0 and the compressive stress which corresponds to the bulk hardness σ_e .

Our previous paper⁽⁶⁾ has shown the significant relation between the depth of the work hardened surface layer normalized by the undeformed chip thickness and the shear angle. Equation (6), the calculation formula for D_H/h_s , is obtained from Eq. (3).

$$\frac{D_H}{h} = \frac{C}{\sigma_e} \frac{F_t}{h} - \frac{D_0}{h} \quad (6)$$

In order to confirm the effectiveness of this formula, it is necessary to investigate every term of Eq. (6) empirically.

3. Experimental Procedure

In order to obtain the data needed in the calculation formula introduced in §2, the following cutting

Fig. 3 Experimental procedure

test was carried out.

3.1 Cutting method

The experiment was carried out using the method of interrupted orthogonal dry cutting, by fixing a workpiece 3 mm in width and 30 mm in length to the holder, installing it in the lathe and cross-feeding the tool, as shown in Fig. 3(a). The orthogonal cutting conducted normally by the milling machine and shaper has its limit in the cutting speed. However, in the cutting method shown in Fig. 3(a), orthogonal cutting can be conducted in the conventional cutting speed zone. The temperature rises with the increase in cutting speed, but, because of the interrupted cutting, the maximum cutting temperature was confirmed by means of a tool-workpiece thermocouple method⁽¹³⁾ to be over 100°C lower than the recrystallization temperature. The effect of the cutting temperature was shown in the experimental equation by Okushima et al.⁽¹⁴⁾ to be negligible within the range of these cutting conditions. 60-40 Brass was used as a workpiece mainly, and S25C and SUS304 were used for comparison. They were annealed beforehand. A throw-away tip, WC (K10), was used as the cutting tool. The cutting conditions are shown in Table 2. The range of conditions and the applicable values for each workpiece are different in order to prevent machine tool chatter and the development of a built-up edge. Yamamoto⁽¹⁵⁾ showed experimentally that the affected work hardened surface layer got deeper with an increase in the number of cuts but in time was stable. In this experiment, the depth of the work hardened surface layer was stable after 5 cutting iterations, and in later trials, the number of cuts was

set as 10. The cutting resistance was measured with a piezoelectric dynamometer, and the shear angle was obtained from the average of 5 chip thickness values measured with a micrometer at the middle part of each chip.

3.2 Method of estimating depth of work hardened surface layer

The part of the workpiece where the cutting condition was stable, 10 mm away from the cutting start point, was cut out with a wire electrical discharge machine, embedded in resin. Then, a cross-section of the workpiece was lapped vertical to the cutting direction, and the cross-sectional hardness distribution was measured vertically from the machined surface with a micro Vickers hardness measuring instrument (test load: 0.49 N), as shown in Fig. 3 (b). The local hardness value was defined as the average of 5 hardness values measured at the same position. The thickness from the machined surface to the point reaching the bulk hardness was recorded as the depth of the work hardened surface layer D_H . The

variation in hardness was within 5%.

4. Results and Investigation of Mechanical Factors

4.1 Cutting resistance

Our previous paper⁽⁶⁾ investigated the relation between the depth of the work hardened surface layer D_H and the cutting conditions, i.e. the rake angle γ , the cutting speed V and the undeformed chip thickness h . It was found that the depth of the work hardened surface layer increased when the cutting resistance was greater. Yuta et al.⁽¹⁶⁾ showed that the depth of the work hardened surface layer beneath the machined surface got deeper with an increase in the thrust force. However, the relation between the cutting resistance and the depth of the work hardened surface layer varies with each different work material, and that relation is not always linear⁽¹⁷⁾. Figure 4 shows that the cutting resistance, the cutting force F_c and thrust force F_t , which depend on the cutting conditions (i.e., the rake angle γ , the cutting speed V , and the undeformed chip thickness h), have an effect

Table 2 Cutting conditions

Work materials	60-40Brass	S25C	SUS304
Rake angle γ deg.	-30, -10, 0, 10, 30	-10, -5, 0, 5, 10, 15, 20	-10, -5, 0, 5, 10, 15, 20
Clearance angle β deg.	6	6	6
Undeformed chip thickness h mm	0.05, 0.1, 0.2, 0.4	0.05, 0.1, 0.2	0.05, 0.1, 0.2
Cutting speed V m/min	10, 50, 100	50, 100, 150	10, 50, 100

N.B. Under lines: Standard values.

Fig. 4 Effect of cutting resistance on depth of work hardened surface layer

Fig. 5 Relationship between ϕ and $F_t/h, F_c/h$

on the depth of the work hardened surface layer. Figure (a) shows the case of 60-40 Brass, Fig.(b), S25C and Fig.(c), SUS304. The depth of the work hardened surface layer varies with each different work material, and the greater the cutting resistance, the deeper the work hardened surface layer, but there is no regularity in this relation.

The thrust force normalized by the undeformed chip thickness F_t/h in Eq.(6) was investigated with the shear angle ϕ obtained from the chip thickness. As shown in Fig.5, there is a significant relation between the shear angle ϕ and the cutting resistance normalized by the undeformed chip thickness F_t/h under the cutting conditions in this investigation. The cutting force normalized by the undeformed chip thickness F_c/h showed the same results.

4.2 Coefficient of thrust force and distance from machined surface to thrust force acting point

Figure 6 is an example of the relation between D and F_t/σ_D . This figure shows that a shear deformation zone is found not more than 0.2 mm below the machined surface and that the line in this graph is not linear because of the great change in the deformation strain. Considering the plastic deformation zone as a zone with D more than 0.2 mm⁽⁶⁾, C and D_0 in every cutting condition were obtained from the linear part

Fig. 6 Relationship between D and F_t/σ_D

of the graph with Eq.(4).

Figure 7 shows the effects of the cutting conditions on C , D_0 and shear angle ϕ in the case of 60-40 Brass. From the figure, the following can be seen.

(1) In every work material, the coefficient of the thrust force C is constant even if the rake angle γ , the cutting speed V and the undeformed chip thickness h vary.

(2) The greater the undeformed chip thickness h , the larger the distance from the machined surface to the thrust force acting point D_0 .

(3) If the undeformed chip thickness h is constant, D_0 increases as the shear angle ϕ decreases. The same results were obtained with S25C and SUS304.

As shown in Fig. 1, D_0 is considered to be related to the contact length between the rake face and the chip, and assumed to be a function of $h/\sin \phi$ ⁽¹⁸⁾. Therefore, considering Eq.(6), the relation between $1/\sin \phi$ and D_0/h was investigated. Figure 8 shows the relation between $1/\sin \phi$ and D_0/h . It is significant. From Figs. 7 and 8, it was found that the dominant factors of D_0 were the undeformed chip thickness h and shear angle ϕ . The relation between the coefficient of the thrust force C and the shear angle ϕ was also investigated. Figure 9 shows the relation between ϕ and C , and that C is nearly constant

Fig. 8 Relationship between $1/\sin \phi$ and D_0/h

Fig. 7 Effects of cutting conditions on C , D_0 and shear angle in the case of 60-40 Brass

regardless of the shear angle ϕ in every work material.

4.3 Effectiveness of calculation formulas

The immediate mechanical factors affecting the depth of the work hardened surface layer were determined from these results, and every term of Eq. (6) was studied. F_t/h and D_0/h were functions of the shear angle. C and σ_e were constants. Now, the calculated values of the depth of the work hardened surface layer were obtained by substituting F_t/h , D_0/h , C and σ_e in Eq. (6). Figure 10 shows the relation between the shear angle ϕ and the depth of the work hardened surface layer normalized by the undeformed chip thickness D_H/h , and values were calculated for every work material. It was found that D_H/h was a function of the shear angle ϕ .

In Fig. 5, 60-40 Brass and S25C are about the same in terms of the relation of the cutting resistance to the shear angle, but in Fig. 10 they are different in the depth of the work hardened surface layer. There are two reasons for this: first, as shown in Figs. 8 and 9, C and D_0/h differ in every work material; second, considering Eq. (3), the compressive stress equivalent to the bulk hardness σ_e is assumed to be different in every work material. S25C and SUS304 are about the same in the coefficient of the thrust force C . Since

Fig. 9 Relationship between ϕ and C

Fig. 10 Relationship between ϕ and D_H/h in work materials

they are very different in the ratio of the thrust force to the shear angle, as shown in Fig. 5, the depth of the work hardened surface layer is assumed to be different.

5. Conclusion

In order to investigate why there is a significant relation between the shear angle and the depth of work hardened surface layer normalized by the undeformed chip thickness, an orthogonal metal cutting test was carried out using 60-40 Brass, S25C and SUS304. The following results were obtained:

(1) In the stress distribution beneath the machined surface, a theoretical model was suggested based on the thrust force, the coefficient of the thrust force, the distance from the machined surface to the thrust force acting point and the compressive stress equivalent to the bulk hardness. This theoretical model showed that these mechanical factors directly affect the depth of the work hardened surface layer.

(2) The distance from the machined surface to the thrust force acting point and the coefficient of the thrust force affect the depth of the work hardened surface layer, and these two factors are different in every work material. The coefficient of the thrust force has a constant value in every work material even if the shear angle varies, but the distance from the machined surface to the thrust force acting point normalized by the undeformed chip thickness varies according to the shear angle.

(3) There is a significant relation between the thrust force normalized by the undeformed chip thickness and the shear angle in every work material within the range of these experimental conditions.

(4) As for the depth of the work hardened surface layer in this research, 60-40 Brass and S25C are about the same in the ratio of the cutting resistance to the shear angle. However, the depth of the work hardened surface layer was considered to be different because of the distance from the machined surface to the thrust force acting point, the coefficient of the thrust force and the compressive stress equivalent to the bulk hardness. The thrust force which is required to cut S25C is different from that required to cut SUS304, though the shear angle is the same. The depth of the work hardened surface layer was considered to be different.

(5) By using the proposed theoretical model under these cutting conditions, it was found that the depth of work hardened surface layer normalized by undeformed chip thickness was a function of the shear angle. Thus, from this experiment it was clear that the proposed theoretical model using the immediate mechanical factors acting on the depth of the work

hardened surface layer was valid.

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