Abstract

For energy saving more and more high performance materials are to be applied. Welding of high performance materials or cladding of high wear resistance materials are critical research points for their wide application. In the paper laser welding of a 1000MPa complex phase steel and a novel TiB₂ reinforced aluminum metal matrix composite were investigated, where the weld formation, microstructure and mechanical properties of welded joints were discussed. Further a laser clad wear-resistant coating with a new designed Fe-based powder was introduced in term of microstructure and wear resistance.

1. Introduction

In order to reduce fuel consumption and release of CO₂ gas for protecting the environment more and more high performance materials have been developed and applied. High performance materials could be the materials that have ultra high strength, high specific strength, or high specific stiffness, such as composite materials, ultra high strength steels, titanium alloys, magnesium alloys, high wear-resistance coatings, etc. For the application of many such materials in manufacturing their weldability should be considered. Currently laser has been a widely used heat source for welding and cladding. In this paper research of laser welding of two high performance materials and one laser clad high performance coatings is reported. For welding and cladding experiments a CO₂ Laser source (TRUMPF TLF15000T) with a maximum output power of 15 kW and beam focus diameter of 0.86 mm was employed.

2. Laser welding of a 1000 MPa complex phase steel

The rapidly increased output of the world's automobile has led to serious environment problem such as exhaust emissions. The fuel consumption and automobile emissions are proportional to the automobile weight. In order to reduce the weight without losing vehicle safety, to apply advanced high-strength steels (AHSS) in the car body is an
efficient way [1]. High-strength complex phase (CP) steel as one of AHSS has been developed with high strength and sufficient ductility resulted from low alloying and controlled cooling. For developed 1000MPa grade CP steel a variety of alloying elements with certain content are added, which could influence the weldability. Welding research on CP steels focused on resistance spot welding and arc welding [2,3]. Laser welding has been widely used in automobile industry because of its great advantages: high welding speed, high weld quality, narrow heat affected zone (HAZ) and very low distortion. Due to the special thermal cycle characteristic of laser welding, it is necessary to investigate the laser welding of this 1000MPa CP steel.

2.1. Base material and laser welding condition

The chemical composition of the 1000MPa CP steel with a sheet thickness of 3 mm is listed in the table 1. The microstructure of the CP steel consists of very fine ferrite, a higher volume fraction of martensite and bainite, and some austenite. The grain size is about 4 ~ 8μm. Its yield strength, tensile strength and elongation are 730MPa, 1020MPa and 13% respectively. For welding pure helium gas was used as side-blowing gas, and no filler wire was added.

Table 1. Chemical composition (mass%) of 1000MPa CP steel

<table>
<thead>
<tr>
<th>composition</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cr</th>
<th>Mo</th>
<th>Ti</th>
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<tbody>
<tr>
<td>content</td>
<td>0.17</td>
<td>0.29</td>
<td>1.74</td>
<td>0.018</td>
<td>0.0043</td>
<td>0.1~0.3</td>
<td>0.1~0.3</td>
<td>&lt;0.1</td>
</tr>
</tbody>
</table>

With a laser power of 13kW and a welding speed of 5m/min the 1000MPa CP steel sheet was successfully autogenous laser welded in full penetration. No weld defects such as pores and cracks were found. In the Fig. 1 the joint cross section is shown. From the Fig.1a it can be seen that the weld seam is quite narrow, whose upper width is around 2mm. The width of the heat affected zone (HAZ) is less than 0.8mm. The HAZ, which lies between the base metal (BM) and weld metal (WM), consists of coarse grained (CG) region, fine grained (FG) region and incomplete recrystallization (IR) region, see Fig. 1b.

Fig. 1. Macro cross section of laser welded joint (13kW laser power and 5m/min welding speed)

2.2. Microstructure of welded joint

In Fig. 2 the scanning electron microscope (SEM) presents the microstructure of the coarse grained HAZ (CGHAZ, the most critical region in HAZ) and the weld metal center. The left side of the bond line in Fig.2a is the CGHAZ, whose microstructure is almost the lath martensite (LM), and grain size about 12 ~ 18μm. The right side of the bond line is the weld metal, whose microstructure is acicular martensite (AM). In the weld center (Fig. 2b) the lath martensite is mainly to be observed. Further TEM analysis has indicated that there was retained austenite in the weld metal.
2.3. Mechanical property of welded joint

The microstructure of the weld indicates a possible higher strength than the base metal. To evaluate the mechanical property hardness test of the weld joint, tensile test of welded joint as well as of weld seam, and transverse bending test were done.

The hardness test with a test load of 500g showed that the highest hardness occurred in the weld seam with a value more than 400HV. From HAZ to the base metal the hardness fell from 400HV to about 300HV. The tensile test results (Fig. 3) showed that the welded joint had tensile property similar to the base metal; its 11% elongation was somewhat lower than the BM (13%). All specimens of weld joints broke in base metal. Furthermore the direct tension of weld seam in its longitudinal direction showed 1000MPa yield strength and 1300MPa tensile strength, much higher than the BM, but a relative low elongation of 8.5%. The weld joint could be bent transversely till 180°, but no obvious deformation occurred in the weld area.

Too high hardness would bring negative influence on the service performance of welded joints. Therefore, it tried using a following TIG arc during the welding to reduce the hardness of weld seam. Fig. 4 describes the hardness profiles of welded joints under different arc current value. It could be found that the hardness in weld seam center dropped from about 440HV to 350 HV when the arc current increased from 0 to 75A. The hardness in HAZ near the bond line was in most case still as high as about 400HV.

Fig. 3a) Tensile property of base metal, welded joint and weld seam
3. Laser welding of an in situ TiB$_2$ reinforced aluminum metal matrix composite

In situ particulate reinforced aluminum metal matrix composites (MMCs) are taken as promising materials due to their many advantages, such as well wetting with Al matrix, cleaner particulate/matrix interface, and no pollution in application [4,5]. TiB$_2$ particulate reinforced Al matrix composites (TiB$_2$/Al MMCs) can have great application potential for high-temperature resistance, wear resistance and high damping property. A sum of research work was done on fusion welding of Al MMCs [6-9]. To promote its application laser welding of this new functional and structural material was investigated. In consideration of problems such as pores, poor weld formation and degradation of reinforcement that often occur at the fusion welding of Al MMCs it, in this part the weld porosity and microstructure as well as mechanical property were discussed.

3.1. Experimental material

The in situ TiB$_2$ reinforced aluminum metal matrix composite, marked as TiB$_2$/ZL101, is reinforced by 13 % mass fraction of TiB$_2$ particles. The compositions of ZL101 are listed in Table 2. In the ZL101 alloy the TiB$_2$ particles are distributed uniformly, whose size lies in the nanoscale, and they have a clean interface with Al matrix. Bead-on-plate welding was performed on welding pieces with the plate thickness of 6mm.

Table 2. Chemical composition of ZL101 (mass %)

<table>
<thead>
<tr>
<th>compositions</th>
<th>Si</th>
<th>Mg</th>
<th>Zr</th>
<th>Fe</th>
<th>Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>content</td>
<td>6.67</td>
<td>0.45</td>
<td>0.42</td>
<td>0.14</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

3.2. Effect of process parameters on porosity

At the welding of aluminum alloys the porosity in weld is more related to protection and remaining time of weld pool. At the autogenous CO$_2$ laser welding with side-blowing gas it has two gas blowing directions to choose: the gas blowing direction against or same as welding direction. Fig. 4a and Fig. 4b show the weld cross sections under these two different gas blowing directions, where the welding speed was 3m/min and the laser power was around 8.5kW. It is obvious to see that under the gas blowing direction same as welding direction no big pores are found in weld, which means that in this blowing direction the gas protection on weld pool was achieved. The existing of two small pores in the weld root indicates an insufficient degassing in weld pool during welding. To increase the remaining time of weld pool, i.e. the degassing time for pores, the welding speed could be reduced. Fig. 4c shows a pore-free weld cross section which was welded at the traveling speed of 2m/min and the same gas blowing direction as Fig. 4b.
3.3. Microstructure and tensile property of welded joint

The microstructure of the weld seam in cross section was observed under SEM. Fig. 5 presents the microstructure of weld seam of the joint shown in Fig. 4c and that of base metal. Distributed in the aluminum matrix (in dark color) are TiB$_2$ particles in cluster form (in grey). Through comparison it could be found that TiB$_2$ clusters were dispersive and uniform after laser welding, and became smaller.

In Table 3 the results of tensile test on welded joint and base metal are listed. The welded joint has similar strength and elongation to base metal, whose tensile specimens broke in base metal side.

Table 3. Tensile property of welded joint and base metal

<table>
<thead>
<tr>
<th>Samples</th>
<th>Rm (MPa)</th>
<th>Rp$_{0.2}$ (MPa)</th>
<th>A (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base metal</td>
<td>202</td>
<td>130</td>
<td>2.6</td>
</tr>
<tr>
<td>Welded joint</td>
<td>205</td>
<td>126</td>
<td>2.1</td>
</tr>
</tbody>
</table>

4. Laser clad wear-resistant coating with new designed Fe-based powder

Laser cladding is an advanced technology which deposits protective coatings against wear and/or corrosion on mechanical parts with low heat input. Since the end of the last century laser cladding technology has been brought into a huge amount of consideration, and was applied for rebuilding and coating of different parts such as worn turbine vanes, tools, molds, the tip of the turbine blades, and turbine bolts [11-15]. Laser cladding offers many advantages over conventional coating processes, such as minimal dilution, minimal distortion, and better surface quality. However, the biggest problem in laser cladding is cracking susceptibility of clad alloy layer with high hardness [16-17]. Crack-free coatings of cobalt or nickel based hard alloys on steel substrates is difficult to obtain if
their hardness is greater than 50HRC (509HV) [18]. Two kinds of crack will occur in cladding layer: solidification crack and cold crack. Solidification cracking may be caused due to the liqation of low melting components. Cold cracks originate from residual stress induced during laser cladding. Although the reduction of temperature gradients by pre- or post-weld heating can help to avoid cracks, these methods cost rapid solidification of laser processing. So, it is necessary to design a new microstructure to avoid solidification crack and cold crack.

In this work, a Fe-based alloy coating with retained austenite distributed along interdendrite was introduced, which was deposited on a middle carbon steel substrate by means of laser cladding with a new designed powder.

4.1. Experimental condition

The composition of the powder used in the laser cladding is listed in Table 4. A main feature of the powder is that the carbon content is reduced to 0.85%. A small amount of CeO was added in order to refine the structure. The substrate material is a medium carbon steel with 0.45% C content (AISI 1045) and with dimensions of 250mm×200mm×10mm. Cladding was carried out by the use of the CO₂ laser at a power of 7500W. The cladding speed is 700mm/min, the powder feed rate around 22g/min, and Argon flow rate 10L/min. The laser cladding passes were overlapped by 40 percent in the width. Argon acted as powder delivering gas and weld shielding gas.

The coating’s microstructure was analyzed by optical microscopy, scanning electron microscopy, and X-ray diffraction (XRD Cu Kα radiation). Microhardness tests were done on the clad cross-section from the clad surface to the substrate. Its wear resistance property was tested with a MM-200 type wear tester using a block-on-ring arrangement in emulsified cutting fluid. The dimensions of the block specimens were 7mm×7mm×30mm. Friction load on the specimens was 200N and 300N, about 4MPa and 6MPa per mm² respectively. The sliding speed was 2.7m/s, and friction time is 1 hour. The cold roller steel 9Cr2Mo was selected for comparison of wear resistance.

| Chemical composition (wt, %) of the cladding powder |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| C               | Cr              | Ni              | Mo              | W               | V+Ti           | Si              | B               | CeO             |
| 0.85            | 6.5             | 1.5             | 2.0             | 1.5             | 0.8–1.0        | 0.5             | 0.45            | 0.3             |

4.2. Microstructure of the coating

Fig. 6 shows the cross-section image and the microstructure of laser clad coating. As shown in Fig. 1 (a), the cladding layer is free of cracks and has a good metallurgical bonding to the base metal. The thickness of the coating is about 1.1mm. During laser cladding the solidification in coating proceeded epitaxially from the melted substrate on. The structure of the coating exhibits typical dendrite shape. Fig.1(b) shows the SEM morphology of the microstructure in the coating center, which consists of martensite, retained austenite and carbide particles. Martensite, austenite, and (Cr,Fe)₃C carbide were identified by X-ray diffraction analysis taken from the cross-sections of the cladding layer, as shown in Fig.1(c).

![Fig. 6. Microstructures of laser clad coating and XRD pattern](image-url)

(a) Optical micrograph of the coating; (b) SEM micrograph taken from the center of the coating
4.3. Microhardness and wear resistance of the coating

Fig. 7 (a) shows the measured hardness distribution across the coating under the load of 1kg. The coating has a uniform hardness distribution in the direction of thickness. The average hardness is 895HV.

Under the same wear time 1 hour, the wear weight loss of the coating was 0.010g under load 200N and 0.83g under load 300N, and that of 9Cr2Mo steel was 0.024g and 0.26g respectively. The comparison in Fig. 7 (b) shows obviously that the wear resistance of the coating is at least two times of 9Cr2Mo steel; at higher wear load it is even better. By SEM observation of the worn surfaces tested under 300N load, furrow marks and some block peeling off were found on both materials, but on the coating surface the furrow marks were light. Further fatigue damage was found on 9Cr2Mo steel surface.

5. Conclusion

1) The 1000MPa grade complex phase steel is welded by a CO₂ laser with a sufficient weld quality. Microstructure of the coarse grained HAZ and the weld metal mainly consists of a great deal of lath martensite. The welded CP steel joint has the strength as high as base metal. The mechanical property of weld seam is in good correspondence with its martensitic microstructure, its tensile strength reaches 1300MPa.

2) The new in situ TiB₂ particulate reinforced ZL101 aluminum matrix composite was successfully welded with high power CO₂ laser. Full-penetration welds with minimum defects were obtained at low welding speed (2m/min) and when gas blowing direction same as welding direction. The distribution of TiB₂ particles in weld metal is more uniform than in the base metal. The strength and elongation of the welded joint is similar to base metal. The tensile specimens broke in base metal side, which indicates a higher strength of the weld seam.

3) The phases in the coating clad with a new Fe-based powder consist of martensite, retained austenite and carbide.
particles. Hardness of the coating is 895HV in average and has a uniform profile across the section. Under high sliding speed and high load (200N and 300N), the wear resistance of the coating was at least one times higher than 9Cr2Mo cold roller steel.

References