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Effect of Composition on the Mechanical Properties and Wear Resistance of Low and Medium Carbon Steels with a Biomimetic Non-Smooth Surface Processed by Laser Remelting

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Abstract: To study the effect of laser biomimetic treatment on different material compositions, five kinds of steels with different carbon element contents were studied by laser remelting. The characteristics (depth, width), microstructure, hardness, tensile properties, and wear resistance of the samples were compared. The results show that when the laser processing parameters are fixed, the characteristics of the unit increase with an increase of carbon element content. Moreover, the hardness of the unit also increases. Compared with the untreated samples, when the carbon content is 0.15–0.45%, the tensile strength of the laser biomimetic samples is higher than that of the untreated samples. For the biomimetic samples with different carbon content, with an increase of carbon content, the tensile strength increases first and then decreases, while the plasticity of the biomimetic samples decreases continuously. The bionic samples have better wear resistance than that of the untreated samples. For bionic specimens with different carbon elements, wear resistance increases with an increase of carbon element content.

Keywords: composition; laser bionic unit; tensile properties; wear resistance

1. Introduction

Natural organisms live in harsh and complex environments for long periods, so their body surfaces must possess a strong ability to resist external damage. A non-smooth morphology, non-smooth structure, and different material compositions on the surface of the organism are typical biological coupling characteristics [1–5]. Various non-smooth features provide an organism with an appropriate combination of strength and toughness and play a unique role in resisting external alternating stress or direct damage. For example, dragonfly wings [6,7] are often in a vibrational state without failing, which is the result of the collaborative effect of the wing surface's grid shape and the wing vein's sandwich structure composed of multiphase materials. The desert scorpion [8] has been subjected to the erosion by sandstone permanently without damage, which is the result of the collaborative effect of its non-smooth surface and multiple layers of soft connective tissue under the skin; shellfish [9–11] have been eroded by seawater frequently without crack initiation, which is the result of their non-smooth surface composed of an alternating soft and hard structure and the coupling effect of the composite materials. Thus, inspired by the coupling characteristics of the surfaces of organisms, constructing

a bionic non-smooth structure on the surface of mechanical parts to obtain specific properties has become a new surface modification method.

Laser remelting treatment [12–15], as a new technology, can be combined with coupled bionics to offer a new approach for manufacturing bionic non-smooth structures. In this process, a high energy laser beam irradiates the surface of the workpiece, making the laser radiation region of the workpiece rapidly melt. Then, the region is quickly solidified via heat conduction from the substrate, so the obtained microstructure is different from the matrix, and when the selected laser processing parameters are appropriate, the grain will be refined. The material's hardness is also much improved based on the pattern [16–18]. In this way, the non-smooth bionic structure with soft and hard phases is processed on the surface. Among these structures, the hard structure processed by laser fusion is called the bionic unit [19].

Previous studies [20–23] have shown that the improvement of material properties is closely related to the biomimetic unit. Materials with non-smooth structural biomimetic units have good wear resistance and fatigue resistance. The properties of the biomimetic unit are closely related to their composition, the microstructure of their matrix material, and their laser processing parameters. For example, Meng [24] studied the unit microstructure and thermal fatigue resistance of different kinds of die steel after laser biomimetic treatment. Zang [25] compared the microstructure and mechanical properties of H13 steel with different microstructures after laser biomimetic treatment. At present, the effect of the material composition on laser biomimetic treatment is rarely discussed in the literature. Therefore, in this paper, the low and medium carbon steels commonly used in industry were chosen as the research object, and we studied the influence of carbon content on the characteristics, microstructure, and mechanical properties of the bionic unit by machining the strip bionic unit on its surface. Finally, the wear experiments of samples with different carbon content were demonstrated. The purpose of this study is to provide a reliable theoretical reference for laser remelting strengthening of different carbon steel parts in actual industrial production and to serve industrial production practices.

2. Experimentation

2.1. Materials

Samples of 15 steel, 25 steel, 35 steel, 45 steel, and 55 steel with carbon content of 0.15%, 0.25%, 0.37%, 0.45%, and 0.58%, respectively, were selected. The matrix samples are represented by A1, A2, A3, A4, and A5, respectively, and their chemical components are shown in Table 1. Laser biomimetic samples are represented by LR-A1, LR-A2, LR-A3, LR-A4, and LR-A5.

Table 1. The compositions of the samples (wt.%).

Groups	C	Si	Mn	S	P	Fe
A1	0.15	0.11	0.28	<0.01	<0.01	Bal
A2	0.25	0.21	0.53	<0.01	<0.01	Bal
A3	0.37	0.18	0.61	<0.01	<0.01	Bal
A4	0.45	0.20	0.55	<0.01	<0.01	Bal
A5	0.58	0.25	0.75	<0.01	<0.01	Bal

2.2. Experimental Methods

The wear samples were cut into the samples to be processed (with a volume size of $20 \times 30 \times 6 \text{ mm}^3$) using an electric spark machine (DK7732, Huadong Group, Hangzhou, China), and the samples were processed successively with waterproof abrasive paper of different granularities to remove the traces of wire cutting. Then, an ultrasonic cleaner was used to clean the samples, thereby removing the residual oil and debris on the surface of the sample to achieve a smooth and clean surface.

A bionic strip specimen was fabricated using a solid-state pulsed Nd: YAG laser with a wavelength of $1.064\ \mu\text{m}$ and maximum output power of 500 W. The processing schematic diagram is shown in Figure 1. The laser processing parameters are shown in Table 2.

Figure 1. The schematic diagram of laser bionic processing.

Table 2. Laser processing parameters.

Energy (J)	Pulse Duration (ms)	Frequency (Hz)	Scanning Speed (mm/s)	Beam Diameter (mm)
16.88	8	5	1	1.59

The sample was cut in the direction perpendicular to the incident direction of the laser using an electric spark machine. The cross-section was sequentially milled and polished. Pickling was carried out using a 4% nitric acid solution. Characterizations of the cross-section of the unit were carried out using an optical microscope (Zeiss, Axio Image A2m, Oberkochen, Germany). The microstructure of the unit and the substrate were observed using an electron scanning microscope (Zeiss, EV018, Oberkochen, Germany). The X-ray diffractometer (Rigaku D/Max 2500PC, Tokyo, Japan) was used for phase analysis.

Microhardness testing was performed on a microhardness tester (HVS-1000A, Beijing, China). The load was 1.962 N, and the holding time was 10 s. A schematic diagram of the hardness is shown in Figure 2.

Figure 2. The position of the hardness measurement points.

The tensile test was carried out on a hydraulic servo test machine (MTS 810, MTS Systems Corporation, Eden Prairie, MN, USA) at room temperature and the crosshead speed is 1 mm/s. Figure 3a shows the dimensions of the tensile specimen after laser bionic treatment. Three test specimens for each set were tested and averaged as the final result. After the test, the tensile fracture morphology for all samples were analyzed.

Figure 3. The bionic specimens used for (a) tensile and (b) wear testing.

Figure 3b shows a schematic of the wear sample after laser bionic treatment. The schematic of the reciprocating sliding wear testing machine developed by the laboratory is shown in Figure 4. During the experiment, the friction pair was fixed, and the sample located in the card slot was linearly reciprocated. The friction pair material is made of quenched gray iron (800 HV), the eccentric speed is 690 r/min, the wear time is 600 min, and the load is 100 N. All experiments were carried out at room temperature under dry conditions.

Figure 4. Schematic of the sliding wear tester.

Before and after the wear test, the samples were cleaned with an ultrasonic cleaner, dried for half an hour, and then weighed before and after wear by an electronic balance (FA2400, Shanghai jinmin instrument equipment co. LTD, Changshu city, China); then, the weight loss was calculated. Each

experiment was repeated three times, and the final results were averaged. Finally, the wear surface morphology was observed with a surface profiler (NT9100, Brock, Germany).

3. Results and Discussion

3.1. Cross-Section Morphology and Size of the Biomimetic Units with Different Carbon Content

Figure 5 shows the cross-sectional morphology of biomimetic unit with different carbon content. It can be seen that the cross-sectional morphology is parabolic, and the unit is composed of two parts: One part is a fusion zone with a bright white color, and the other part is a heat-affected zone (HAZ) in contact with the matrix. Table 3 lists the cross-sectional dimensions of the bionic unit with different carbon contents. It can be concluded from Figure 5 and Table 3 that when the laser processing parameters are the same, as the carbon content increases, the unit characteristics are also increased. The unit characteristics are mainly related to the laser processing parameters and the thermophysical properties of the material [26]. When the laser processing parameters are the same, the thermal conductivity is the determining factor of the unit's characteristics. For carbon steel materials, thermal conductivity increases as the carbon content increases. A material with high thermal conductivity propagates heat at a faster rate, and its fusion zone is wider and deeper. The unit characteristics with different carbon content show this rule.

Figure 5. The cross-section of the biomimetic units: (a) LR-A1, (b) LR-A2, (c) LR-A3, (d) LR-A4, and (e) LR-A5.

Table 3. Unit characteristics of different materials.

Groups	Unit Width (μm)	Unit Depth (μm)
LR-A1	947.30	543.32
LR-A2	1116.43.84	579.24
LR-A3	1241.64	607.29
LR-A4	1265.4	663.37
LR-A5	1346.02	726.47

3.2. Microstructure and Phase Composition of Different Carbon Content Matrixes and Bionic Samples

3.2.1. The Microstructure of the Matrix

Figure 6a–e shows the microstructure of the matrix materials. It can be seen that the matrix structure of the five materials is the same, consisting of pearlite and ferrite; with an increase of carbon content, the ferrite content decreases, and the pearlite content increases.

Figure 6. The microstructure of base material samples: (a) A1, (b) A2, (c) A3, (d) A4, and (e) A5.

3.2.2. The microstructure of the unit

Figure 7a–e shows the microstructure of the unit remelting zone of the laser biomimetic sample. Although the carbon content of the base material is different, the microstructure of the laser fusion zone is the same (which is composed of lath martensite and plate martensite). With an increase of carbon content, the content of the plate martensite gradually increases, and the content of lath martensite decreases. This is due to the different carbon content of the material.

Figure 7. The microstructure of remelting zone of biomimetic unit: (a) LR-A1, (b) LR-A2, (c) LR-A3, (d) LR-A4, and (e) LR-A5.

3.2.3. Phase Analysis

Figure 8a–e shows a comparison of the XRD between the matrix (A1–A5) and the biomimetic unit (LR-A1–LR-A5), and Figure 8f shows an XRD comparison diagram of the biomimetic unit (LR-A1–LR-A5). The results show that the main phase of the matrix is ferrite, and the phase of the laser biomimetic unit is martensite.

Figure 8. X-ray diffraction profiles of the biomimetic units and matrixes: (a) A1, (b) A2, (c) A3, (d) -A4, (e) A5; (f) comparative diffraction curves of LR-A1–LR-A5.

At the same time, Jade was used to analyze the half-height and width of the diffractive peak (FWHM) of the matrix and unit with different carbon content. The results show that the FWHM of the matrix materials are A1: 0.140° , A2: 0.219° , A3: 0.239° , A4: 0.249° , and A5: 0.300° ; the laser biomimetic

samples' FWHM is 0.239° , 0.243° , 0.282° , 0.286° , and 0.519° . The FWHM of the bionic unit of the same material is larger than that of the matrix material. Here we use Scherrer's formula [27]:

$$D = \frac{K\lambda}{\beta \cos \theta'} \quad (1)$$

where D is the grain size, K (K value is 0.89) is the Scherrer constant, λ is the wavelength of the X-ray, β is the full width at half maximum, and θ is the Bragg diffraction angle. It can be seen that under the same testing conditions, the grain size of the unit has been refined to different degrees, and the order of the grain size of the unit is LR-A5(67 nm) < LR-A4(121 nm) < LR-A3(123 nm) < LR-A2(143 nm) < LR-A1(145 nm).

3.3. Mechanical Properties of Varying the Carbon Content Matrix and Bionic Samples

3.3.1. Microhardness of Matrix and Unit

The microhardness of the base materials A1, A2, A3, A4, and A5 are 126 HV, 176 HV, 250 HV, 270 HV, and 320 HV, respectively. Figure 9a is the microhardness curve of the bionic unit along the X-axis direction, and Figure 9b is the microhardness curve of the bionic unit along the Y-axis direction. Figure 9a,b show that the hardness of the remelting zone and the HAZ of the biomimetic unit are higher than those of the matrix, and the hardness of the bionic unit is gradually increased as the carbon content increases. This also echoes the microstructure changes in Figure 7. After calculation, the average hardness of the bionic unit after laser fusion treatment is 321, 343, 466, 493, and 659 HV. The degree of hardness improvement is 155%, 89%, 86%, 83%, and 106%, relative to the respective matrix.

Figure 9. The hardness of the biomimetic unit: (a) section profile along the X-axis and (b) section profile along the Y-axis.

3.3.2. Tensile Properties of Specimens

To compare the tensile properties of the samples with different carbon contents after laser bionic treatment, the bionic units with the same volume proportions were processed on the surface of the base material. The effect of carbon content on the tensile properties of the biomimetic samples was investigated. Figure 10a–e shows the stress–strain curves of the different carbon-containing untreated samples and laser bionic samples; the corresponding yield strength (YS), tensile strength (TS), and elongation (EL) are shown Table 4. To compare the tensile properties of each biomimetic sample, the tensile property improvement ratio [28] is used to analyze the strengthening effect of different biomimetic samples. The tensile property change ratio refers to the percentage of yield strength, tensile strength, and elongation change of the biomimetic sample compared to the untreated sample, which are represented by YSC , TSC , and ELC , respectively.

Figure 10. Tensile curves of bionic samples and untreated samples with different carbon contents: (a) A1, (b) A2, (c) A3, (d) A4, and (e) A5.

Table 4. Tensile test results of the bionic treatment samples and untreated samples.

Groups	YS (MPa)		YSC (%)	TS (MPa)		TSC (%)	EL (%)		ELC (%)
	Untreated	Treated		Untreated	Treated		Untreated	Treated	
A1	275	342	24.36	428	440	2.80	39	19	−34.48
A2	285	387	35.79	440	532	20.91	24	14	−41.67
A3	295	390	32.20	636	656	3.14	21	10	−52.38
A4	268			631	639	1.26	18	3	−83.33
A5	414			652	618	−5.21	15	2	−86.67

From Figure 10 and Table 4, it can be concluded that when the carbon content is in the range of 0.15–0.37%, the bionic sample shows a ductile fracture, and when the carbon content is in the range of 0.45–0.58%, the bionic sample shows a brittle fracture. When the carbon content is in the range of 0.15–0.37%, the tensile strength and yield strength of the samples after laser biomimetic treatment are better improved compared to the untreated sample. However, the tensile strength of the bionic samples with carbon content in the range of 0.45–0.58% decreased, especially the tensile strength of the bionic sample with a carbon content of 0.58%, which is even lower than that of the untreated sample.

Figure 11 shows a comparison of the tensile curve of bionic samples with different carbon contents. It can be seen that when the carbon content is between 0.15% and 0.37%, the strength of the biomimetic sample increases, and when the carbon content increases to 0.45%, the tensile strength begins to decline. The elongation of the biomimetic samples decreases continuously with increasing carbon content.

Figure 11. Comparative tensile curves of different bionic samples.

3.3.3. Tensile Fracture Morphology of Samples

Figure 12a–e shows the fracture morphology of untreated samples with different carbon contents. After plastic deformation, dimples and tearing ridges appear in the fracture of the sample. Furthermore, as the carbon content increases, the number of dimples increases, indicating that the strength of the samples also increase.

Figure 12. Fracture surfaces of the untreated samples: (a) A1, (b) A2, (c) A3, (d) A4, and (e) A5.

Figure 13a–e shows the fracture morphologies of the units. It can be seen that the fracture morphologies are different from those of the untreated samples. When the carbon content is between 0.15% and 0.37%, more dimples appear in the fracture of the bionic unit, and the dimples become smaller and deeper. Furthermore, as the carbon content increases, the dimples gradually decrease. For the tensile properties of the specimen, the smaller and deeper the dimple, the more energy required to break the sample. When the carbon content is 0.37%, tearing ridges and cleavage planes appear at

the fracture of the biomimetic unit, indicating that the sample has a brittle fracture tendency. When the carbon content increases to 0.45–0.55%, the sample experiences a brittle fracture, and the fracture morphology has obvious tearing ridges, cleavage step, and a river pattern, further verifying that the tensile properties are inferior.

Figure 13. Fracture surfaces of the units: (a) LR-A1, (b) LR-A2, (c) LR-A3, (d) LR-A4, and (e) LR-A5.

3.4. Wear Properties of Samples

3.4.1. Analysis of Wear Loss

To compare the wear performance of the samples with different carbon content after laser biomimetic treatment, the biomimetic unit with the same volume proportions was processed on the surface of the base metal. The effect of carbon content on the wear properties of the bionic samples was studied. Figure 14 shows the weight loss of the bionic samples and untreated samples with different carbon content. It can be seen that the wear loss weight of the laser biomimetic samples is significantly reduced compared to that of the untreated samples. To compare the antiwear properties of the biomimetic samples, the weight loss reduction percentage [29] (*WLRP*) is defined, as shown in Equation (2):

$$WLRP = \frac{WL_{Untreated} - WL_{treated}}{WL_{Untreated}} \times 100\% \quad (2)$$

where $WL_{Untreated}$ is the wear-loss weight of the untreated sample, and $WL_{Treated}$ is the wear-loss weight of the treated sample.

The *WLRP* order of the laser biomimetic samples with different carbon content is: LR-A1 (31.01%) < LR-A2 (31.72%) < LR-A3 (36.08%) < LR-A4 (48%) < LR-A5 (67.76%). This order is due to the different hardness between the materials leading to differences in wear resistance. When the hardness of the sample is higher, the wear resistance is better, and the wear loss is smaller.

Figure 14. Mass loss of samples.

3.4.2. Analysis of Wear Morphology

Figure 15a–e shows the wear morphology of the untreated samples with different carbon content. It can be seen that a large amount of spalling and deep furrows occurs during the wear process, especially when the carbon content is low. Therefore, the main wear forms of the untreated sample are adhesive wear and abrasive wear.

Figure 15. Wear morphology of the untreated samples: (a) A1, (b) A2, (c) A3, (d) A4, and (e) A5.

Figure 16a–e shows the wear morphology of the laser biomimetic samples with different carbon content. Compared with the wear morphology of the untreated sample, it can be seen in the difference between the unit and the matrix that the unit does not have large peeling or deep furrow phenomena, indicating that the wear resistance of the unit is better than that of the matrix. By comparing the wear morphology of LR-A1–LR-A5, it can be seen that the density and depth of the furrows on the units also gradually reduced, indicating that with an increase of carbon content, the wear resistance of the laser biomimetic samples also gradually improves. This process corresponds to the weight loss and the hardness of the unit.

Figure 16. Wear morphology of the bionic samples: (a) LR-A1, (b) LR-A2, (c) LR-A3, (d) LR-A4, and (e) LR-A5.

4. Conclusions

In this paper, the effects of carbon content on the characteristics, microstructure, hardness, and properties of the bionic unit were studied, and the response of the base material, with different compositions, to laser bionic treatment was obtained. The conclusions are as follows:

1. The unit characteristics (depth and width) are affected by the laser parameters and the parent material's composition. When the laser processing parameters are constant, the unit characteristics increase as the carbon content increases. The order of the unit characteristics is LR-A1 < LR-A2 < LR-A3 < LR-A4 < LR-A5.
2. Under the same laser processing parameters, the microstructure of the remelting zone with different carbon content is the same—composed of martensite. With an increase of carbon content, the content of lath martensite decreases, and the content of plate martensite increases, which increases the hardness of the biomimetic unit.
3. Compared with untreated samples, the tensile strength of the biomimetic sample with the same volume fraction of the unit increases when the carbon content is 0.15–0.45%; when the carbon content is higher than 0.45, the tensile strength is reduced. For laser biomimetic samples, as the carbon content increases, the tensile strength of the biomimetic sample first increases and then decreases, while the plasticity decreases. the degree of improvement in tensile strength is LR-A5 < LR-A4 < LR-A1 < LR-A3 < LR-A2; the degree of plasticity reduction is LR-A1 < LR-A2 < LR-A3 < LR-A4 < LR-A5.
4. Compared to the untreated samples, the wear resistance of the bionic specimens with the same volume fraction of the unit shows better improvement. For the laser biomimetic samples, as the carbon content increases, the wear resistance increases.
5. This study indicates the application feasibility of laser remelting strengthening for different carbon steel parts in manufacturing industry.

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Conflicts of Interest: It is submitted to be considered for publication as an “Original research work” in your journal. This paper is new. Neither the entire paper nor any part of its content has been published or has been accepted elsewhere. It is not being submitted to any other journal. And there is no conflict of interest in this article.

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