Microstructure and properties of plastic deformed martensite induced by laser shock processing

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Firstly, $45^{\#}$ steel was quenched by the NEL-2500A rapidly axial flow CO_2 laser. The experimental parameters were the laser power of 750 W, the laser beam diameter of 4 mm, the scanning velocity of 7 mm/s. The thickness of coating layer was 0.1 mm and the width was 8 mm. Secondly, the martensite induced by laser quench was shocked by Nd:YAG laser. The parameters of laser shock processing were the wavelength of 1.06 μm, the pulse duration of 23 ns, and the output energy of 16−20 J. The laser was focused on a spot of ϕ7 mm. K9 optical glass was used as confinement. The sample was coated with black paint 86-1 (the thickness is about 0.025 mm). By testing and analysis of samples which were treated by laser quench and laser quench+shock with transmission electron microscope (TEM), it was discovered that the surface layer of martensite was deformed plastically by laser shock processing. In the secondary hardened zones, there were a lot of slender secondary twin crystal martensites, dislocation tangles, and cellular dislocations. Compared with that of the hardened zones through laser quench only, the residual stress and mechanical properties of the secondary hardened zones were improved and increased through laser compound method.

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There have been many experimental and theoretical reports about laser quench and laser shock processing in the past years[1−5]. But it has been nearly empty on the research of theory and experiment of laser shock processing the martensite induced of metal materials by laser quench. Compared with traditional shot peering, there are four characteristics in laser shock processing as follows: 1) The shock wave pressure induced by laser is very high, which may reach several gigapascals; 2) The deformed rate of metal materials is very rapid; 3) There is high strain rate, which may reach 10^7 s^{-1}; 4) With the efficient protection of coating isolating the heat induced by laser shock processing, the plastic deformation of martensite is only due to the action of force induced by laser shock wave, so which do not accrue temper phenomena. Therefore, the theoretical and experimental studies of the martensitic plastic deformation induced by laser shock is very important, whether in developing the fields of laser application or exploring the mechanism of martensitic transformation under condition of the super high pressure and high strain rate.

The experimental material is $45^{\#}$ steel. Its chemical composition (wt.-%): C 0.42−0.5, Si 0.17−0.37, Mn 0.5−0.8, P$\leq$0.035, S$\leq$0.035, Ni$\leq$0.25, Cr$\leq$0.25, Cu$\leq$0.25. Its mechanical properties: E = 201 GPa, ν = 0.293, σ_b = 600 MPa, $\sigma_{0.2}$ = 520MPa, δ = 16%, $HV_{0.2}$ = 273. Heat treatment: quench and temper. The size of sample is $30\times20\times10$ mm^3. In the experiments, the sample surface is coated by opaque material (black paint 86-1) as absorbing layers of laser quench and laser shock processing. K9 optical glass was used as the confinement medium whose size is $\phi19\times4$ mm.

Laser quenching experiments were performed by the NEL-2500 rapidly axial flow CO_2 laser in our laboratory. The experimental parameters were optimized. In all laser quenching experiments, the laser power was 800 W, the diameter of laser beam was 4 mm, the scanning velocity was 7 mm/s. The thickness of coating layer was 0.1 mm and the width is 8 mm. After laser quench, the width of the surface hardened zone of $45^{\#}$ steel was 3.6 mm and its depth was 0.56 mm.

Laser shock processing experiments were performed by the high power Nd:YAG laser with wavelength of 1.06 μm, pulse duration of 23 ns, and output energy of 16−20 J. The laser was focused on a spot of ϕ7 mm. K9 optical glass was used as confinement medium, one of its sides connected with the sample was coated by black paint 86-1 (the thickness was about 0.025 mm), the laser intensity was about 2.0 GW/cm^2 on spot, the peak pressure induced by laser shock wave was over the Hugoniot elastic limit of $45^{\#}$ steel 1.225 GPa, which was able to ensure the sample to be deformed plastically.

Micrographs were gained by the HITACHI's transmission electron microscope (TEM), whose accelerate voltage was 200 kV. The surface microhardness measurements of the hardened zone of $45^{\#}$ steel were performed on HVS-1000 digitalized microhardness tester with a 2-N load. The time of packing process was 10 s. Sliding abrasion tests were conducted on an MM-200 abrasion tester, its maximum operation pressure is 2000 N. Sliding ability is about 100%. Abrasion block is made of GCr15, its microhardness is about HRC58. The size of all samples was the same as $8.0\times19.5\times10$ mm^3. Three kinds of different hardened samples of $45^{\#}$ steel were tested by laser quench+shock, nitriding, and laser quench, respectively. In the experiments, 5 samples of every treatment methods were performed on sliding wear. The MM-200 abrasion tester was operated with the turn rate of 200 rpm, load of 19.6 N, and wearing time of 2 hours per sample. The experiments of testing residual stress in the hardened zones were performed on the X-350 residual stress test equipment. The positions of testing residual stress were in the center of the hardened zones by laser quench and laser quench+shock.

Martensitic micrographs of the hardened zone of $45^{\#}$ steel have been gained for laser quench and laser quench+shock by using TEM. Figures 1(a) and (b) show the first martensite microstructures of the hardened zone by laser quench, which indicate the presence of lath martensite and dislocation martensite, respectively. Figure 1(c) shows secondary martensite microstructure after laser shocking the first martensite. Compared with first martensite, the shapes of secondary martensite have changed obviously, the sizes of the secondary martensite become finer than that of the first martensite. A lot of slender secondary twin crystal martensite is across in the first martensite. Figure 1(d) shows that the first martensite is broken and becomes a great number of secondary plate martensites. The relation orientations between adjacent lath martensites induced by laser quench are parallel. But after treated by laser shock processing the first martensite becomes footmark-like and secondary twin crystal martensites, and a lot of dislocation ties is produced between secondary plate martensites or lath martensites. Figure 1(e) and (f) show TEM micrographs of cellular and high tie dislocation of second martensite, respectively. The high density dislocation ties in the secondary hardened zone of $45^{\#}$ steel not only improve the hardness of the material surface and strength of material, but also prevent from metal lattice slipping and fatigue crack extension, so that it can improve the resistant fatigue strength of the metal material.

Compared with $\mathrm{HV}_{0.2}273$ of the $45^{\#}$ steel substrate surface, the average microhardness of the hardened zone surface of $45^{\#}$ steel was about $\mathrm{HV}_{0.2}850$ by laser quenching processing, increased by 200%. Compared with that of the hardened zone by laser quench, the average microhardness of the secondary hardened zone surface of $45^{\#}$ steel by laser shock was about $\mathrm{HV}_{0.2}972$, increased by 15%.

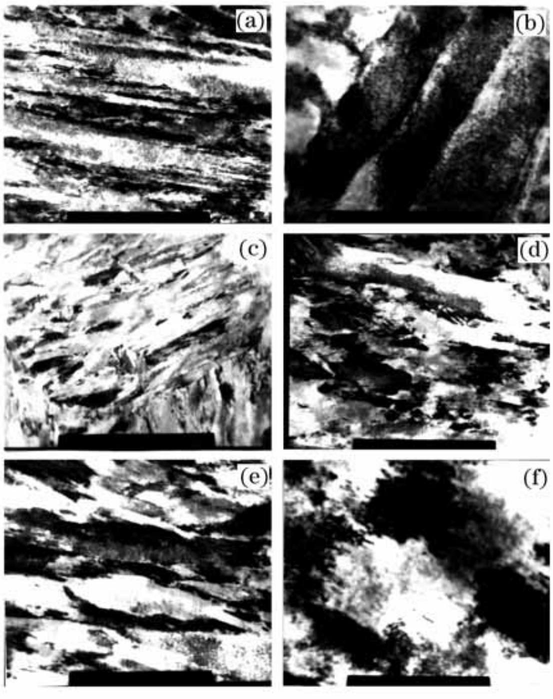

Fig. 1. Comparison of matensite microstructures of the hardened zone of $45^{\#}$ steel by laser quench and laser compound treatment. (a): Lath martensite by laser quench; (b): dislocation martensite by laser quench; (c) and (d): finer martensites by laser compound treatment; (e) and (f): cellular dislocation.

The results of sliding wear experiments of the samples are shown in Table 1 with different treatment methods. Every abrasion value is arithmetic mean of 5 samples tested by the same hardened method. The dispersity of every group abrasion values tested is very little. No crossing is in each group datum. The datum is very high reliable. Under the same conditions, the average loss weight of different samples was 0.84 (by nitriding processing), 0.45 (by laser quench processing), and 0.21 mg (by laser quench+shock processing), respectively. The wearability of the hardened zone by laser quench increased nearly one times than that of $45^{\#}$ steel treated by nitriding processing. While the wearability of the secondary hardened zone by laser quench+shock improved about one times than that of the hardened zone by only laser quench.

Figure 2 shows the in-depth residual stress distributions of the hardened zones of $45^{\#}$ steel by laser quench and laser quench+shock processing. In the hardened zone by laser quench, the peak value of residual compressive stress is about −210 MPa. About in 0.45-mm hardened zone along the depth direction, the residual compressive stress became residual tensile stress of 181 MPa, with effecting depth of about 1.7 mm. While in the secondary hardened zone by laser quench+shock, the maximum residual compressive stress is −350 MPa, its effecting depth is about more than 2.0 mm. Furthermore, by laser shock processing, the residual tensile stress of the hardened zone induced by laser quench has been completely eliminated.

After laser shock processing the first martensite zone induced by laser quench, there was a bright concave on

Table 1. Comparison of Loss Weight of Different Strengthened Processing Methods for $45^{\#}$ Steel

Sample	Wear Mass Loss (mg)	Time (h)
Nitriding	0.84	2
Laser Quench	0.45	2
Laser Quench+Shock	0.21	2

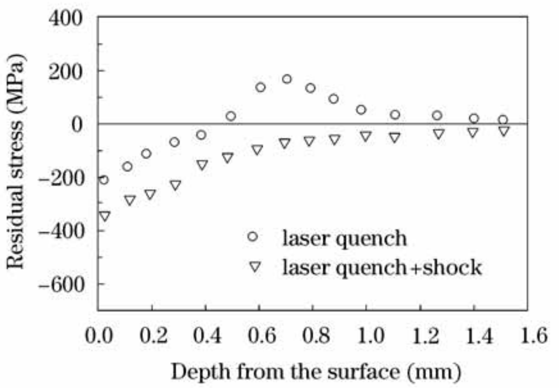

Fig. 2. Comparison of the residual stresses of hardened zones of $45^{\#}$ steel by laser in different strengthened methods.

the surface of the hardened zone, the maximal depth of the concave was about 7 μm. And there was no micro-crack in the strengthened surface layer by electron probe micro analyzer (EPMA), but an obvious plastic strengthened surface layer appeared, which are the presence of disposing of fiber orientation[6]. The above analysis indicate that first martensite had the plastic deformation. Because of the protection of the coating, the surface roughness of the secondary hardened zone by laser shock did not increase, and there are no dot erosion and vaporization in the surface of the secondary hardened zone.

Through analysis and comparison of micrographs and mechanical properties of the first martensite induced by laser quench and the secondary martensite induced by laser quench+shock, we can find that, first, the slender microstructure of the secondary martensite is able to further improve the hardness, strength, and toughness of metal materials, and may adjust the state of residual stress distribution and properties of residual stress in the secondary hardened zone (see Fig. 2). Secondly, the high density dislocation ties in the secondary hardened zone of $45^{\#}$ steel not only improve the hardness of the material surface and strength of material, but also prevent from lattice slipping and extension of fatigue crack of metal materials, so it can improve the resistant fatigue strength of the metal materials also[2,5]. Thirdly, the micro-crack was not found in strengthened surface layer by EPMA, which indicates that the deformation of laser shock processing brittle martensite induced by laser quench is a kind of the super plastic deformation. So the technique of laser shock processing may be applied to treating the brittle materials. Finally, carbide was not found in the microstructure of the secondary hardened zone by laser shock, which indicates that laser shocking martensite did not make tempered phase. So we may get that the secondary transformation of martensite induced by laser shock is only due to the action of the force induced by laser shock wave.

This paper studied and analyzed the experimental results of laser shocking martensite induced of $45^{\#}$ steel by laser quench. Several conclusions were obtained as following.

1) The surface layer of the first martensite zone by laser shock had obviously plastically deformed strength. The surface microhardness of the secondary hardened zone by laser shock increased by 15%.

2) Compared with the wearability of the hardened zone by laser quench, the wearability of the secondary hardened zone by laser shock increased about 1 time.

3) After laser shock processing the first martensite zone, which made the complex residual stress of the hardened zone by laser quench into a kind of signal residual compression pressure stress. The maximum residual compression stress reaches −350 MPa, so it can improve resistant fatigue life of a complex workpiece.

4) By the analysis on the microstructure of the secondary hardened zone by laser shock, it was found that the surface layer of the first martensite has been broken into pieces and becomes finer secondary martensite by laser shock wave. A great of slender secondary twin crystal martensites have been produced in the secondary hardened zone. Simultaneously, there are a large number of the high dislocation densities and dislocation tangles. So the plastically deformed strength of the secondary martensite induced by laser shock may efficiently improve integration mechanical properties of metal materials.

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