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Investigation of mechanical and metallurgical properties of titanium alloys by using laser and GTA welding

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Abstract

Titanium alloys are widely used in many fields such as the automotive, aerospace and chemical industries. In some applications, titanium alloys are needed for use with particular welding methods. These are GTAW, GMAW and laser welding. In this study, Titanium Grade-2 (Cp-Ti) plates were welded using laser welding and GTAW. Tensile and flexural tests were applied to the welded samples. The microstructure and SEM images of main material and welded regions were studied and microhardness measurements were performed. Tensile and flexural strengths of laser welded samples were higher than those of GTA welded samples. The microhardness values of the weld-zone of laser welded samples were lower than those of the GTA welded samples welding zone. In microstructure and SEM investigations, the oxide structures and splashes of molten metal appearing like drops were identified. The width of the weld-zone in laser welding was in a narrow range.

Key words: Ti alloys, laser welding, mechanical properties, gas tungsten arc (GTA) welding

1. Introduction

Titanium has become an attractive material because of its low density and higher mechanical properties/density ratio. Because of its high strength and high corrosion resistance, titanium has become the preferred engineering material in recent years. However, because of its lower wear resistance it cannot be preferred in engineering applications which include friction and wear [1–5]. Titanium-based materials gain preference by their low density, high strength, high corrosion resistance and high fracture strength. They are also preferred in the aircraft and aerospace industry, chemical industry, medicine, marine, automotive industry, and the biomedical industry [6, 7]. All traditional machining processes are applicable to these materials, but because of their particular properties these materials have some difficulties in machining processes. Because of its high corrosion resistance, titanium and its alloys are widely used in dental implants, chemical industry apparatus, oil industry pipes, shipbuilding, fasteners and exhaust systems in the automotive industry, jet engines in aircraft, and in the aerospace industry and construction industries.

Although titanium and alloys have the feature of high corrosion resistance at low temperatures, it is undesirable to weld them in atmospheric air as they have an increasing tendency to react with oxygene, hydrogen, carbon and nitrogen [2, 8, 9]. Titanium is chemically reactive at high temperatures. While welding, titanium alloys pick up oxygen and nitrogen from the atmosphere. Choi and Choi investigated the effect of GTA welding condition according to mechanical properties of pure titanium and they reported that if oxygen or nitrogen in the air infiltrates into the welding metal zone (WMZ), the hardness of the titanium welding will increase. Therefore, the welding of titanium requires complete gas shielding [2].

The welding processes recommended for use when welding titanium and its alloys are: tungsten inert gas (GTA) welding, metallic inert gas (MIG) welding, diffusion welding, (both spot and seam) electron beam welding, friction stir welding and laser welding [5, 10]. Before the welding of titanium and its alloys, it is ne-

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cessary to clean the oxide layer of the surface, and the welding zone must be prevented from making contact with atmospheric air. In titanium constructions, the material properties, weldability and mechanical behavior of the different welding methods must be evident.

Some research about welding of titanium alloys has been carried out. Akman et al. used pulsed Nd-YAG laser welding technique to join 3-mm thick Ti6Al4V plane sheets. They determined that the ratio between the pulse energy and pulse duration was the most important parameter in defining the penetration depth [7]. Kahraman et al. investigated the effect of welding current on the plasma arc welding of pure titanium [11]. Yunlian et al. investigated the mechanical properties of laser-beam welding and gas tungsten arc welding of titanium sheets and found that microhardness values of the welding zone of GTA welded titanium specimens are higher than laser welded specimens [9]. Kahraman et al. reported that the increasing welding current increased the hardness of weld metal and heat affected zone (HAZ). This increase was attributed to oxygen concentration in the weld [11]. Li et al. found that the hardness of the weld metal of Fiber Laser GMA hybrid welding of commercially pure titanium is higher than the hardness of the heat affected zone and the hardness of the base metal part, and he stated that it was related to the oxygene contact during the welding [1]. Akbarimousavi and GohariKia investigated the mechanical properties and microstructure of dissimilar cp-titanium and AISI 316L austenitic stainless steel continuous friction welds, and they reported that if oxides on the material were not cleaned before welding, these oxides penetrated into the welding zone and it caused a reduction in the strength of the joint [6].

In this study, 2.5 mm thick commercially pure titanium sheets (Cp-Ti) were welded by laser welding and TIG welding methods. The mechanical properties of the titanium sheets which were welded by different welding methods were investigated.

2. Experimental study

$1000 \times 450 \times 2.5\,\mathrm{mm}^3$ sized Titanium Grade 2 sheet which is referred to material in the studies $250 \times 450 \times 2.5\ \mathrm{mm}^3$ sized piece, which is going to be used in laser welding $125 \times 450 \times 2.5\,\mathrm{mm}^3$ sized pieces, which are to be used in GTA welding $125 \times 450 \times 2.5\,\mathrm{mm}^3$, and two pieces were cut with a wire erosion cutting machine. The chemical composition of the titanium sheet (Grade-2) is shown in Table 1.

The sheets which were used in the laser welding were cut sharply with a wire erosion cutting machine suitable for DIN EN ISO 4136 (2011-05) as tensile and bending samples. The material surfaces were cleaned with an acetone and then fixed. The parameters shown in Table 2 with the pulsed Nd: YAG laser butt-welding without the welding wire were used.

Two plates of $125 \times 450 \times 2.5\,\mathrm{mm}^3$ in size were welded with GTA butt-welding. The titanium plates were welded by using a ERTi-2 filler rod as one pass, but the double surface was welded with GTA welding as is stated in AWS A5.16-70. The GTA welding parameters are shown in Table 3.

All tensile tests were carried out by using Shimadzu AG-IS (100 kN) tensile testing device and extensometer. Experiments were conducted at room temperature and $1\,\mathrm{mm\,min}^{-1}$ pulling speed. The bending tests of the samples were done by using a Shimadzu AG-IS 100 kN device, according to support distances of BS EN ISO 5173. The bending speed of the machine was $1\,\mathrm{mm\,min}^{-1}$. Vickers micro-hardness measurements of the samples were done by using 300 g force for 10 s in 500 μm distance between the welding zone and main material.

Microscophic studies were done by using Nikon stereo microscope. Samples were sanded with 220, 400, 600, 800, 1000 and 1200 grid SiC abrasives. Then they were polished with 3 μ diamond paste. They were etched by using 50 ml H_2O, 40 ml HNO_3 and 10 ml HF solution for 15 s.

Table 1. Titanium Grade-2 chemical composition (wt.%)

Element	Fe	C	N	O	H	Ti
	0.15	0.02	0.02	0.13	0.02	Bal.

Table 2. Laser welding parameters

Pulse duration	5 ms
Pulse repetition rate	30 Hz
Pulse energy	9 J
Peak power	1.8 kW
Average power	270 W
Focal location	focused on 1 mm below the surface of the material
Speed	$4\,\mathrm{mm\,s}^{-1}$
Shielding gas	argon

Table 3. GTA welding parameters

Polarization	DC (+)
Voltage	220 V
Current	80 A
Filler rod	ERTi-2
Shielding gas	argon

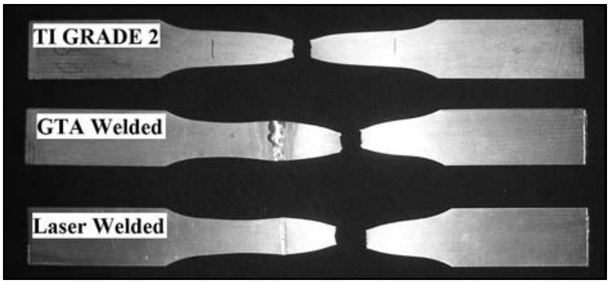

Fig. 1. Views of specimens after the tensile tests.

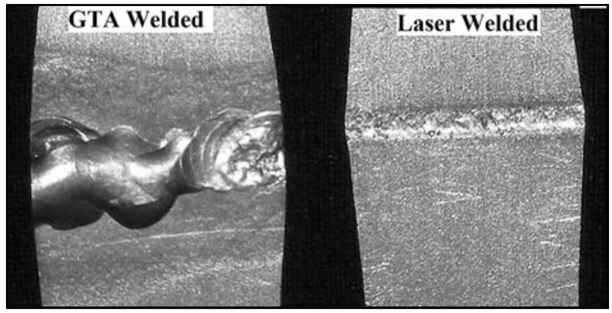

Fig. 2. Welded seams.

3. Results and discussion

Each tensile test was repeated three times depending on the type of each sample, and then the average value was taken as the tensile strength. The tensile test data is given in Table 4. The test results of the samples are shown in Fig. 1 and welded seams are shown in Fig. 2.

Three point bending test data of samples are given in Table 5.

The comparative microhardness measurement results of the samples are shown in Fig. 3.

Figures 4–6 show the joint area structures by the GTA and laser welding methods. The surfaces of the welded joints indicate structures composed of dendritic grains in the center of the welded seam. The size of the grains by the GTA is larger than this with laser welding.

SEM studies of laser-welded samples are shown in Figs. 7 and 8.

SEM studies of GTA welded samples are shown in Figs. 9–11. Studies are performed from welding zone to main metal zone.

A result of the tensile test obtained from SEM studies of fracture surfaces of samples taken from the example is shown in Fig. 12.

Ductile fracture occured after the tensile tests on the specimens (Fig. 12).

At the end of the tensile and bending tests, the laser-welded samples had a higher tensile strength

Table 4. Tensile test data of specimens

Specimen	Yield strength ($N\,mm^{-2}$)	Tensile strength ($N\,mm^{-2}$)
Base material	368.7 ± 12.5	410.3 ± 7.9
Laser welded	359.6 ± 5.4	388.7 ± 9.6
GTA welded	305.95 ± 5.2	349.3 ± 11.1

Table 5. Bending test data of sample

	Flexural strength ($N\,mm^{-2}$)
Base material	759 ± 16.3
Laser welded	747 ± 22.5
GTA welded	636 ± 94.3

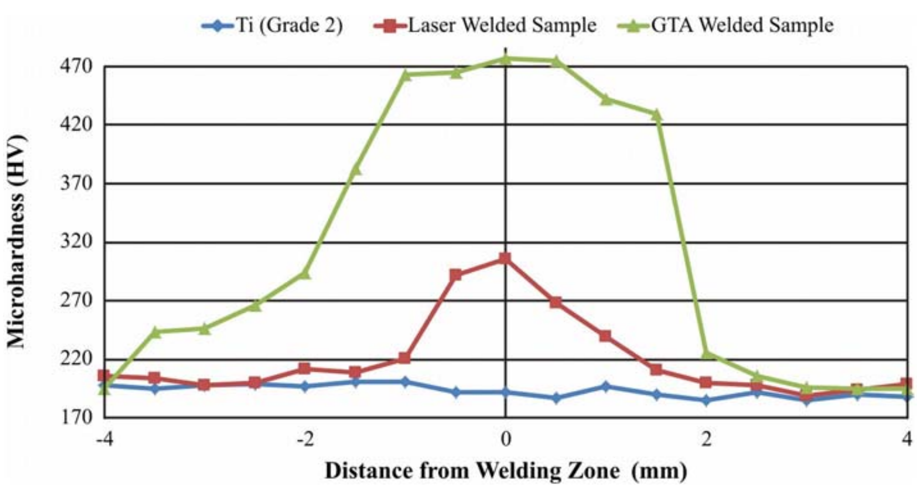

Fig. 3. Microhardness measurements graphs.

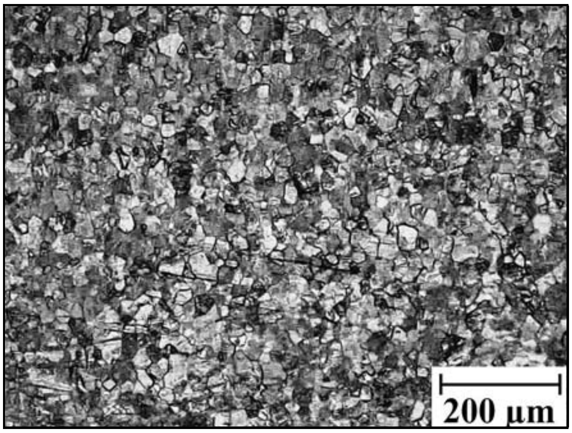

Fig. 4. Microstructure of main material.

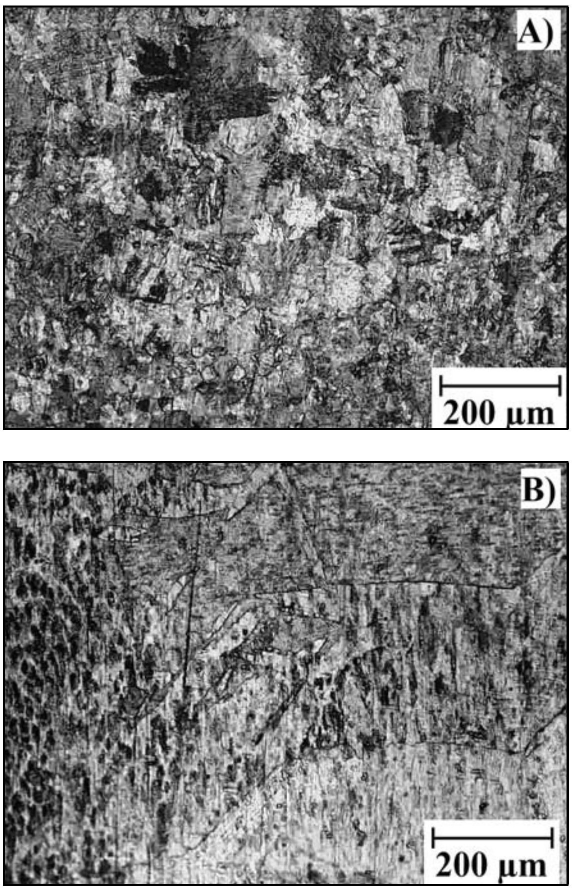

Fig. 5. A) Structure of GTA welded sample's main material – heat affected zone (HAZ); B) microstructure of GTA welded sample's HAZ.

and a higher flexural strength than the GTA welded samples (Tables 4, 5).

According to the literature, laser welded samples of titanium alloys have higher tensile strength than gas tungsten arc welded and electron beam (EB) welded samples because the welding area of the laser welding of titanium alloys has a narrow range and during welding low heat input is provided [12].

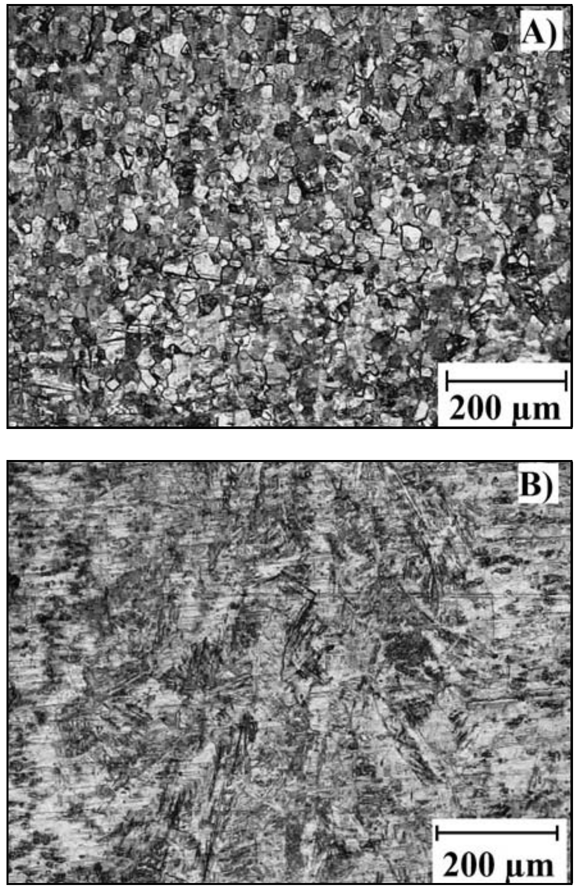

Fig. 6. A) Microstructure of laser welded sample's main material zone; B) microstructure of laser welded sample's welding zone.

The comparative microhardness measurement results of the samples are shown in Fig. 3.

The welding zone of GTA welded specimens hardness is higher than the laser welded specimens hardness. Microhardness measurements of the laser welded sample hardness distribution are lower and the width of the welding area is narrower compared to the GTA welded sample. In both welding methods higher hardness values are obtained than in the parent metal. White oxide grain structures are shown on the surface of GTA welded samples (Fig. 10), and are determined by momentary EDS analysis during SEM analysis. HAZ has a much narrower range in laser welded samples than GTA welded samples (Fig. 8). Cracked structures are found in GTA welded specimens as shown in Fig. 11. These cracks are combined with applied stress and cause decrease in bridging stress.

After the tensile tests of welded samples breaking occurs in the base metal part, macro images were ana-

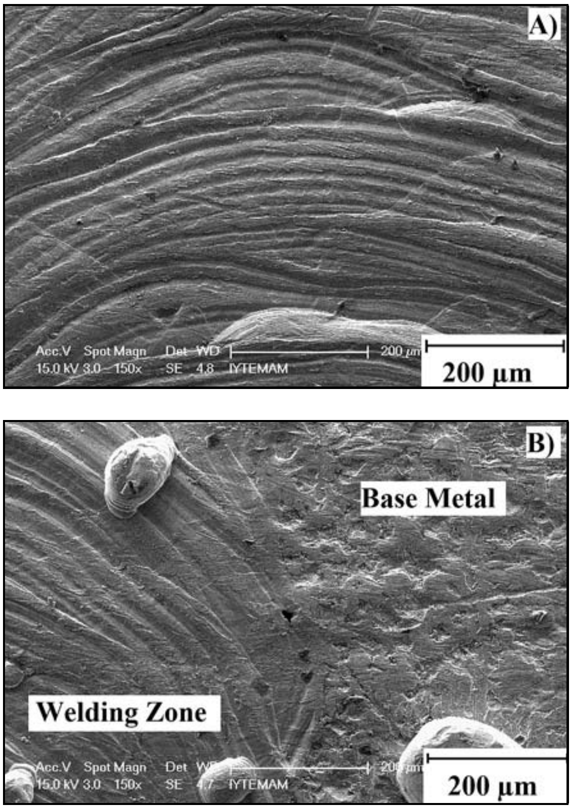

Fig. 7. A) Laser welded sample's welding zone; B) laser welded sample's HAZ – main material zone.

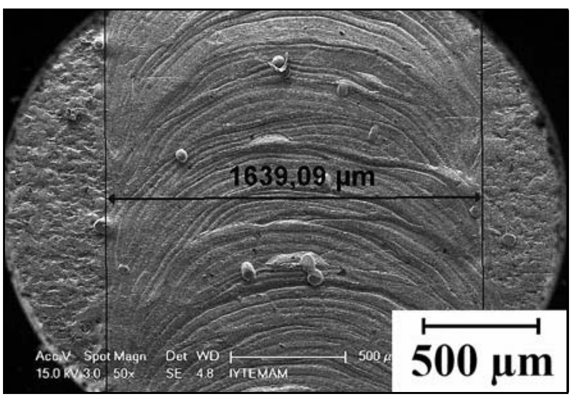

Fig. 8. Laser welded sample's width of the welding zone.

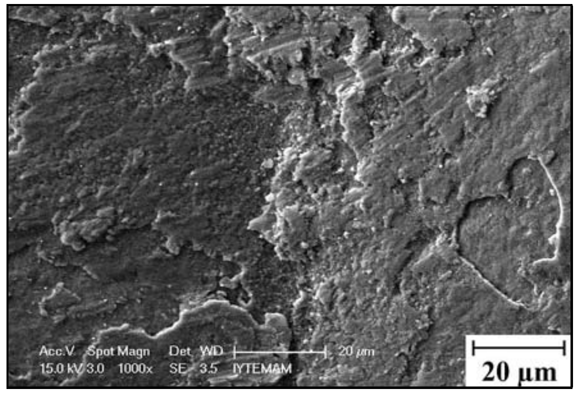

Fig. 9. GTA welded sample's base metal – welding metal.

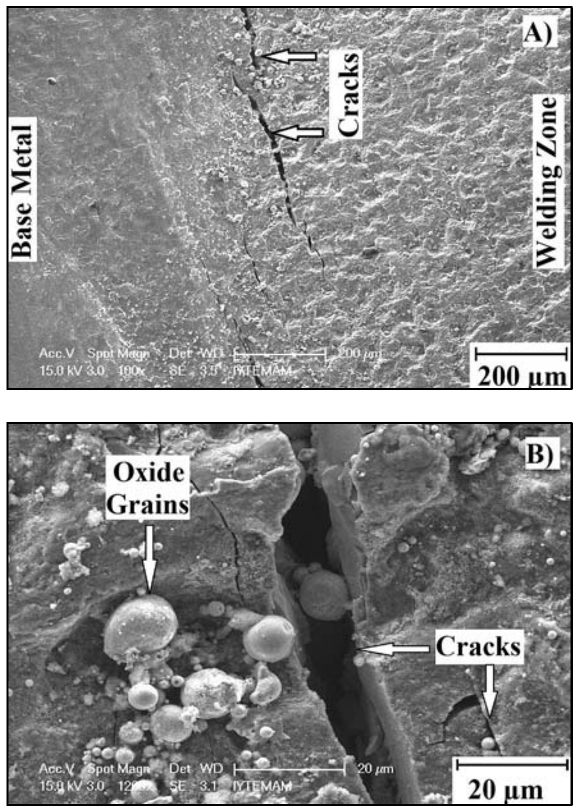

Fig. 10. GTA welded specimen consisting cracks in the HAZ: A) 100×; B) 1200×.

lyzed, and a result of the tensile test obtained from SEM studies of fracture surfaces of samples taken from the example is shown in Fig. 12.

Laser welded samples have less microstructural changes compared to GTA welded samples.

Laser-welded specimens of weld metal and base metal parts of the small splashes of molten weld pool during laser welding of titanium particles were determined by elemental analysis (Fig. 7). The quality of the surface of GTA welded specimens are degraded (Fig. 9).

SEM examinations of GTA welded samples have a narrow and short cracks. These caused the decrease in the mechanical properties of the material.

As a result for constructions which include titanium materials, the best welding method is laser welding.

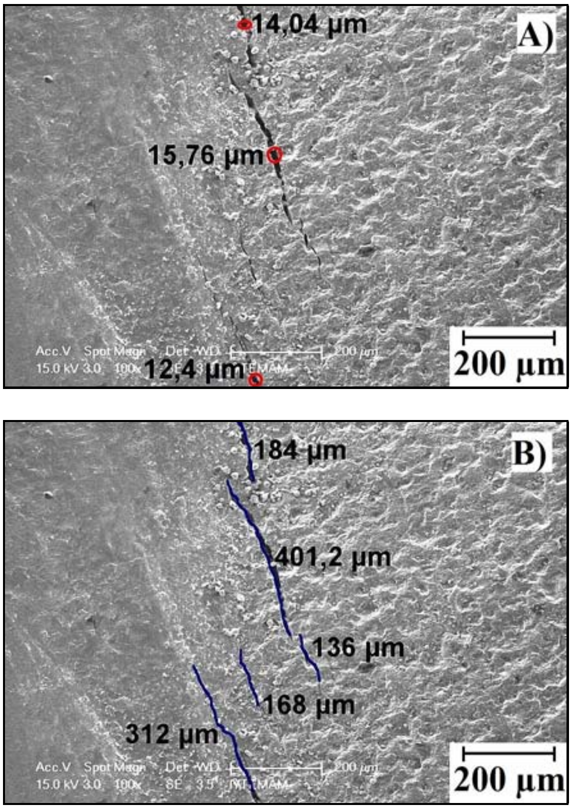

Fig. 11. A) Measurement of the length of the cracks of GTA welded samples in HAZ; B) measurement of the width of the cracks of GTA welded samples in HAZ.

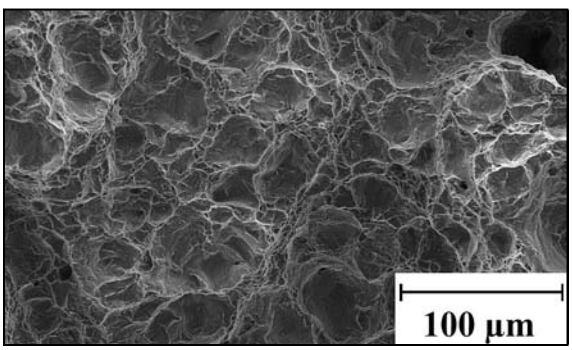

Fig. 12. Fracture surface of main material.

4. Conclusions

In both welding methods of macroscopic examinations, the welding zone of laser welded specimens welded seam is bright silver, and that of GTA welded specimens welded seam is grey.

Titanium alloys have very low losses in terms of mechanical properties of laser welding applications, but GTA welding applications composed of heterogeneous structures have some reduction in mechanical properties.

Titanium welded joints can also be promoted to expand the use of titanium materials.

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