The Influence of Welding Speed on the Properties of Dual-Phase Steel Welded Joints

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Abstract

In this study, Nd:YAG laser was used to laser weld DP steel, and the effects of different welding speeds on the microstructure and mechanical properties of the welded joints were explored in detail by means of metallurgical microscope, Rockwell hardness tester and universal tensile tester. The experimental results show that the microstructure after welding can be divided into six zones: Fusion Zone (FZ), Coarse Grain Heat Affected Zone (CGHAZ), Fine Grain Heat Affected Zone (FGHAZ), Intercritical Heat Affected Zone (ICHAZ), Subcritical Heat Affected Zone (SCHAZ), and Base Metal (BM). With the increase of welding speed, the weld width shows a trend of increasing and then decreasing, while the organization of the weld zone is gradually refined. The yield strength and tensile strength of the welded joints also increased firstly and then decreased with the increase of welding speed. In the range of welding speeds from 4 m/min to 5.5 m/min, the tensile strength and elongation at break of the welded joints reached the optimum values of 1277.88 MPa and 1.97%, respectively, when the welding speed was 5 m/min.

Keywords

DP Steel; Laser Welding; Microstructure; Mechanical Properties.

1. Introduction

Under the background of global advocacy of energy saving and emission reduction as well as increasing requirements for automotive performance, the automotive industry is developing rapidly in the direction of lightweighting [1]. Advanced High Strength Steel (AHSS) has attracted much attention in this wave of development due to its excellent performance. Numerous scientific research results have shown that AHSS is effective when applied to automobile manufacturing [2]. The lower density of AHSS compared to conventional steel provides an excellent balance between strength and ductility, resulting in a significant reduction in body weight and hence fuel consumption. In the process of automobile driving, lighter body means lower energy consumption, which is not only in line with the concept of environmental protection, but also improves the overall economy of the automobile, and because of this, AHSS has been widely used in the automobile industry.

In the research field of high-strength steels, dual-phase steels (DP steels) have been the focus of research [3]. From the initial theoretical exploration, to the continuous experimental verification, and then to today's mature applications, DP steel has experienced an in-depth and comprehensive research process. A large amount of detailed data shows that DP steel has always occupied a leading position in the proportion of AHSS used in automobile body structures, and the microstructure of DP steel consists of a ferrite matrix phase and a martensitic phase dispersed therein [4]. Ferrite phase as the matrix of the material, the atomic arrangement is relatively loose, giving the material good plasticity, so that when it is subjected to a certain degree of deformation without fracture; martensite phase is formed in the rapid cooling process of the high-strength phase, which is distributed in the ferrite matrix, to play a reinforcing role, significantly increase the material strength [5]. This unique microstructure allows the DP steel has excellent mechanical properties, it is high strength, when

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subjected to huge external forces can still maintain structural stability; force can be moderately extended to adapt to the complex molding process; molding process is simple, easy to large-scale production; strain hardening rate is high, in the deformation process continues to strengthen itself; perfect balance between the strength and ductility, has a good resistance to collision ability and fracture toughness, welding process It is also more convenient to meet the needs of industrial production in all aspects [6]. Therefore, the use of thin thickness of DP steel in the manufacture of automotive parts, not only to meet the performance requirements of the parts, but also to effectively realize the automobile weight reduction, reduce fuel consumption, for the sustainable development of the automotive industry to provide strong support.

In the preparation process of advanced high-strength components, welding technology is crucial, which directly affects the quality and performance of components. At present, resistance spot welding and laser welding are widely used in this field, of which laser welding has significant advantages. From the mechanism of action, laser welding using high energy density of the laser beam, so that the energy is highly focused on the welding area, instantaneous melting or gasification of the material, the formation of deep fusion welding. This characteristic brings many advantages: welding speed, than the traditional resistance spot welding efficiency significantly increased, meet the needs of industrialized mass production; weld depth and width ratio is large, the heat-affected zone is small, can effectively control the deformation of the workpiece, to ensure the accuracy and stability of the components; through the precise control of the laser parameters and the use of advanced guidance and positioning system, to achieve the complex shape of the components of the precise welding. Moreover, laser welding is highly stable and controllable, and the mechanical properties of the weld are excellent, which is suitable for all kinds of advanced high-strength steels, light alloys and new composite materials, and provides key support for advanced manufacturing technology [7]. At present, scholars have carried out research on laser welding of duplex steel. The current research on laser welding parameters are mainly focused on laser power, welding speed, the amount of defocusing and the type and flow of shielding gas and other key aspects. Laser power directly affects the welding heat input and the formation of the molten pool [8], the welding speed determines the heat input and cooling rate, which in turn affects the microstructure and mechanical properties of the weld [9], the amount of defocus can optimize the energy distribution and weld shape by adjusting the focal point of the laser beam [10], and the shielding gas (e.g., argon or a mixture of gases) is used to prevent oxidation of the molten pool and stabilize the welding process[11]. By systematically studying these parameters on the microstructure and mechanical properties of welded joints, the application of laser welding technology can be further improved to meet different materials and working conditions.

This study uses laser welding technology on the implementation of DP steel welded joints, aimed at in-depth investigation of the laser welding speed on the DP steel weld and the heat affected zone microstructure evolution of each micro-zone, and analyze the mechanical properties of welded joints. Through this study, to provide basic technical support for the practical application of DP steel laser welded structural components, to help improve the level of DP steel in the field of welded structural components.

2. Experimental Materials and Methods

2.1 Experimental Materials

The steel plate used in the experiment was 1.2 mm commercial DP high strength steel provided by an automotive steel institute, and the chemical composition of the test steel is shown in Table 1.

Table 1. Chemical composition of test steel

Elemental	C	Si	Mn	P	S	Al	N	Nb
Content (%)	0.22	0.60	2.42	0.006	0.003	0.033	0.004	0.03

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2.2 Laser Welding Experiment

The welding equipment used was a TruDisk5001 Nd:YAG laser manufactured by Trumpf, Germany. For butt welding, the welding direction was perpendicular to the direction of steel plate rolling, and the laser beam was directed vertically into the surface of the specimen. The maximum power of the laser was 5000 W. Pure argon was used as the protective gas, and the gas flow rate was 20 L/min. When the laser power was 2 kW and the amount of defocus was -3 mm, the welding speeds selected were 4 m/min, 4.5 min, 5 m/min, and 5.5 m/min. 240-mesh and 400-mesh abrasive paper was used to sand the surface of the steel plate to be welded and its surrounding Before welding, use 240 mesh and 400 mesh sandpaper to sand the surface of the steel plate to be welded and the area around it, and then rinse the surface with anhydrous ethanol to remove impurities and oil.

2.3 Performance Characterization Tests

The metallographic specimens were set, polished, and etched with 4.0% volume alcohol nitrate solution for 6 s. The macroscopic morphology was observed with Leica's DMI8A inverted optical microscope (OM), and the micro-hardness of the joints was tested with Shanghai Aolong Xindi's HVS-1000Z digital microscopic Vickers hardness tester. The microhardness of the joints was tested by HVS-1000Z digital micro Vickers hardness tester of Shanghai Aolong Xindi Company, the loading load was 5N, the holding time was 15s, the spacing of adjacent hardness points was 100μm, and 3 specimens were intercepted under each parameter for the tensile performance test, and the final results were taken as the average of the 3 specimens. The tensile test was carried out using UTM4304 material tensile testing machine (Shenzhen Sansi Zongheng Technology Co., Ltd.) with a tensile speed of 0.5 mm/min.

3. Experimental Results and Analysis

3.1 Microstructure Analysis

Fig. 1 shows the OM diagram of the weld seam of DP steel welded with welding power of 2 kW, out-of-focus amount of -3 mm, passing argon gas of 20 L/min, and changing the welding speed. From the figure, it is observed that there is a clearly recognizable boundary line in the transition region between the weld and the base metal. The morphology of the weld seam is relatively regular, the width of the top and bottom remains consistent, and the whole is in the shape of a straight cylinder. With the help of the metallographic diagram, it can be found that there is a close correlation between the width of the weld zone and the welding speed, and with the gradual increase of the welding speed, the width of the weld zone shows a tendency of increasing and then decreasing. Specifically, when the welding power is set to 5.5 m/min, due to the laser welding speed is relatively fast at this time, the laser beam energy transmitted through the small hole is low, resulting in less heat input to the material, which produces a narrower molten pool, and ultimately make the weld width to reach the minimum value. When the welding speed is slowed down to 5 m/min, the weld width reaches its maximum value. As the welding speed slows down, the weld width first becomes wider and then narrower. With the gradual increase in welding speed, the length of time that the laser acts on the material per unit of time is significantly reduced. From the point of view of energy transfer, the heat input decreases sharply, and the material absorbs insufficient heat to maintain a good weld response. The weld high temperature reaction time is greatly reduced, the atomic activity is reduced, the atomic diffusion coefficient becomes smaller, and the weld tissue diffusion is inhibited. Upon inspection, the width of the weld zone becomes narrower, the strength and sealing decreases, the degree of softening in the softening zone decreases, the flexibility and plasticity of the weldment deteriorates, and it is more likely to be brittle and cracked in the subsequent processing or in use, which seriously affects the quality of the weld and its service life [12].

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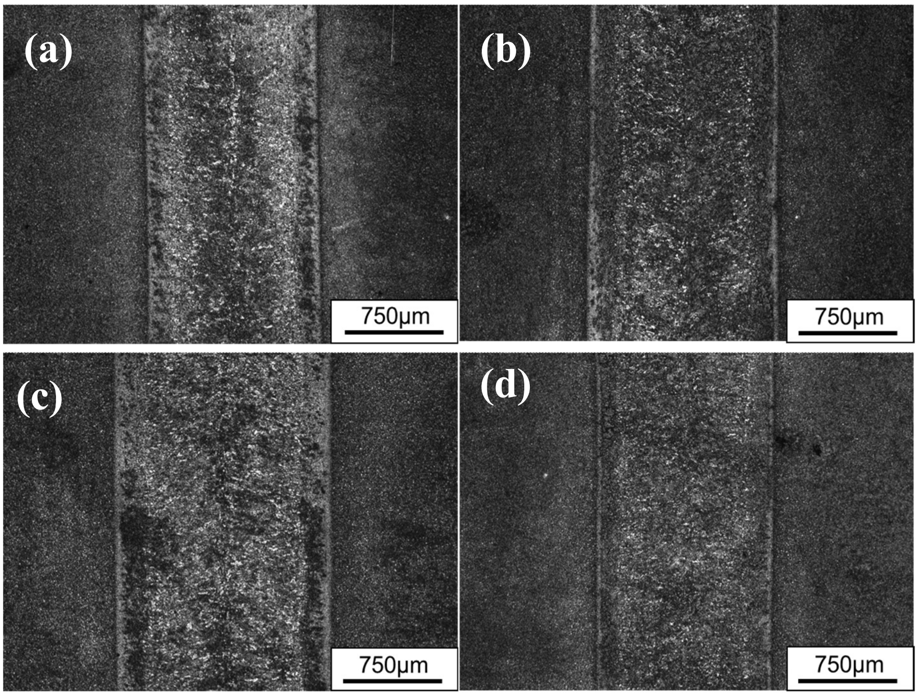

Figure 1. OM images of DP1500 steel welded at (a)4m/min; (b)4.5m/min; (c) 5m/min; (d)5.5m/min;

During the laser welding process, the distance between the various regions of the welded joint and the center of the welding heat source varies. As a result, under the scanning electron microscope, each region presents a different organization and morphology. As shown in Figure 2, the microstructural changes of DP steel joints after welding are analyzed with 2kW power, 5m/min speed, -3mm out of focus, and 20L/min of argon gas. The organization of welded joints is usually divided into six different regions, namely, Fusion Zone (FZ), Coarse Grain Heat Affected Zone (CGHAZ), Fine Grain Heat Affected Zone (FGHAZ), Intercritical Heat Affected Zone (ICHAZ), Subcritical Heat Affected Zone (SCHAZ), and Base Metal (BM) [13]-[14]. In Figure 2, the organization characteristics and formation process of each region are as follows: Figure 2 (a) shows the FZ, whose organization composition is mainly martensite. During the welding process, the DP steel tissue is melted by heat and transformed into austenite, which is subsequently transformed into coarse and regularly arranged martensite under rapid cooling conditions. Figure 2 (b) shows the CGHAZ. At the time of welding, the temperature of this region is slightly lower than that of the weld zone. During the heating stage, the austenite grains in the coarse crystalline zone begin to grow, and after rapid cooling, they are transformed into a coarse martensitic organization. Figure 2(c) presents the FGHAZ, where the martensite morphology of the slat is relatively small. The temperature of the fine-crystalline zone is lower than that of the coarse-crystalline zone during welding, and its cooling rate is faster than that of the coarse-crystalline zone during cooling. After completing austenitization, the fine grain zone is able to cool down at a faster cooling rate, which in turn results in the formation of a relatively finer organization [15]. Figure 2 (d) shows the ICHAZ, which has a ferrite structure at temperatures between Ac1 and Ac3. Upon cooling of the newly formed austenite, martensite, lath martensite, and massive ferrite are formed. Figure 2(e) shows the SCHAZ, where the temperature rises to the temperature range of tempered martensite during welding, but remains below the Ac1 temperature. In this zone, tempered martensite grains, ferrite, and a small amount of residual austenite can be observed. Figure 2(f) shows the BM, consisting of dark ferrite grains and gray islands of martensite.

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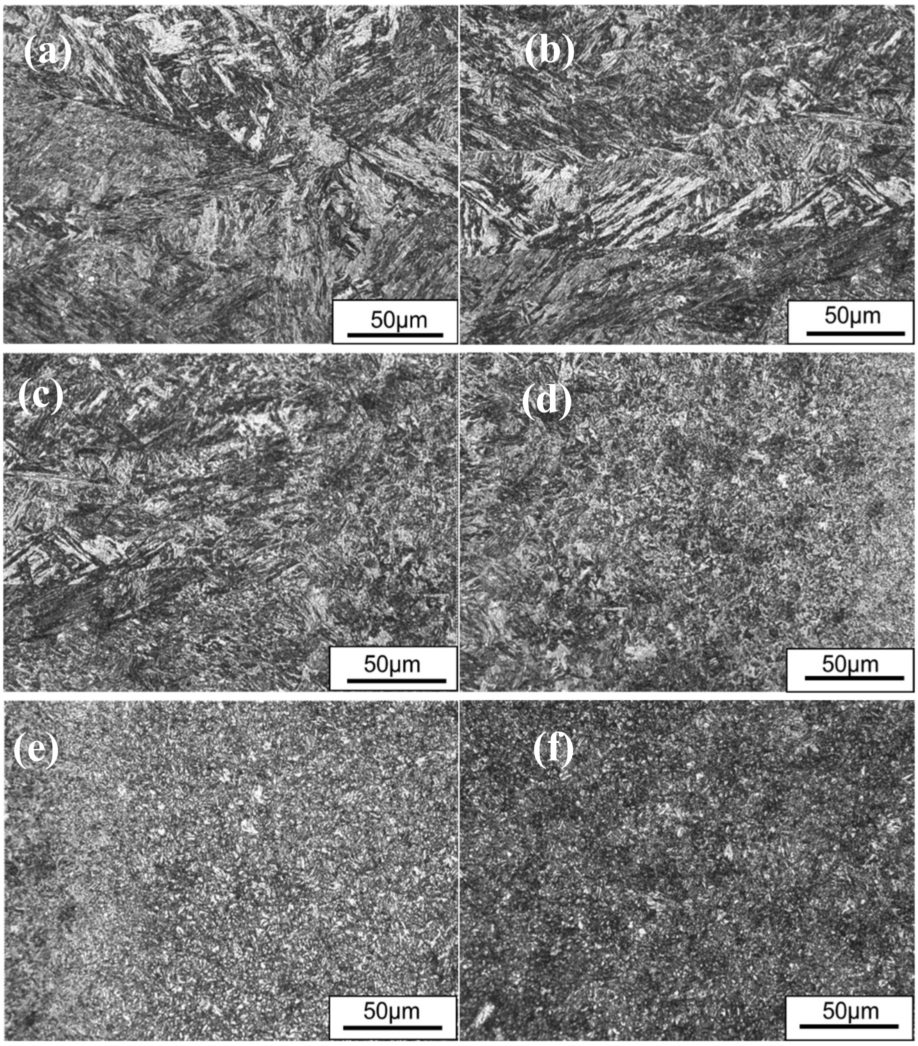

Figure 2. Microstructures of the welded joints of DPsteel welded at a power of 2 kW, a speed of 5 m/min, a defocusing amount of -3 mm and an argon flow rate of 20 L/min.

3.2 Mechanical Properties Analysis

Figure 3(a) visualizes the dynamic changes of the mechanical properties of DP steel under different welding speeds, and the corresponding mechanical property data are recorded in Table 2. Through the in-depth analysis of these precise experimental data, it can be clearly found that, with the gradual increase of the welding speed, the mechanical properties of the DP steel show a typical trend of increasing and then decreasing. Especially noteworthy is that when the welding speed is set to 4.5m/min, the phenomenon of DP steel not welded through occurs, and this anomaly provides a key warning for the optimization of the welding process. Meanwhile, Fig. 3(b) also clearly shows the variation curves of microhardness of DP steel under different welding speeds. The trend of microhardness is nearly the same as that of the mechanical properties of the material, which shows an increasing and then decreasing trend with the continuous increase of the welding speed.The research results of Wang et al. in the related field show that the degree of softening increases significantly as the width of the softening zone becomes wider and wider. Moreover, with the gradual increase of heat input, the tensile strength, yield strength, and elongation of welded joints will be the first to show an increasing trend. However, when the softening zone size exceeds a certain limit value, the mechanical properties will inevitably decrease. The conclusion of this study is highly consistent with the results obtained in this experiment [16]. From the microhardness map, we can observe more intuitively that the hardness of the weld zone is at the highest level in the whole region due to the very high martensite content and coarse morphology of the weld zone. In the softening zone, there is a clear valley of hardness values. This is mainly due to the fact that the volume fraction of martensite

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in the soft zone is lower compared to the weld zone and the base metal, and the carbon content is also lower, which results in the lowest hardness value due to a combination of factors [17].

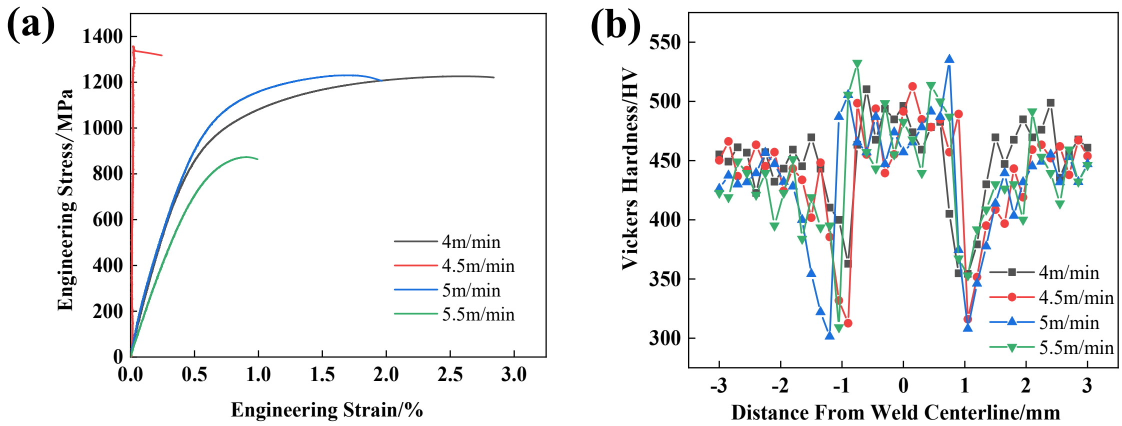

Figure 3. (a) Engineering Stress-Strain Curves (b) Microhardness distribution of the welded joints of DP steel welded with different speeds;

Table 2. Comparison of mechanical properties of DP steels at different welding speeds

Welding Speed /m·min^{-1}	Tensile Strength / MPa	Yield Strength / MPa	Uniform Elongation / %	Rupture Elongation / %	Strong Plastic Product / GPa%
4	1227.50	910.72	2.57	2.84	3.49
4.5	1356.96	1356.96	0.02	0.25	0.34
5	1277.88	1198.05	1.69	1.97	2.52
5.5	876.06	831.49	0.89	0.99	0.86

4. Discussion

As an advanced joining technology, laser welding shows excellent application efficiency in the field of metal material welding and is widely used in the welding process of various metal materials. In the laser welding process of DP steel, the welding speed becomes one of the key process parameters affecting the quality of welded joints, which has an important influence on the microstructure and mechanical properties of welded joints. In terms of weld width, there is a complex nonlinear relationship between welding speed and weld zone melt pool size. With the gradual increase of welding speed, the weld zone molten pool size shows a trend of increasing and then decreasing. When the welding speed is set to 5.5m/min, due to the limited energy input per unit time, the heat absorbed by the material can only maintain a small amount of tissue melting, which leads to a narrower melt pool size. When the welding speed is reduced to 5m/min, the heat gained by the material per unit time increases, a large number of tissues melt, and at the same time, the reaction time of the weld zone is prolonged in the high temperature environment, which promotes the diffusion process of atoms, resulting in an increase in the width of the weld zone. However, too slow a welding speed can also bring a series of negative effects. When the welding speed is below a certain threshold, the weld heat-affected zone expands dramatically and the softening of the softened zone increases significantly. This change in microstructure can lead to an increase in the unevenness of the joint hardness and strength distribution, which seriously affects the comprehensive mechanical properties of the joint. In practical engineering applications, the non-uniform hardness and strength distribution may lead to stress concentration phenomenon when the joint is subjected to load, reducing the fatigue life and load carrying capacity of the joint, thus affecting the reliability and stability of the welded structure. Therefore, in the process of optimizing the laser welding process of DP steel, the influence of welding speed on weld width, heat-affected zone and mechanical properties of the joint must be considered comprehensively in order to achieve high-quality welded joints.

From the microstructure point of view, DP steel welded joints can be clearly divided into 6 different zones, which are Fusion Zone (FZ), Coarse Grain Heat Affected Zone (CGHAZ), Fine Grain Heat Affected Zone (FGHAZ), Intercritical Heat Affected Zone (ICHAZ), Subcritical Heat Affected Zone(SCHAZ), and Base Metal (BM).Among these 6 zones, Fusion Zone, Coarse Grain Heat Affected Zone, Fine Grain Heat Affected Zone is martensite. Among them, the martensite organization in the Fusion Zone shows a coarse lath-like morphology. The Intercritical Heat Affected Zone, on the other hand, is composed of martensite and ferrite together, and the Subcritical Heat Affected Zone is mainly composed of tempered martensite and ferrite. Due to the influence of temperature distribution in the welding process, when the organization transitions from the Fusion Zone to the base metal zone, its size shows a gradually decreasing trend of change. In addition, when the welding speed is gradually reduced, the cooling time is prolonged accordingly, which results in a more homogeneous composition distribution. In this case, the original coarse martensite organization in the Fusion Zone will gradually become fine, and its distribution will be more regular.

In terms of mechanical properties, the appropriate welding speed can obtain good strength of welded joints. When the welding speed is 5m/min, the welded joint has uniform organization, tensile strength of 1277.88MPa, yield strength of 1198.05MPa, uniform elongation of 1.69%, and fracture elongation of 1.97%, which is able to withstand large tensile loads. Once the speed is too fast, there will be defects such as unwelded through, and these defects will weaken the strength of the joint, when the welding speed is 5.5m/min, the tensile strength is 876.06MPa, the yield strength is 831.49MPa, the uniform elongation is 0.89%, and the elongation at break is 0.99%, and the mechanical properties of the joint are poor. And when the speed is too slow, the degree of softening in the softening zone rises, and the strength of the joint decreases as well. When the welding speed is reduced to 4m/min, the tensile strength is 1227.50MPa, the yield strength is 910.72MPa, and the mechanical properties decrease. The trend of material microhardness change is the same as the trend of mechanical properties change, both rise first and then fall.

In the laser welding of DP steels, precise control of the welding speed is essential. It is necessary to consider the melt pool, microstructure, mechanical properties and other factors, through the continuous optimization of welding speed parameters, in order to obtain high-quality welded joints.

5. Conclusion

(1) The overall DP steel weld is in the shape of a straight cylinder, and the weld zone becomes wider and then narrower as the welding speed increases while keeping the welding power, the amount of defocusing and the flow rate of shielding gas unchanged.

(2) After laser welding, the joint organization can be divided into six regions. They are Fusion Zone (FZ), Coarse Grain Heat Affected Zone (CGHAZ), Fine Grain Heat Affected Zone (FGHAZ), Intercritical Heat Affected Zone (ICHAZ), Subcritical Heat Affected Zone (SCHAZ), and Base Metal (BM). Among them, the Fusion Zone consists of coarse slate martensite.

(3) 4m/min ~ 5.5m/min welding speed range, with higher welding power, the mechanical properties of the material first rise and then fall. When welding at a speed of 4m/min, the tensile strength of the material is 1227.50Mpa and the elongation at break is 2.84%. When the welding speed is 4.5m/min, the material is not welded through and the elongation at break is only 0.25%. Continuing to increase the welding speed to 5.5m/min, the tensile strength of the material decreases to 876.06Mpa and the elongation at break decreases to 0.99%.

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