

## Research on Stress and Strain of 304 Stainless Steel in Turning Process Based on Oxley - Welsh Theory

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**Keywords:** Oxley-Welsh Theory, Work Hardening Effect, Shear Flow Stress, Hydrostatic Stress, Experimental Research.

**Abstract:** Considering the size effect, temperature effect and hardening effect of the material in the shear zone, the shear strain and the shear strain rate of the material in the shear zone are studied by theoretical calculation and experimental study. Hydrostatic stress and shearing flow stress with the cutting amount of change. The results show that the stress difference between hydrostatic stress and shearing flow stress is largest when the cutting amount is  $V_c = 60\text{m} / \text{min}$ ,  $f = 0.15\text{mm} / \text{r}$ , and  $a_p = 1\text{mm}$ , and the material even plasticity Deformation of the best, the workpiece has good service performance, in the course of work to withstand the impact load capacity is relatively strong.

### Introduction

As for the hardening of metal materials, related research institutions and scholars at home and abroad have conducted some studies. Professor Yang Ruicheng, Lanzhou University of Technology, [1] has studied 304, 410S, 430 and 409L four kinds of stainless steel material hardening behavior, which shows that 304 stainless steel hardening capacity is much higher than the other three kinds of stainless steel. Zhou Xiaofen of Shanghai University [2] has studied the tensile strain hardening behavior of TWIP steel, showing that the strain hardening during the tensile process is dislocation strengthening stage and twin strengthening stage. Wang Zhifu of Xinjiang Petroleum Exploration Research Institute mainly has studied the effect of strain rate on strain hardening at room temperature, from the two aspects of strain rate sensitivity index and strain hardening index [3-4], which shows that the strain rate has a certain sensitivity on the strain hardening behavior of 304 stainless steel. Qingdao University of Technology, Yang Yong [5] has proposed the constitutive model of material construction method based on orthogonal cutting theory. By the cutting test, the result shows that aerospace aluminum alloy in the cutting process has obvious strain hardening characteristics. Terherst M [6] of Aachen Machine Tool Laboratory in Germany has studied strain hardening hindering the movement of dislocation in the forming process of cold metal, to improve the fatigue strength and load-carrying capacity of the workpieces. Then, establishing the model of the strain hardening of the workpieces by DEFORM finite element software investigates the effects of temperature and strain rate on the flow stress, which is verified by the microhardness test. Bambach M. [7] of the Brandenburg University of Technology in Germany has developed a strain hardening model for two test materials by the isothermal hot compression test of titanium aluminide and comparing the work hardening behavior of 25MoCrS4 surface hardened steel. And the flow stress is accurately predicted over a wider range of deformation conditions. The above results from different angles carry out the study of stress and strain and work hardening. Based on the Oxley-Welsh theory, considering the size effect of the shear zone, the material hardening effect and the temperature effect, combined with the cutting experimental data, the effects of the cutting amount on the stress-strain of the material shear zone, hydrostatic stress and shear flow Stress with the cutting amount of change.

### Cutting Experiments

Cutting experiments using carbide new micro-pit tool, tool working angle shown in Table 1, test machine for the C6136HK CNC lathe, dynamometer for the Kistler-9257B, the workpiece diameter of 60mm 304 stainless steel bar, the workpiece material physical and mechanical properties shown in Table 2, cutting force test platform shown in Figure 1.

Table 1. Geometric angles of the tool

Geometric angle	Tool angle $\epsilon_r$	Rake angle $\gamma_0$	Clearance angle $\alpha_0$	Inclination angle $\lambda_s$	Main cutting edge angle $K_r$	Approach Angle $\psi_r$
Value (°)	80	8	7	-5	95	-5

Table 2. Property parameters of material

Material	Density (g/cm <sup>3</sup> )	Tensile strength(MPa)	Hardness	Poisson's ratio	Elastic modulus (GPa)
Tool	13.8	520	91.8HRA	0.23	540-600
Workpiece	7.93	1080	30HRC	0.247	206



Figure 1. Cutting test platform

Cutting experimental program and experimental data as shown in Table 3 .

Table 3. Cutting test scheme and test data

NO.	$v_c$ (m/min)	$f$ (mm/r)	$a_p$ (mm)	$a_c$ (mm)
1	180	0.15	1	0.2933
2	150	0.15	1	0.2960
3	120	0.15	1	0.3077
4	90	0.15	1	0.3130
5	60	0.15	1	0.3210
6	150	0.3	1	0.3967
7	150	0.25	1	0.3293
8	150	0.2	1	0.3160
9	150	0.15	1	0.2960
10	150	0.1	1	0.2027
11	150	0.15	2.5	0.3150
12	150	0.15	2	0.2997
13	150	0.15	1.5	0.2909
14	150	0.15	1	0.2960
15	150	0.15	0.5	0.2635

### Oxley-Welsh Theory

In the past, all kinds of shear angle theory formulas did not consider the work hardening of the material being machined. Merchant assumed that the shear stress was independent of the shear strain. Lee-Shaffer and Shaw assumed that the material to be machined was the ideal rigid-plastic material. The effects of work hardening and strain rate effects were considered by Oxley.

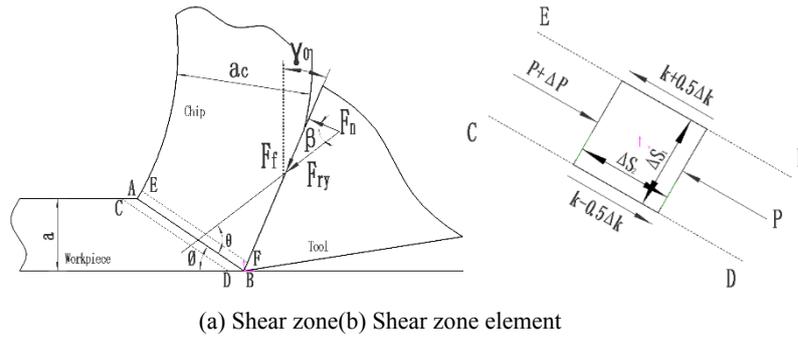


Figure 2. The model of shear zone

According to Figure 2 (a),  $\phi$  is the Shear Angle;  $\gamma_0$  is the Rake Angle;  $\beta$  is the Friction Angle;  $\psi_r$  is the Tool Clearance Angle;  $a$  is the Cutting Thickness; the angle between Cutting force ( $F_r$ ) and AB is  $\theta$ ;  $v_c$  is the Cutting Speed;  $f$  is the federate; AB, CD, and EF represent shear planes;  $\Delta s_1$  is the width of the shear zone;  $\Delta s_2$  is The length of the shear zone element AB:

$$a = f \cdot \cos \varphi_r. \tag{1}$$

$$\phi = \theta - \beta + \gamma_0. \tag{2}$$

$$\gamma = \frac{\cos \gamma_0}{\sin \phi \cdot \cos(\phi - \gamma_0)}. \tag{3}$$

$$\gamma = \frac{\cos \gamma_0}{\cos(\phi - \gamma_0)} \cdot \frac{v_c}{\Delta s_1}. \tag{4}$$

The material passing through the band-like shear region as shown in Figure. 2 (b), AB shear stress is the shear flow stress  $k$ ; the normal stress is hydrostatic stress  $p$ . Let the total flow stress along the AB normal shear flow be  $\Delta k$ ; The total stress change along the AB is  $\Delta p$ ;  $p_A$  and  $p_B$  are the hydrostatic compressive stresses at point A and point B respectively. Considering the balance of the elements in the shear zone, then:

$$\Delta p = \frac{\Delta k}{\Delta s_1} \cdot \Delta s_2. \tag{5}$$

$$p_A - p_B = \frac{\Delta k}{\Delta s_1} \cdot \frac{a}{\sin \phi}. \tag{6}$$

Considering the equilibrium condition, then:

$$p_A = k[1 + 2(\frac{\pi}{4} - \phi)]. \tag{7}$$

Figure 3 (b) for the ideal cutting plasticity curve, the figure available:

$$\Delta k = m \cdot \gamma. \tag{8}$$

In the formula,  $m$  is the slope (the work hardening rate) of the plastic stress-strain curve at the average shear strain rate in the shear zone; and  $\gamma$  is the shear strain along EF.

$$\frac{a}{\Delta s_1 \cdot \sin \phi} = 10. \tag{9}$$

$k_0$  is the initial shear flow stress;  $p_a$  is the average shear flow stress in the shear zone;  $m$  and  $k_0$  can be calculated according to the results of Kececioglu's study [8], and finally the shear flow stress  $k$  in the shear zone and the average shear flow stress  $p_a$  can be calculated. According to the

formulas (2), (3), (8), (9), (10) and (12), the Oxley-Welsh cutting model is given by Eq. (13).

$$k = k_0 + \frac{\Delta k}{2} \tag{10}$$

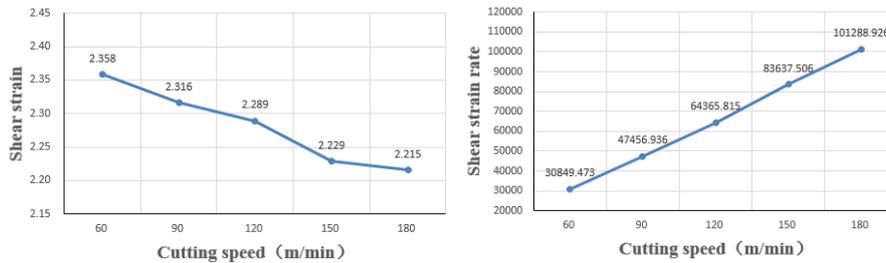
$$p_a = \frac{p_A + p_B}{2} \tag{11}$$

$$\tan \theta = \frac{p_a}{k} \tag{12}$$

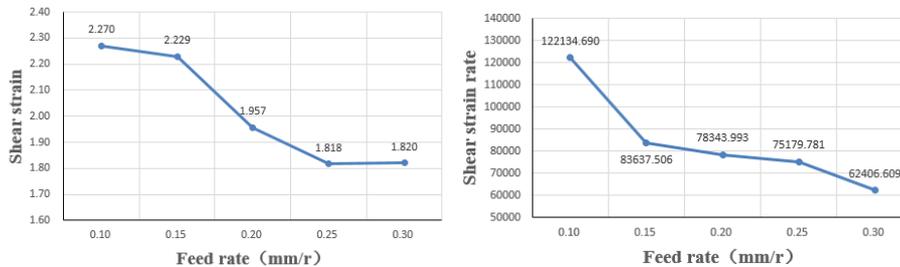
$$\phi = \tan^{-1} \left[ 1 + 2 \left( \frac{\pi}{4} - \phi \right) - \frac{10m \cos \gamma_0}{2k_0 \sin \phi \cos(\phi - \gamma_0) + m \cos \gamma_0} \right] - \beta + \gamma_0 \tag{13}$$

### Analysis of Experiments and Simulation Results

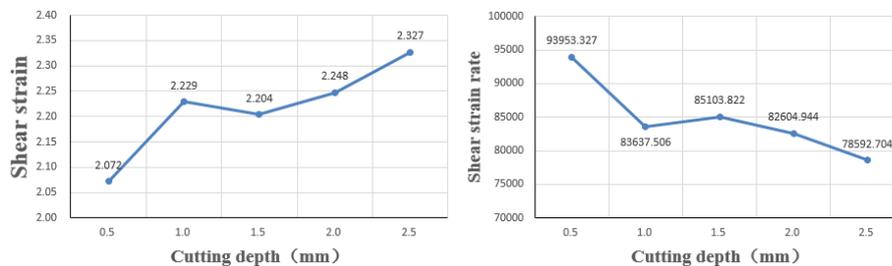
According to the above-mentioned Oxley-Welsh cutting model and cutting experimental data, the variational trend that shear strain and shear strain rate of the shear zone vary with the cutting amount in the cutting of the 304 stainless steel are obtained by the formulas (1) to (13), as the Figure 3 shows.



(a) Influence of cutting speed on shear strain (b) Influence of cutting speed on shear strain rate



(c) Influence of feed rate on shear strain (d) Influence of feed rate on shear strain rate



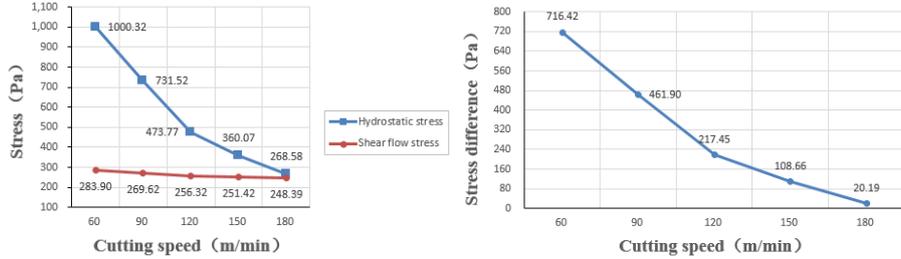
(e) Influence of cutting depth on shear strain (f) Influence of cutting depth on shear strain rate

Figure 3. The change trend of shear strain and shear strain rate with cutting parameters

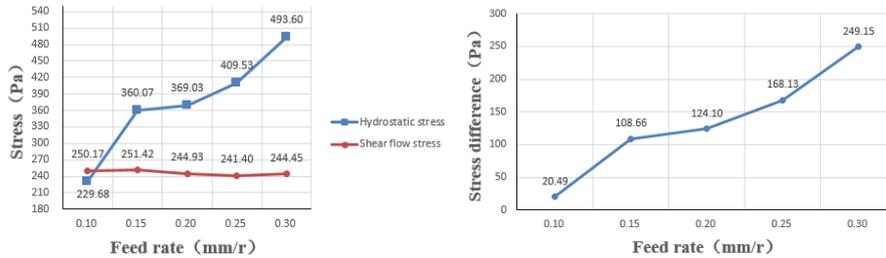
According to Figure 3 (a) and Figure 3 (b), the shear strain of the shear zone decreases gradually with the increase of the cutting speed, while the shear strain rate increases gradually with the increase of the cutting speed. From Figure 3 (c) and Figure 3 (d), with the increase of feed rate, the shear strain of the shear zone decreases slowly at the initial stage; decreases sharply at the middle

stage; slightly increases at the final stage, whereas the shear strain rate decreases sharply at the initial stage; slightly decreases at the middle stage; sharply decreases again at the final stage. As shown in Figure 3 (e) and Figure 3(f), with increasing cutting depth, the strain of the shear zone shows a fluctuating upward trend, while the shear strain rate shows a downward trend.

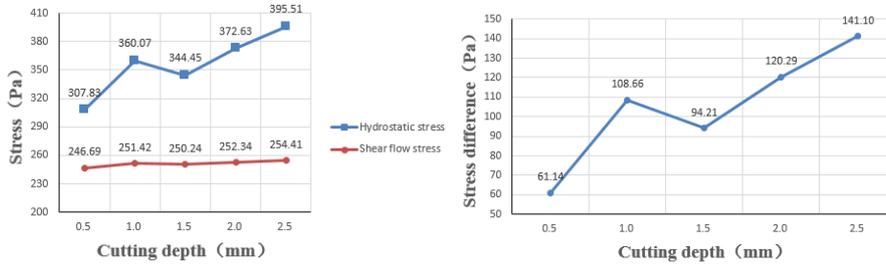
Based on the results shown in Figure 3 and then through the formulas (5) to (13) a series of numerical calculation, you can draw the relationship of the cutting amount on the shear flow stress and hydrostatic stress, as shown in Figure.4.



(a) Influence of cutting speed on stress(b)Influence of cutting speed on stress difference



(c)Influence of feed rate on stress(d)Influence of feed rate on stress difference



(e)Influence of cutting depth on stress (f)Influence of cutting depth on stress difference

Figure 4. Influence of cutting parameters on shear flow stress and hydrostatic stress

As it can be seen from Figure 4 (a), with the increase of cutting speed, the hydrostatic and shear flow stress tend to decrease. And the hydrostatic stress decreases more obviously, while the shear flow stress decreases more slightly. As shown in the Figure4 (c), the shear flow stress decreases slowly with the increase of the feed rate, and the variation range is smaller; whereas the hydrostatic stress appears to increase sharply first; slightly increases in the middle; and sharply increases at last. According to the curve in the Figure4 (e), with the increase of cutting depth, the hydrostatic pressure and shear flow stress tend to increase, and the magnitude of hydrostatic pressure increase is larger than the shear stress's. Similarly, comparing the Figure4 (b),Figure4 (d) and Figure4 (f), the gap between hydrostatic stress and shear flow stress in the shear zone decreases with the increase of cutting speed. While the influence of the variation of feed rate on the stress difference is gradually increasing. With the increase of cutting depth, the stress difference shows a trend of increasing. The comprehensive analysis shows that the stress difference between the hydrostatic stress and the shear flow stress is larger when the cutting speed is relatively smaller, the feed rate larger, and the cutting depth larger. When the cutting amount is:  $V_c=60\text{m/min}$ 、 $f=0.15\text{mm/r}$ 、 $a_p=1\text{mm}$ , the stress difference

between hydrostatic stress and shearing flow stress in the shear zone is the largest, and the even plastic deformation of the material is the best.

## Conclusions

In this paper, cutting experiments were carried out to study the influence of material hardening effect on the cutting process. Through the combination of cutting experiments, calculation and theoretical analysis, this paper draws the following conclusions:

(1) The shear strain increases with the increase of the cutting speed, and then increases with the depth of cutting. The shear strain rate increases with the increase of the cutting speed, With the increase of feed rate gradually decreases, with the increase of cutting depth decreases.

(2) The difference between the hydrostatic stress and the shear flow stress decreases with the increase of the cutting speed, but increases with the feed rate and increases with the cutting depth.

(3) When the cutting amount is:  $v_c = 60\text{m} / \text{min}$ ,  $f = 0.15\text{mm} / \text{r}$ ,  $a_p = 1\text{mm}$ , the stress difference between the hydrostatic stress and shearing flow stress of the material shear zone is the biggest, and the material has the best plastic deformation, In the course of work to bear the impact load capacity is relatively strong.

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