

Impact Toughness and Fracture Mechanism of the Surface Laser Hardened Components of 45 Steel

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Abstract In this study, the impact of laser quenching on 45 steel (V-shaped notch) is researched and the effect of laser power on the fracture toughness is investigated. The specimens surface and fracture morphology are examined by optical microscope and scanning electronic microscope (SEM). Dimple characteristics are observed on the fracture surface of original specimens. As comparison, there are brittle fracture characteristics in the crack initiation zone of laser hardened specimens. Our results indicate that the fracture toughness of laser hardened specimen is reduced. Moreover, the surface fracture toughness decreases with increasing of the laser power.

Key words laser technique; laser surface hardened layers; fracture toughness; brittle; fracture

OCIS codes 140.3390; 140.3590

表面激光相变硬化45钢的冲击韧性及其断裂机理

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摘要 用激光相变硬化技术制备45钢冲击试样(V型槽口),并对试样进行冲击试验,研究了激光功率对45钢激光表面硬化冲击试样冲击韧性值的影响。通过光学显微镜和扫描电镜(SEM)观察了试样表面显微组织和断口的形貌特征。对常规热处理试样和激光表面硬化试样断口进行对比分析。结果表明,常规热处理试样断裂后断裂表面均表现出韧性断裂后的韧窝特征,激光硬化层起裂区呈现脆性断裂特征。经激光硬化后钢件的断裂机制发生改变,导致激光硬化试样冲击韧性值的下降。45钢激光表面硬化冲击试样冲击韧性值随着激光功率增加而逐渐减少。

关键词 激光技术;激光相变硬化;冲击韧性;脆性;断裂

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1 Introduction

Laser treatment on the surface of metal material is often carried out to improve various useful performances. By laser hardening, a structure with high hardness, small grain size and surface compressive stress can be expected^[1,2]. During the laser quenching process, a substrate is rapidly heated up to the austenitizing temperature by laser and then cooled down at a very fast rate^[3]. Generally, the physical, chemical and mechanical properties are improved for all kinds of needed mechanical parts. Some researchers have demonstrated that the impact toughness of laser-processed materials can be improved by the laser quenching technique^[4]. However, the brittleness phenomenon of the laser hardened layer hasn't been studied^[5], and the plasticity and toughness of materials need to be analyzed.

As an engineering index, the impact toughness of material is an important dynamic property, which directly affects the safety and reliability of the metal structure. Being sensitive to surface defects, the impact test can be used to examine the performance of laser hardened layer. In this work, the phase transformation of steel by laser hardening was studied. Also, we inspected the impact fracture morphology and fracture types, and then investigated the effect of laser hardening on the impact

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strength and fracture of 45 steel.

2 Materials and experimental procedures

Firstly, all the specimens were quenched at 850 °C and 520 °C for tempering treatment. After the processing, the hardness value was measured as 35HRC. Then the laser treatment was performed in a 3.0 kW CL-3000 type numerical controlled alternating-current CO₂ laser system in an argon atmosphere. By using the uniform beam technology, the laser surface-hardening was carried out with the beam power of 900~1500 W, focus area of 15 mm×1 mm and scanning speed of 600~700 mm/min. The block samples had the size of 55 mm×10 mm×8 mm. A V-shaped notch region on the samples was hardened by the laser treatment.

After that, microstructural changes were examined by microhardness tests on the samples. And the microstructure was observed by ESEM XL30 scanning electron microscope (SEM).

Complying with the regulations of GB/T228-2002, impact experiments were executed in JBN-300 automatic hammer impact machine. The impact toughness of the V-notch specimen was evaluated at room temperature. All the specimens were placed along the deposition direction with the notch perpendicular to the deposition direction and located in the middle of the laser hardened samples. Five specimens were tested for each condition, and the impact toughness was calculated by the equation:

$$\alpha_k = \frac{A_k}{S_0}, \quad (1)$$

Where A_k is the shock absorption function and S_0 is the gap sectional area of the samples (cm²).

3 Results and discussion

3.1 Microstructure

The microstructure was examined of the hardening layer, transition layer and substrate layer^[6-7]. As shown in Fig.1, after laser hardening treatment, the surface displayed the lath martensite and lamellar martensite with low residual austenite content. The substrate contained some tempered martensite and undisclosed carbides plus little retained austenite.

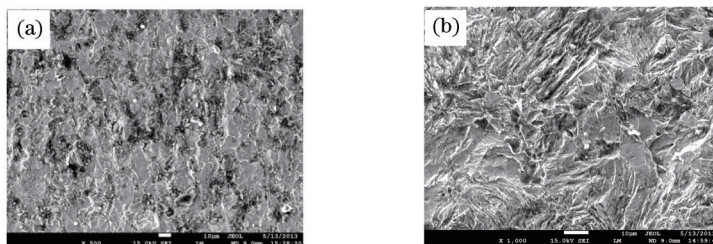


Fig.1 SEM images of the 45 steel samples (a) before and (b) after the laser surface-hardening ($P=1200$ W, $V=700$ mm/min)

The surface hardness of original V-notch specimen was measured with the average value of 35HRC. After the laser quenching, the hardness of the treated layer was significantly improved to 65.5~68.5HRC, as listed in Table 1. The depth of hardened layer increased with the laser power increasing^[8-9], and the hardness reduced gradually in the depth direction. Apparently, with the increase of laser power output, the facular average density increased accordingly. Since the surface area to absorb the energy remained, a higher temperature on the metal surface can be achieved. With the rapid transfer matrix, the area of metal surface in the phase change temperature above Ac₃ also increased, which led to the increase of the depth of hardened layer.

Table 1 Measurement of the 45 steel samples hardened by the laser beam

Sample number	1	2	3	4	5	6	7	8	9
Beam power /W	1500	1300	1100	900	1500	1300	1100	900	700
Scanning speed /(mm·min ⁻¹)	700	700	700	700	600	600	600	600	600
Hardness /HRC	65.1	62.3	60.5	58.1	68.5	67.8	62.5	61.5	60.2
Depth of hardened layer /mm	0.46	0.33	0.21	0.19					0.15

3.2 Impact toughness

Table 2 and Table 3 display the impact test results with the average values of measurement on five

specimens. It should be noted that the impact toughness of laser hardened samples was evidently lower than that of the original samples^[10].

The surface fracture toughness decreased with the increasing of laser power. With the laser power of 900 W and the scanning speed of 700 mm/min, the surface fracture toughness was 40.18 J/cm². With the laser power of 1500 W and the scanning speed of 600 mm/min, the minimum value is 15.58 J/cm². It is clear that the increase of laser power resulted in the increase of the surface hardness and the depth of hardened layer, but also led to the increase of brittleness of the sample^[11].

Table 2 Fracture toughness of the samples hardened by laser beam

Sample number	Beam power /W	Scanning speed /(mm·min ⁻¹)	Fracture toughness α_k /(J·cm ⁻²)
1	1500	700	30.49
2	1300	700	34.21
3	1100	700	37.82
4	900	700	40.18
5	1500	600	15.58
6	1300	600	30.00
7	1100	600	35.90
8	900	600	39.16
9	700	600	40.68

Table 3 Fracture toughness of the original samples

Sample number (V-notch)	1	2	3
Fracture toughness /(J·cm ⁻²)	48.13	42.51	45.44
Hardness /HRC	45.3	43.01	42.5

According to experiment results Table 1 and Table 2, The relationship between laser power and fracture toughness can be obtained, Approximate formula of the relationship between laser power P and fracture toughness α_k can be gained.

When the scanning speed was 700 mm/min,

$$\alpha_k = 2 \times 10^{-8} P^3 - 9 \times 10^{-5} P^2 - 1.407 \times 10^{-1} P + 4.765. \quad (2)$$

When the scanning speed was 600 mm/min,

$$\alpha_k = -2 \times 10^{-8} P^3 + 3 \times 10^{-5} P^2 - 1.76 \times 10^{-2} P + 45.291. \quad (3)$$

When the laser power was greater than 1300 W with the scanning speed of 600mm/min, during the laser quenching process, the specimen surface was in a molten state. The surface melting destroyed the morphology of the gap, and increased the brittleness of the sample. Therefore, the measured fracture toughness declined dramatically.

According to these results, the laser treatment caused higher hardness but brittle structure, particularly in the surface region. The impact toughness value was apparently reduced after the laser hardening. This can be attributed to the higher hardness of the martensitic structure of the laser hardened layers, which led to the large internal organization stress and the increase of brittleness and crack sensitivity of the sample.

3.3 Fractography

The fracture surface of the impact specimens was carefully examined by SEM, as shown in Fig.2 and Fig.3. The crack initiation zone, crack propagation zone and shear rupture zone can be found on the fractured surfaces^[12] (Fig.2). Crack originated from the notch edge on the surface and propagated rapidly during the impact loading process with high strain rate. On the fracture surface of the laser hardened samples, there were large fraction of cleavage facets and small fraction of shallow dimples [Fig.2(a),(b),(c)]. On the contrary, much fewer cleavage facets and larger fraction of dimples can be found on the fracture surface of the original samples.

The micro-morphology of the vicinity of substrate and the interface with laser hardened layer are shown in Fig.3. Cleavage facets and tear ridges were clearly observed in the regions of crack initiation, which belong to the brittle fracture. Dimples and cleavage facets as well as some secondary cracks were

visible in the region of crack propagation. However, ductile dimples dominated in the shear rupture zones. The shear ductile dimple morphology was also observed in the regions of crack initiation of original samples. It can be seen that the cleavage facets and tear ridges belong to the ductile fracture, and the fracture morphology changes can be attributed to the laser surface hardening. It is well known that hard materials are usually brittle and sustain a relatively small fracture strain. Therefore, the impact toughness value was reduced.

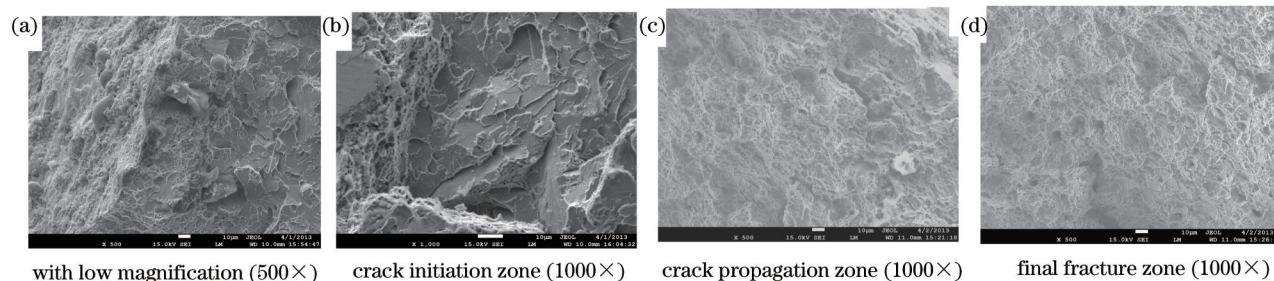


Fig.2 Micro-morphology of impact fracture of laser hardened samples

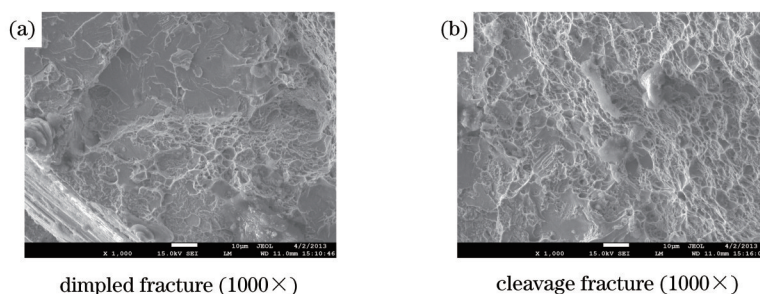


Fig.3 Micro-morphology of the vicinity of substrate and the interface with laser hardened layer

4 Conclusion

- 1) The fracture toughness of laser hardened specimen can be reduced by laser hardening.
- 2) With the increase of laser power, the surface hardness increased, while the fracture toughness decreased gradually.
- 3) As brittle fracture characteristics, large fraction of cleavage facets was observed in the crack initiation zone of the laser hardened samples.

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