MATEC Web of Conferences **136**, 01004 (2017) DOI: 10.1051/matecconf/201713601004
D2ME 2017

Investigation on the High-speed Precision Shearing of 5140 Steel Bars Pre-grooved by Laser

Yuanzhe Dong[1,], Wei Zhong[1], Yujian Ren[1], Shengdun Zhao[1,a] and Lijun Zhang[2]

[1] *School of Mechanical Engineering, Xi'an Jiaotong University Xi'an, Shanxi, China*

[2] *College of Electromechanical Engineering, China University of Petroleum, Qingdao, China*

Abstract. A new blanking method is proposed to improve the quality of metal bars, by introducing the laser pre-grooving and high-speed precision shearing technology. The working principle is introduced, and the calculation method of the laser groove depth is given. By means of finite element method, the elastic-plastic deforming, damage initiation and crack propagation behaviour of a 5140 steel bar under high-speed shearing are obtained; furthermore, the corresponded shear force-displacement property is analysed in detail. After that, high speed shearing experiments are done of laser grooved 5140 steel bars. The results show that the 5140 steel bar undergoes rapid elastic and little plastic deformation before crack, and micro cracks initially appears in the lateral area with the damage value of 0.53; then main vertical cracks form and extend along the shearing direction; the fracture section of the billet is flat and smooth, with a section inclination of 0.3°and a weight tolerance of 0.35%.

1 Introduction

Blanking of metal bars are the first process to produce most mechanical parts, such as gears and shafts in gearboxes, chain pins in motorcycles and bicycles, rings and rollers in bearings, precision pipe joints and standard metal parts (screws, bolts, nuts), and has enormous application in automobile, rail transit, and petrochemical equipment manufacturing industries.

Traditional blanking method use shearing dies with sharp blade to cut metal bar directly at a speed of 0.3~0.5m/s [1]. During the process, the area of the bar contacted to the blades first collapses, and then crack initiates and extents deviating from the vertical direction as the whole bar inclines due to bending. At last, billets are produced with horseshoe-shape cross sections and burrs, and need further section-machining process, together with problems such as badly wear of blades.

Several methods have been proposed to improve the blanking quality. High-speed precision shearing method enhances the brittleness of metals by increasing the loading speed [2], and research shows that the shearing velocity, when more than 5 m/s, can effectively improve the flatness and roundness of billets' section with a high efficiency. However, there are still collapse zones left at the contact area of bars, together with serious problems as wear and breakage of the blade. Low stress blanking method, based on the crack technology, firstly cut annular grooves on the surface of the bars to generate stress concentration, and then apply circumferential cyclic load to accelerate the initiation and extension of fatigue crack [3, 4], which can obtain billets with high quality section. Whereas, the blanking efficiency is relatively low(6~8 billets per minute); on the other hand, the stress grooves with

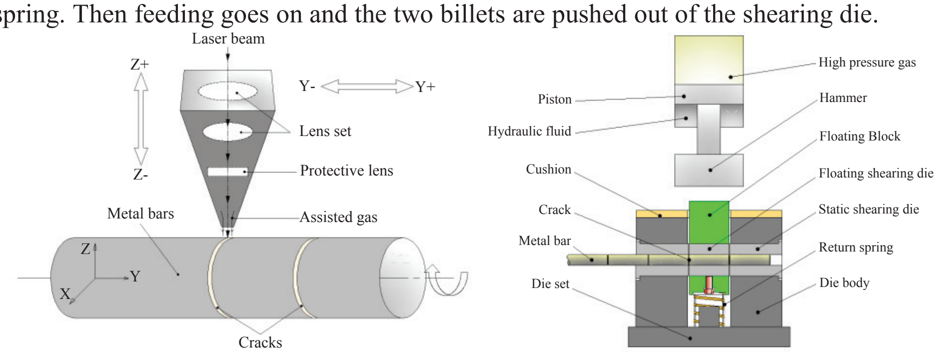
V shape profiles [5] are mainly processed by lathe or milling, which don't generate severe stress concentration, and grooving of hard materials is still difficult.

According to above reasons, this paper presents a novel combined blanking method of metal bars with laser pre-grooving and high-speed precision shearing, which firstly preprocesses ring-shape grooves on the surface of bars by laser, and then applies high-speed impact on the radially restrained metal bars to complete the separation. Take 5140 steel bars for example, which is widely used in manufacturing industry, shearing simulation and experiments are further done.

2 Working Principle of the Method

The whole working principle of the method is shown in Fig.1. Fig.1 (a) is the schematic diagram of the laser rotary grooving of metal bars. Suppose that a metal bar with diameter D rotates around the central axis Y at speed *n*, the laser beams form a series of circular contours with radius *r* on the bar surface. Compressed air are used as auxiliary gas to combust and blow slags, and the material is removed layer by layer to produce a certain annular groove with width *w* and depth *h*. And then equally spaced annular grooves are processed in sequence according to the length of the billets, through the linear interpolation movement of the laser head.

Fig.1 (b) shows the principle of the novel high-speed precision shearing. The pre-grooved metal bar is firstly radially constrained in the invented double-side shearing die [6] to avoid bending, and the first two circular grooves are placed between the floating shearing die and the two static shearing dies. Then the hammer impacts the floating block at a speed of 5~10m/s, so that the cracks propagates quickly and vertically from the tip of the first two grooves and two pieces of billets are obtained simultaneously. After that, the hammer is lifted by hydraulic fluid, and the floating block is reset by the spring. Then feeding goes on and the two billets are pushed out of the shearing die.



(a) laser rotary grooving (b) novel high-speed precision shearing

Figure.1. Schematic of the Combined Blanking Method

Fig.2 further illustrates the laser rotary grooving process. Fig.2 (a) shows the scanning trajectory of laser spots, and the overlap length δ of two adjacent holes determines the continuity of the annular groove. Suppose the number of spots in one circle is m, then m and δ can be calculated as follows:

$$m = (\frac{60}{n}) / (\frac{1}{f}) = \frac{60f}{n} \tag{1}$$

$$\delta = \begin{cases} 2r - \frac{\pi n D}{60f}, n < \frac{120rf}{\pi D} \\ 0, n \geq \frac{120rf}{\pi D} \end{cases} \tag{2}$$

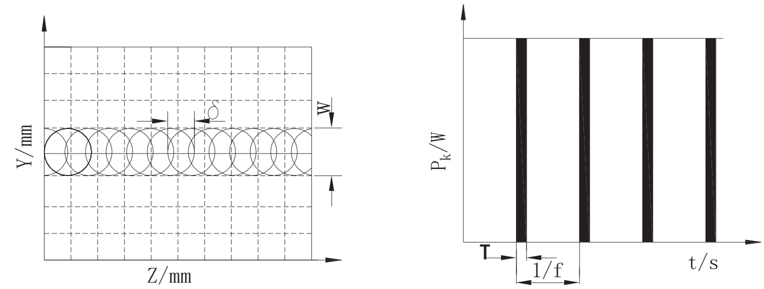
Fig.2 (b) shows the pulse waveform of the Nd:Yag laser. The adjustable parameters include peak power P_k, pulse width τ, pulse frequency f. Its pulse intensity I_0 can be calculated by formula (3).

$$I_0 = P_k / \pi r^2 \tag{3}$$

The width w of the groove is mainly determined by the radius r of the laser spots. The depth h is calculated as follow:

$$h=\int_0^t \frac{q(t)}{\rho[c(T_b-T_0)+L_f+L_v]}dt \tag{4}$$

c is the specific heat, T_0 and T_b is the initial and the boiling temperature of the material, L_f and Lv are the latent heat coefficients of fusion and vaporization [7], and $q\ (t)$ is the time-dependent heat flux.



(a) Scanning trajectory (b) Pulse waveform

Figure 2. Scanning trajectory and pulse waveform of of the Nd:Yag laser

3 Simulation of the High–speed Shearing Process

In the finite element model, the mass of the hammer and the initial impact energy are set as 200kg and 8kJ separately, providing a loading speed of 8.9m/s. Take 5140 steel bar as example, the elasticity modulus E is 210GP, and poison's ratio ν is 0.3. As an axial symmetry problem, half part of the grooved bar are analyzed. Its geometric parameters are as follows: billet length L=200mm, bar diameter D=26mm, depth of the groove h=1.51mm, width of the groove w=0.36mm. The actual radial clearance between the bar and the shearing dies is 0.5 mm.

The Normalized Cockcroft & Latham [8] formula is used as the fracture criterion, and the material cracks when the energy density exceeds the critical failure value. The expression is as follow.

$$D=\int_0^{\bar{\varepsilon}_f} \frac{\sup(\sigma_1,\sigma_2,\sigma_3)}{\sigma_{eq}}d\bar{\varepsilon}_p \ge D_c \tag{5}$$

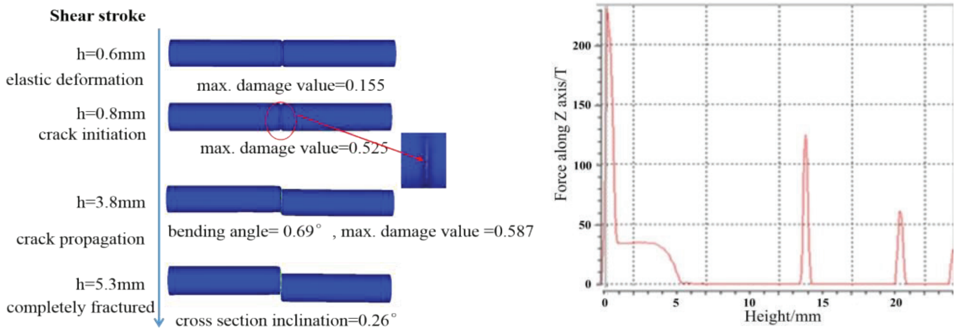
In equation (5), $\sup(\sigma_1,\sigma_2,\sigma_3)$ is the maximum principal stress when it fractures, σ_{eq} is the equivalent stress, $\bar{\varepsilon}_p$ is the equivalent plastic strain, and $\bar{\varepsilon}_f$ is the critical equivalent plastic strain.

Fig.3 shows the total mechanics behavior of the 5140 steel bar at different shear strokes and the corresponded shear force. As shown in Fig.3 (a), at stroke of 0.6mm, no obvious collapse and bending occur in the contact area of the bar. The maximum damage value of 0.53 appears in the lateral area of the annular groove, which exceeds the critical fracture threshold of 0.52, so that the material in that zone begins to crack; at stroke of 4.2mm, the part of the bar in the floating shearing die bends a very small curvature of 0.69 °, and the maximum damage value is 0.785 at the circumferential lateral area of the annular groove, so that the crack extends rapidly; when the stroke is 7.8mm, the bar has completed separation. The fracture section of the billet is flat and smooth with no collapse, and the inclination of the fracture section is only 0.26 °, showing that the new blanking method can produce billets with high accuracy.

Fig.3 (b) shows the load-displacement curve during high-speed shearing. It has the characteristics of rapid elastic deformation, slight plastic deformation, instantaneous fracture and multiple-impact contacts. When the stroke is less than 0.8mm, the bar undergoes rapid elastic-plastic deformation to crack, and the maximum shear force is 232T; when the stroke is between 0.8mm and 3.8mm, the crack extends rapidly with static shear force of 34T; when the stroke exceeds 3.8mm, the bar fractures

 DOI: 10.1051/matecconf/201713601004

immediately, and the value of the shear force gradually decreases to zero. Then the floating block rebounds and contacts the hammer several times with the help of the return spring, resulting in sudden fluctuation of shear force.

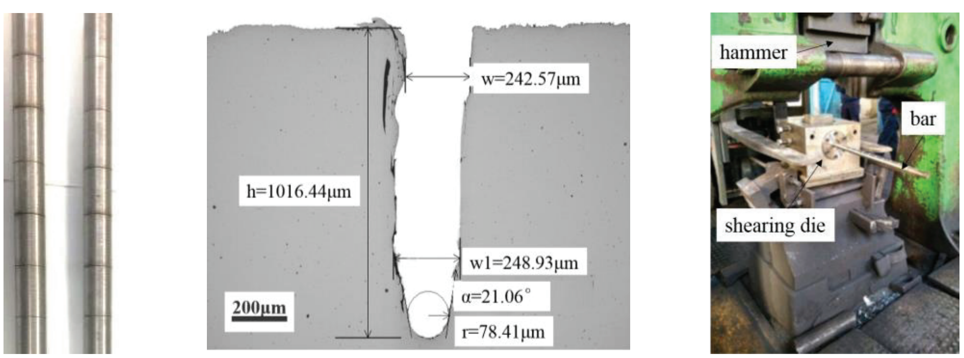


(a) fracture behavior (b) shear force-displacement curve

Figure 3. Fracture behavior of 5140 steel bar and corresponded shear force

4 Experimental results and discussion

Fig.4 (a) is the photo of the pre-grooved 5140 steel bars with diameter of 26mm. Fig.4 (b) shows one the the laser grooves on the bars, and the average width *w* and depth *h* of the grooves are 1.51mm and 0.24mm separately. The shearing experiment was done on the hydro-pneumatic hammer test bed as shown in Fig.4 (c). In this experiment, the pre-grooved 5140 steel bars were first placed in the invented shearing die, and then cropped at a speed of 8.9m/s.



(a) pre-grooved 5140 steel bars (b) profile of the laser groove (c) laboratory setup

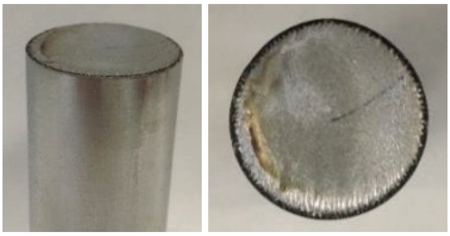
Figure 4. Experimetal materials and setup

4.1 Macro-fracture analysis of the 5140 billets

Fig.5 shows the profile and fracture appearance of a 5140 steel billet cropped with the new blanking method. The cross section of the billet is smooth and nearly round, and no horseshoe-shaped collapses produced; the section inclination is 0.3°, the weight tolerance is only 0.35%.

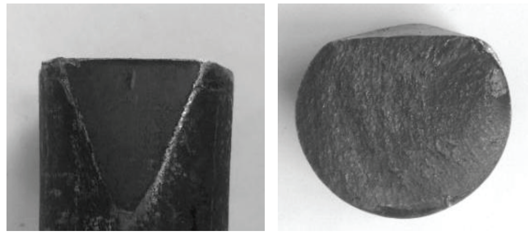
Fig.6 shows the result of the traditional warm blanking of the 5140 steel billet. The billet has an obvious horseshoe cross section, which is rough and out of round. The section inclination is up to 4.1°, and the weight tolerance is 2.5%, so that the extra plane blade cutting process is needed, leading the total time consumed to hundreds of seconds.

Compared with the traditional method, the new method can effectively improve the quality of the billets by more than 12 times and 6 times in accuracy of section inclination and weight tolerance separately.



(a) front profile (b) fracture section

Figure 5. 5140 steel billet by the new method

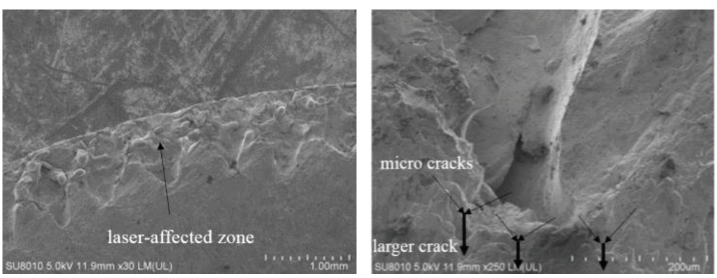


(a) front profile (b) fracture section

Figure 6. 5140 steel billet by traditional blanking method

4.2 Micro-fracture analysis of the 5140 steel billets

The micro fracture morphology of the 5140 steel billet cropped by the new method is further analyses with the scanning electron microscopy (SEM) . As shown in Fig.7 (a), the width of the residual heat affected zone is less than 2mm. Fig.7 (b) magnifies the tip of the groove with 250 time, and it is obvious that the several micro cracks initiate at the tip. The opening angle of the groove increase to 76.1°，which reveals that the material at the bottom is first pulled to both sides, producing micro cracks under the tensile stress. After that, the micro cracks propagate and converge to form some larger vertical cracks and they extend along the shearing direction.



(a) laser-affected zone (b) tip of the groove (250 times)

Figure 7. Micro-fracture morphology of the 5140 steel billet

5 Conclusion

This paper presents a combined blanking method of metal bars with laser pre-grooving and high-speed precision shearing. Take 5140 steel bars as example, the finite element model is established and the results show that the shearing process has characteristic of rapid elastic deformation, slight plastic deformation and instantaneous fracture, and the fracture section of the billet is flat with no collapse. High-speed shearing experimental results further verify that method can efficiently improve the quality of 5140 steel billets with smooth and nearly round section. Specifically, compared to the traditional blanking method, the shearing surface inclination of 5140 steel billets is 0.3°, and the weight tolerance is only 0.35%, the precisions of which improve more than 12 times and 6 times separately. The blanked billets can be directly used for precision forming without extra turning process.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (Grant No. 51335009, 51575532), Major National Science and Technology Project of China (Grant No. 2009ZX04005-031).

References

1. C. Gaudillière, N. Ranc, A. Larue, et al. *Investigations in high speed blanking: cutting forces and microscopic observations*. EDP Sciences,6,1221-1221 (2010)
2. J.H. Fu, Y.T. Li, B.F. Lei, et al. *Experiment research on the high-speed precision shearing of metal bar*. Journal of Mechanical Engineering, 41(5):154-156 (2005)
3. R.F. Zhao, S.D. Zhao, B. Zhong. *Experiment Study on Novel Precision Cropping Machinery Using Rotary Striking Action*. Applied Mechanics & Materials, 281,287-292 (2013)
4. B. Zhong, S.D. Zhao, R.F. Zhao, et al. *Numerical and experimetal investigation on the influence of main motor rotational frequency in fine-cropping*. ARCHIVE Proceedings of the Institution of Mechanical Engineers Part C Journal of Mechanical Engineering Science, 228(3),514-524 (2014)
5. B. Zhong, S.D. Zhao, R.F. Zhao, et al. *Investigation on the influences of clearance and notch-sensitivity on a new type of metal-bar non-chip fine-cropping system*. International Journal of Mechanical Sciences, 76(6), 144-151 (2013)
6. S.D. Zhao, Y.Z. Dong, F. Jing, et al. *A high-speed double - sided shearing method for radially restrained metal bars with low stress*. CN201610606879.3 (2016)
7. K. Kheloufik, E.H. Amara. *Numerical Investigation of the Effect of Some Parameters on Temperature Field and Kerf Width in Laser Cutting Process*. Physics Procedia, 39(7),872-880 (2012)
8. A. Reyes, M. Eriksson, O.G. Lademo, et al. *Assessment of yield and fracture criteria using shear and bending tests*. Materials & Design, 30 (3): 596-608 (2009)