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Influence of laser treatment on the fatigue of notched bar

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Abstract: Fatigue cutting is a new approach for separating material. Man-made fatigue can be realized by applying a rotating bending load to a notched bar. To better utilize the new method, laser treatment is adopted in this study. After laser radiation at the notch root, the fatigue cycle of the bar drops dramatically. Based on the experimental result, we draw the conclusion that the fatigue of the bar is influenced by the shape of the hardened area. A hardened area that has a small axial dimension and a relatively large radial dimension facilitates the fatigue. The desirable hardened area can be obtained by controlling the laser treatment parameters.

Key words: laser treatment; notch; extremely low cycle fatigue; hardened area

Bar stock is the most common form of material in the manufacturing industry. Many raw materials are firstly made into bar stocks in material factories. When a manufacturing process begins, the bar is usually cut by the appropriate length in the first step. In the cutting procedure, some traditional methods are widely used, like sawing, turning, milling, etc. These methods have some common disadvantages. One is that they all require a large amount of energy. Most of the energy is used to turn a layer of metal into cutting chips. Another big disadvantage is the waste of material, for the cutting layer is totally destroyed. To overcome these disadvantages, fatigue cutting is being researched as an alternative. Fatigue cutting is a method of separating material by means of man-made fatigue. According to fracture mechanics, fatigue usually has the feature of brittle fracture under a low stress state. There is not much plastic deformation when fatigue fracture occurs, so the energy consumption is relatively low. Besides, the separation of material is not realized by destroying a whole layer of metal, so the material can be used more economically.

The idea of utilizing fatigue to separate material originated from the analysis of many fracture accidents. In those cases, components failed due to the existence of cracks. This mechanism can be applied to the separation of material, where a deliberately made flaw of a notch replaces a crack. Like crack, a notch can greatly decrease the strength of a component. Many researches on the notch effect and notch sensitivity have been carried out[1-6]. Some cutting experiments have also been reported[7-9]. Fatigue cutting of bar stock is comparatively easy to realize, because it is convenient to make a notch and exert a fatigue load.

To further facilitate the fatigue, laser treatment is taken into consideration. Laser has the properties of low beam divergence (almost parallel) and single wavelength, which permit laser energy to be focused on a very small area to produce high energy density. In recent years, industrial lasers have become available for metal working, such as cutting, welding, surface hardening and glazing. In many previous studies, laser treatment is used to strengthen the components[10,11]. However, it can also be used for an opposite purpose. We are interested in finding a treatment method to facilitate fatigue. An experiment is thus carried out.

1 Experiment

The experiment has three steps: ① The preparation of specimens; ② The notch roots of the specimens are radiated by laser; ③ Fatigue cutting is carried out.

1.1 Specimen preparation

The material of the specimens is medium carbon steel of 45. The chemical composition of the steel is shown in Tab.1. The geometry of the specimens is presented in Fig.1. After rough machining, the specimens are normalized to eliminate stresses. They are heated to 840 ℃ and kept for 1 h, then cooled in open air. Finally, the specimens are machined to the

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required dimensions. The tensile properties of the steel are given in Tab.2.

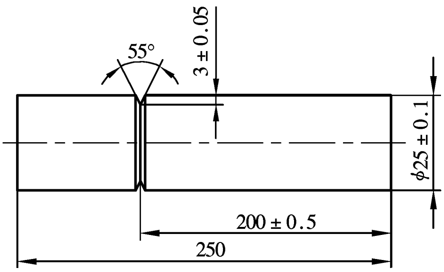

Fig.1 Geometry of the specimens (the notch root radius is 0.05 mm, the unit is mm)

Tab.1 Chemical composition of 45 steel

w(C)	w(Si)	w(Mn)	w(P)	w(S)	w(Cr)	w(Ni)
0.45	0.24	0.62	0.02	0.02	0.15	0.15

Tab.2 Tensile properties of 45 steel (normalized)

Yield strength/MPa	Ultimate strength/MPa	Elongation/%
380	660	26

1.2 Laser treatment

Prior to laser radiation, the notches of the specimens are spray coated with a thin colloidal graphite layer to enhance the absorption of laser. The schematic of the laser radiation is shown in Fig.2. The laser source is a continuous wave CO_2 laser. The output beam is passed through a focusing lens to obtain the desired beam size. The specimen is rotated so that the whole notch root can be treated. There are 15 specimens in 5 groups. The parameters of laser treatment are shown in Tab.3. The No.5 group is not treated so we cannot make a comparison.

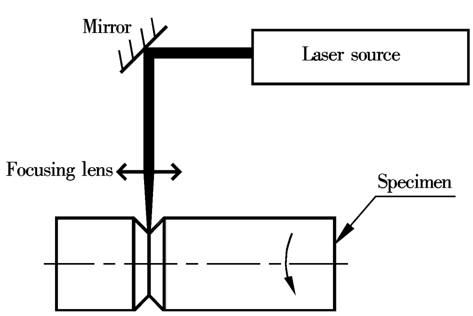

Fig.2 Schematic of laser radiation

Tab.3 Laser treatment parameters

Group	Laser power/W	Laser beam diameter/mm	Processing speed/(mm · s^{-1})
No. 1	120	0.5	20
No. 2	100	0.5	20
No. 3	80	0.5	20
No. 4	60	0.5	20
No. 5	Untreated		

1.3 Fatigue cutting

The fatigue cutting experiment is carried out on a fatigue-cutting machine. The schematic of the experiment is shown in Fig.3. The specimen is clamped in a clamping chuck, which gives the specimen a rotating movement. A transverse moving device exerts a transverse force at the end of the specimen. Therefore, the specimen is under a rotating bending load during the experiment.

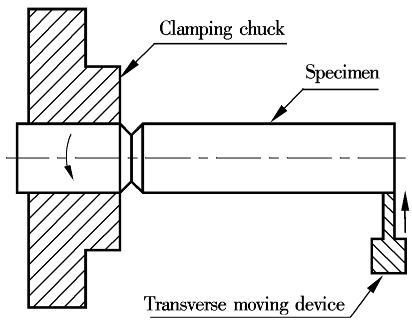

Fig.3 Schematic of fatigue cutting

When the clamping chuck is started, the transverse moving device begins to feed. The speed of the clamping chuck is 120 r/min, and the transverse moving device feeds by 0.2 mm/r. The specimen fatigues after a number of stress cycles. The average fatigue cycles are recorded (see Tab.4). The figures in Tab.4 demonstrate that the specimens fatigue in an extremely low cycle fatigue regime. The fatigue cycles of the specimens drop dramatically after laser treatment.

Tab.4 Fatigue cycle of the specimens

Group	Average fatigue cycles
No. 1	11.7
No. 2	13.5
No. 3	17.0
No. 4	22.3
No. 5	29.0

2 Analysis and Discussion

2.1 Physical theory of laser treatment

When using a laser to radiate metallic material, the heat conduction equation can be written as

$$K\nabla^2 T + q = c\frac{\partial T}{\partial t} \tag{1}$$

where T is the temperature; K is the thermal conductivity; c is the specific heat capacity; q is the internal heat generation rate per unit volume; ∇ denotes the gradient operator[12]. The coordinate system is set up at the notch root with the axis z

pointing to the internal part of the bar. The temperature distribution can be derived as

$$T(z,t) = \frac{2(1-R)\ F_0 \sqrt{kt}}{K} \cdot \left\{ \mathrm{ierfc}\left(\frac{z}{2\sqrt{kt}}\right) - \mathrm{ierfc}\left[\frac{\sqrt{z^2+(d/2)^2}}{2\sqrt{kt}}\right] \right\} \qquad (2)$$

where R is the surface reflection coefficient; F_0 is the average power density; k is the thermal diffusivity; d is the laser beam diameter, and

$$\left.\begin{aligned} \mathrm{ierfc}(x) &= \frac{1}{\sqrt{\pi}}\exp(-x^2) - x \cdot \mathrm{erfc}(x) \\ \mathrm{erfc}(x) &= 1 - \frac{2}{\sqrt{\pi}}\int_0^x \exp(-y^2)\mathrm{d}y \end{aligned}\right\} \qquad (3)$$

For a specific material, R, k, and K are constants. Therefore, the temperature distribution is decided by F_0, t, and d. The shape of the hardened area can be controlled by adjusting the laser power, the processing speed, and the laser beam diameter.

For the medium carbon steel of 45, a hardness gradient appears after the laser treatment[13]. The hardened area is in the surface, which mainly consists of martensite. The hardness of the surface part reaches 800 HV. However, in the deeper part (normal area) the laser treatment has not much influence. There is not phase transformation, and the phase is still a mixture of ferrite and pearlite. The hardness of the normal area is below 300 HV. Therefore, there is a big drop of the hardness in the interface between the hardened area and the normal area.

2.2 Fracture behavior of the specimens

All the specimens are fatigued with extremely low cycles. The experimental results demonstrate that the fatigue cycle varies inversely as the laser power. Since the laser power causes the difference of the hardened areas, we draw the conclusion that the fatigue cycle is affected by the shape of the hardened area. A hardened area with a small axial dimension and a relatively large radial dimension facilitates the fatigue.

In the experiment, the specimens' hardened areas have a small axial dimension of 0.5 mm. It makes the interface between the hardened area and the normal area very close to the notch root, where it is easy for a crack to form due to fatigue stress. The mechanical properties of the hardened area and the normal area are different; the responses of the two areas to the stress are not synchronous. That makes the interface the weakest place, so it would be relatively easy for a crack to form and propagate along the interface. A large radial dimension of the hardened area also accelerates the fatigue, because the deeper the hardened area reaches, the faster the crack would propagate. In the experiment, the No.1 group specimens' hardened area has a large radial dimension of 0.7 mm, which makes the group fatigue with the least stress cycle; the No.4 group specimens' hardened area has a small radial dimension of 0.3 mm, and they fatigue with the greatest stress cycle (except the untreated No.5 group). The experimental results coincide well with the preceding analysis.

If the axial dimension of the hardened area is not small and the radial dimension is not large, the hardened area may not facilitate the fatigue or even retard it. In that situation, the interface is relatively far from the notch root, so the stress at the interface is relatively low, and it cannot cause the start of a crack. A crack would start at the hardened notch root. The formation and propagation of a crack is more difficult in the hardened area, so the fatigue is retarded. Meanwhile, the small radial dimension of the hardened area retards the fatigue too, because the size of the crack is too small even if it has reached the end of the hardened area. Then, as the stress cycle continues, the crack would have two developments. One is that the crack would start propagating along the interface, for the interface is relatively weak. The other is that the crack would restart in the normal area. The shape of the normal area is also like a notch, the large axial dimension of the hardened area would decrease the notch sensitivity, so the restart of the crack would be retarded.

3 Conclusions

Utilizing laser radiation to facilitate fatigue cutting is a new attempt, which is different from previous studies. Our study is a tentative step in this direction. In the experiment, we focus on how laser treatment influences the fatigue of a notched bar and try to find a way to accelerate the fatigue process. The experimental results suggest that the shape of the hardened area has great influence on the fatigue process. The ideal hardened area has a small axial dimension and a relatively large radial dimension. The small axial dimension makes the formation of the crack easier, and the large radial dimension makes the propagation of the crack easier.

Compared with traditional methods, the new method requires less energy and wastes less material. However, the study is still at a preliminary stage.

There are some problems that need to be solved, which include the optimization of parameters, the integration of different steps, the improvement of equipment, etc. We believe those are subjects for future research.

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激光处理对切口棒料疲劳性能的影响

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摘　要　疲劳断料是一种新的分离材料方法.通过对棒料进行切口并施加旋弯载荷,可人为制造疲劳.为了进一步提高断裂的效率,采用激光对棒料切口的根部进行了处理,处理后的棒料疲劳周次大大降低.通过分析实验结果得到:棒料的疲劳受硬化区形状影响,具有较小轴向尺寸和较大径向尺寸的硬化区会促进疲劳.硬化区的形状可以通过调整激光处理参数来控制.

关键词　激光处理; 切口; 超低周疲劳; 硬化区

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