The microstructure and properties of Mo alloying layer after surface alloying treatment induced by continuous scanning electron beam process

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Abstract. Surface alloying by scanning electron beams can improve the microstructure and mechanical properties of steel. In this study, four electron energy densities were selected during the alloying process: $E_1 = 1.5J/cm^2$, $E_2 = 2.9J/cm^2$, $E_3 = 4.5J/cm^2$ and $E_4 = 5.9J/cm^2$. The obtained results show that the sample surface is composed of alloying zone and heat-affected zone. The microstructure of the alloy zone is concealed acicular martensite and molybdenum carbide particles. The microhardness of this area is 1250HV. The sample treated with an energy density of 5.9J/cm\textsuperscript{2} has the least amount of wear. After alloying treatment, the microhardness and wear amount of the scanned samples are significantly improved.

1. Introduction

45 steel is a kind of carbon structural steel, which is widely used in mechanical components such as shafts, gears, bearings and crankshafts. However, with the continuous development of science and technology, such parts are required to have higher hardness and wear resistance\textsuperscript{[1]}. Scanning electron beam (SEB) has the advantages of high energy conversion efficiency, fast heating and cooling speeds, etc., and has been proven to be a promising surface treatment method that can significantly change the structure and mechanical properties\textsuperscript{[2-6]}. In addition to electron beam, physical vapor deposition technology, conventional electroplating, sputtering deposition and other technologies are usually used to improve the surface mechanical properties. Non-equilibrium technology has disadvantages such as poor cohesion and adhesion between coatings. And substrate\textsuperscript{[7-10]}. Scanning electron beam surface alloying is a method that uses CSEBP technology to quickly dissolve one or more alloying elements into the matrix, and obtain an alloy layer with special properties through energy conversion and microstructure changes\textsuperscript{[11-14]}. The alloy layer has strong adhesion, compact structure and greatly improved hardness.

The aim of this study was to improve the microstructure and mechanical properties of 45 steel by plasma spraying and scanning electron beam. The effect of energy density on the Mo alloy layer microstructure, microhardness and wear loss of 45 steel surface layer was studied.
2. Experimental parts
The substrate was annealed 45 steel composed of ferrite and pearlite and was machined into square blocks with dimension of 40mm×40mm×40 mm. The chemical composition of the substrate is given in Table 1.

| C    | Si    | Mn    | S    | P    | Cr    | Ni    |
|------|-------|-------|------|------|-------|-------|
| 0.42 | 0.17  | 0.5   | ≤0.045 | ≤0.04 | ≤0.25 | ≤0.25 |

In this experiment, molybdenum coating was prepared on 45 steel samples by plasma spraying. The process parameters are shown in Table 2, and the coating thickness is 70μm. Then, a scanning electron beam is used to melt the surface of the sample. Electron beam process parameters: acceleration voltage is 70kV, electron beam scanning frequency is 100Hz, focusing current is 178mA, electron beam diameter is 0.25mm, scanning circle diameter is 4mm, electron gun moving speed is 50mm/min, energy density $E$ is $4.5J/cm^2$\cite{15-18}. The scanning electron beam surface alloying method is shown in Figure 1.

| spraying current | spraying voltage | spraying distance | argon pressure | hydrogen pressure | powder delivery pressure | Workpiece movement speed |
|------------------|------------------|-------------------|----------------|------------------|-------------------------|-------------------------|
| 510A             | 35V              | 150mm             | 0.8MPa         | 0.8MPa           | 0.8MPa                  | 50mm/min                |

Use scanning electron microscope to observe the microstructure and take photos, and use EDS energy spectrum scanner to test element distribution. The HMV-ZT microhardness tester was used to measure the microhardness of the surface and cross-section of the sample. The HRS-2M friction and wear test device and electronic balance are used to test the specimens for heavy wear loss.
3. Experimental results
As shown in Figure 2, after scanning electron beam alloying treatment, the alloy layer is composed of acicular martensite, molybdenum carbide particles and Fe-Mo solid solution, the crystal structure is columnar dendrites, and the thickness of the alloy layer is 100 μm. This is because under the scanning electron beam surface alloying treatment, the surface temperature of the sample is much higher than Ac3. During the heat conduction cooling process, the alloy layer has formed acicular martensite and molybdenum carbide particles, and a large amount of Mo alloying elements incorporated into ferrite to form Fe-Mo solid solution. Electron beam surface alloying treatment is a rapid heating and cooling metallurgical fusion process. Therefore, there is a large temperature gradient between the alloy layer and the substrate, and a large amount of Mo alloying elements are incorporated into the alloy layer, which is easy to form component overcooling, resulting in the alloy The layer melting and crystallization temperature increases, and during the heat conduction cooling process of the substrate, the crystal grains grow along the temperature gradient direction to form columnar dendrites.

The cross-sectional morphology and microstructure of E3 sample after continuous scanning electron beam process can be observed in Fig3. As shown in Fig.3(a), the surface strengthening layer of the sample is composed of alloy zone and heat-affected zone. The top layer is alloyed zone whose thickness is about 100μm. The sub-zone is heat-affected zone whose thickness is about 150μm and the zone that the distance from the surface exceeds 250μm is substrate. Concealed needle martensite and Molybdenum carbide particles can be observed in Fig.3(b). Because the temperature of the alloyed zone reaches the highest at a rapid heating rate (10⁸-10⁹K/s) during the CSEBP. The temperature exceeds the phase transformation temperature greatly, and the region occur hundred-percent austenite transformation. Under the effect of rapid heat conduction of the substrate, the cooling rate reaches 10⁷-10⁸K/s, the melted layer occurs quenching effect. The grain of microstructure is highly refined, forming concealed needle martensite, and Molybdenum element and carbon element react chemically to form Molybdenum carbide particles. Fig.3(c) shows that the heat-affected zone is an incomplete phase transformation zone. The heating temperature is between Ac1 and Ac3, after rapid cooling. The microstructure is acicular martensite and ferrite. Fig.3(d) shows that the microstructure of substrate is ferrite and pearlite.
The change of microstructure of the alloyed zone with different energy density is shown in Fig.4. As the energy density increases, the energy absorbed by the alloyed zone and heat-affected zone increases. The austenitizing temperature increases in the alloyed zone and the acicular martensite grains are finer and more Molybdenum carbide particles are formed by the rapid thermal conduction of the substrate. When the energy density reaches 5.9J/cm², the crack occurs in the alloyed zone. This reason is that the beam current is too high. The temperature of alloyed zone is too high, and the cooling rate is too fast.

The variation of microhardness along the depth direction with different energy density is shown in Fig.5. With the increase of the depth, the microhardness decreases nonlinearly and the higher energy density produces the higher microhardness at the same depth position. The highest microhardness in the alloyed zone can reach 1250HV, and the highest microhardness in the heated affected zone reaches 850HV.

![Fig. 4 Different energy density](image)

(a) 1.5J/cm²  (b) 2.9J/cm²  (c) 4.5J/cm²  (d) 5.9J/cm²

![Fig. 5 Microhardness of specimens under different energy density of electron beam](image)

Fig. 5 Microhardness of specimens under different energy density of electron beam

shown in Figure 6, after scanning electron beam surface alloying treatment, the wear resistance of the sample surface is improved. As the energy density increases, the wear amount of the sample surface first decreases and then increases. When the energy density is 4.4 J/cm², the sample wear is the smallest. This is because as the energy density increases, the content of cryptic martensite and molybdenum carbide particles in the alloy layer increases.

![Fig.6 Wear loss under different beam current with the increase of load](image)

Fig.6 Wear loss under different beam current with the increase of load
4. Conclusion

(1) After 45 steel is alloyed by scanning electron beam, a strengthening layer composed of alloying zone and heat-affected zone is formed on the surface of the sample, with a thickness of 120~350μm. The alloy zone is composed of acicular martensite, molybdenum carbide particles, Fe-Mo solid solution and columnar dendrites. When the energy density is 4.4 J/cm², the surface hardness and friction and wear resistance of the sample are optimal.

(2) With the increase of the energy density, the hardness and the depth of the alloyed zone increases. When the energy density reaches 5.9 J/cm², the crack occurs in the alloyed zone due to the large energy density. The wear loss of each sample increases nonlinearly with the increase of load at room temperature. The higher energy density produces the less wear loss at the same load.

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