Generation Mechanism of Residual Stress on Surface Machined in Turning Assisted by Ultrasonic Vibration

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Abstract

The present paper clarifies that the compressive residual stress on the surface machined in turning with ultrasonic vibration (USV) results from the following three phenomena. Those are the minor vibration of a cutting tool in the depth-of-cut direction, the strain rate higher than without USV, and the hardness a little higher than without USV. Another clarification is that the tensile residual stress without USV probably results from higher temperature rise of the machined surface.

1 Introduction

In USV cutting, generally, the following phenomena or results are observed; a decrease in chip thickness, a reduction in mean cutting force, a decrease in cutting heat, an improvement in form accuracy & surface roughness, and a prevention of built-up edge generation. Recently Ito[1] reported the occurrence of compressive residual stress on the surface machined with USV under various cutting conditions. The authors investigated the surface roughness, hardness, metallurgical structure, residual stress and corrosion resistance, and made clear the relation between these parameters and corrosion resistance.

The main purpose of the present study is to clarify the generation mechanism of compressive residual stress in USV cutting. Firstly the factors are selected which may affect the residual stress generation, and secondly the effects of these factors are investigated on the residual stress.

2 Experimental method and equipment

Cutting experiments are performed in an external turning of cylindrical bar on a lathe, as shown in Fig. 1. The workpiece made of carbon steel S55C has a diameter of 47mm and a length of 77mm. The cuting tool, which is a TiN coated carbide, is mounted on a torsional USV cutting apparatus, Daktyloi SUM-1, model 1001, manufactured by Fuji Ultrasonic Engineering Co. Ltd., with a frequency of 27kHz and an amplitude of 10µm. The direction of vibration coincides with the primary cutting direction. Cutting test is conducted under cutting speeds of 22.8, 30, 105 and 188m/min, a feed rate of 0.097mm/rev, a chip thickness of 0.2mm and dry. In USV cutting a cutting speed is selected so that it may be smaller than one third of the maximum vibration speed 102m/min.

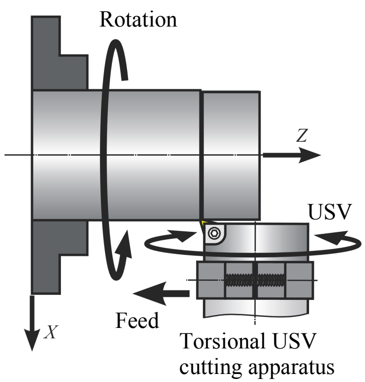


Figure 1: Experimental method of USV turning

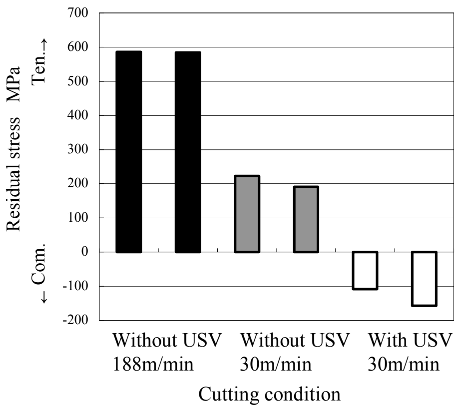


Figure 2: Residual stress on the surfaces machined without/with USV

3 Experimental results, analytical results and discussions

Figure 2 shows an example of the residual stress on the surfaces machined without/with USV and under two cutting speeds. The residual stress with USV is compressive and the others without USV are tensile. In this paper, as factors probably influencing the generation of residual stress, the vibration mode, strain rate, work hardening and cutting temperature are selected.

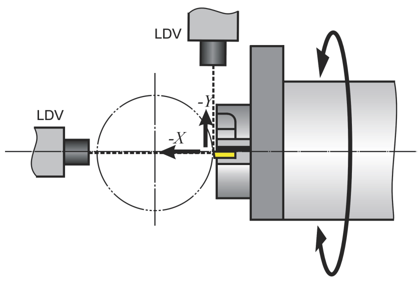


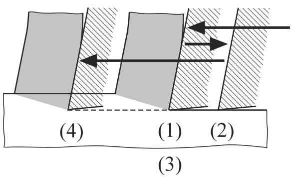
Figure 3: Measuring method for vibration mode of USV cutting apparatus

3.1 Effect of vibration mode of a cutting tool on residual stress

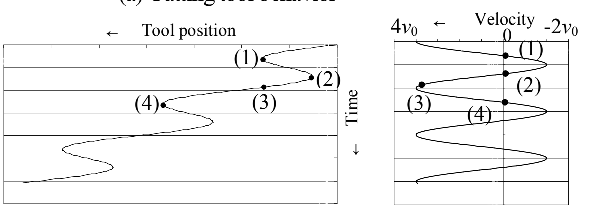
Figure 3 shows the experimental situation of vibration mode of a dummy cutting tool in the *X* and *Y* directions under 27kHz USV condition, which is generated by the tortional USV cutting equipment. This tool has two smooth surfaces perpendicular to *X* and *Y* directions respectively. The result shows that in the primary cutting direction (*Y*) an amplitude of 7.90μm is measured and in the depth-of-cut direction (*X*) one of 1.48μm is observed. The latter fact can make the residual stress compressive. It is similar to the action of particles in shot peening.

3.2 Effect of strain rate on residual stress

In many USV cuttings the mean cutting speed v_0 is chosen such that it becomes lower than one third of the maximum vibration speed v_{vmax}, which is expressed by $2\pi a f$, where a and f are amplitude and frequency respectively. If v_0 is equal to one third of v_{vmax}, the maximum cutting speed v_{max} becomes $4v_0$. As shown in Fig. 4, during one cycle (1)− (4) of USV an actual cutting occurs from (3) to (4) and Fig. 4(c) shows that the cutting occurs with contact of rake face and chip at speeds of (0-4) times of v_0. Therefore, on average at about $2v_0$ a cutting occurs. When in cutting without USV a shear deformation occurs in a finite thickness of shear area, the rate in shear strain also becomes about twice of v_0 if the thickness of shear area is constant in USV



(a) Cutting tool behavior



(b) Change of tool position (c) Change of tool velocity

Figure 4: Tool behavior during ultrasonic vibration cutting

cutting. In a case of $v_0 \fallingdotseq (1/n)v_{vmax}$ where n is a number larger than one, generally, instantaneous cutting speed can take the value in the range of $(0\text{-}(n+1))v_0$. It is considered that the strain rate is proportional to cutting speed and that an increase in strain rate causes an increase in shear yield stress. It, in turn, causes an increase in compressive stress on the shear area and then it leads to an increase in compressive residual stress.

3.3 Effect of work hardening on residual stress

Hardness of the USV turned surface is somewhat higher than that without USV. Another study showed that ahead of shear area the work hardening has already been observed in the hardness distribution around shear area. As a result, compressive stress on the shear area increases and compressive residual stress can occur.

3.4 Effect of the surface temperature around a cutting point under steady cutting

Temperature rise on machined surface should cause larger tensile residual stress when the whole workpiece is cooled down to the room temperature after cutting. From the thermal stress analysis by Timoshenko, the circumferential thermal stress due to the temperature rise after cutting of cylindrical bar surface is derived as Eq. (1).

$$\sigma_\theta = \alpha E (T_a - T_0) / 2 \qquad (1),$$

where α, E, T_a and T_0 are linear expansion coefficient, Young's modulus, outermost temperature and central temperature respectively. If the work material is steel, $\alpha = 11.5\times10^{-6}$/K and E=206GPa. If it is assumed that $T_a - T_0$=50K, σ_θ=59.2MPa.

4 Conclusions

(1) Since the torsional USV cutting equipment has a vibration component in the depth-of-cut direction, it contributes to the compressive residual stress.

(2) Since in cutting with USV cutting speed is several times higher than in cutting without USV, strain rate with USV also is higher than without USV. The fact causes the rise of yield stress and it leads to compressive residual stress.

Reference:

[1] S. Ito: Trans. of 2009 Spring Meeting of Japan Soci. for Preci. Engg., (2009) 987.