Effect of heat input on interfacial characterization of the butter joint of hot-rolling CP-Ti/Q235 bimetallic sheets by Laser + CMT

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Composite structures made of 2 mm-thick titanium and 10 mm-thick carbon steel are widely used in infrastructures such as long-distance gas transportation. However, cracking, which is caused by intermetallic compounds (ICs), is a dominate failure mode in welds of this structure. Thus, a common way to improve the in-service life of is reduce the number of ICs. In this paper, we employ a novel hybrid welding method to fabricate composite structures of TA2 titanium and Q235 carbon steel. Specifically, Ti and carbon steel is welded by laser and double Cold Metal Transfer (CMT) welding, respectively. The microstructure near the interface of Ti and steel is then examined using SEM, EBSD, EDS, with emphasis on the ICs in terms of chemical elements and morphologies. Results show that FeTi and Fe2Ti are the main ICs near the interface, and responsible for the failure of the welds. The effect of welding heat input on the formation of ICs is investigated as well. Results show that ICs are smaller when the heat input is low. Under low heat input circumstance, the tensile strength of the weld can reach up to 420 MPa.

Titanium alloy is one of the good structural materials with low density, high strength, and suitable anti-corrosion properties, however, it lacks the extensive use in the noble material characterization1. Carbon steel alloy is a popular structural material with good mechanical properties, weldability, heat stability, and better economics2. In some extreme environmental condition like petroleum pipeline transportation and equipment manufacturing3, the structures must possess a combination of performances and based on this, the CP-Ti/Q235 bimetallic sheets was made by hot-rolling.

The welding technology is one of the most common methods to connect titanium alloy with steel materials, such as diffusion welding4–6, Tungsten inert gas (TIG) welding7–8, friction welding9–13, soldering14, electron beam welding15–20, and laser arc welding etc.21–23. However, due to large differences in the physical and crystalline chemical properties of the titanium and steel alloys (e.g., specific heat capacity, Ti: 539.1 J/kg·K, Fe: 481.5 J/kg·K; thermal conductivity, Ti:13.8 W/m·K, Fe:66.7 W/MGk; expansion factor, Ti: 8.20 × 10–6·K−1, Fe:11.76 × 10–6·K−1), consequence large distributed residual stress after welding process and would induce cold cracks and delayed cracks or exfoliation of the compound layers. This would generate Fe2Ti, FeTi and other brittle alloys compounds and carbides which lead to the difficulty of the welding process24–31.

In this field, most of the research has been focused on the role of Titanium alloys with stainless steels. Comparative analysis of the previous literature led us to conclude that FeTi,Fe2,O, Fe, Ti, FeTi and other brittle alloys compounds and carbides would also be generated. So, the strength of the welded joints is not very strong and decreases when the welding temperature increases. Some scientists have added Cu, Ag, Mg, Mo and their compounds as intermediate transition layers to weld titanium alloys with stainless steels32–36. Their results showed that the quantity of brittle compounds is decreased but it cannot be eliminated.

Laser arc or laser-MIG arc welding is the most favorite welding technology which could be used to connect dissimilar metals with its better properties of higher power density, larger ratio of depth-to-width of the welds, and lower welding deformation. Cold metal transmission (CMT) welding technology has lower heat input which avoids drops penetration of the structures and realizes no splash droplet transition and better metallurgical interconnection.

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In order to solve the issue of the west to east natural gas transmission, scientists of Pangang Group Research Institute invented new TA2/Q235 bimetallic sheet structures with hot rolling technology. The thickness of the titanium alloy layer has been used as 2 mm along with the 10 mm thickness of the steel alloy layer.

In this work, laser arc welding with CMT welding technology has been optimized with different welding technology tests and employed to systematically investigate the connection of titanium–carbon steel compound structures, the microstructures, distribution of brittle metal alloy compounds, and the thermal strain change process.

Results and discussion

Macrostructure and mechanical properties. The optical macrographs of the sectioned area of the samples are shown in Fig. 1. Figure 1a,b shows the macrographs of the Q235 carbon steel welded joints. The fusion zone was in the perfect forming condition in the first parameter which had lower heat input, weld width: 13.04 mm, penetration: 9.921 mm and no reinforcement. For the second parameter, weld width: 12.57 mm, penetration: 10.27 mm, and reinforcement: 2.3 mm. No any large defect was examined. Figure 1c shows the macrographs of the titanium welded joints. The weld width is about 3.50 mm, the weld width of the back is 1.09 mm, and the bite edge sharpness is 1.09 mm.

Figure 1d shows the results of tensile tests measured for joints processed in different parameters, the ultimate tensile strength (UTS) of the base metal (BM) is slightly higher than that of joints, which is reached 497 MPa. The UTS of the joint in lower heat input (parameter 1) is 420 MPa, which is higher than the UTS of the joint processed in parameter 2 (397 MPa). The total elongations of BM and both of joins is 13.2%, 13.8% and 13.9%, respectively.

Microstructural and phase analysis. Optical micrographs of the sectioned area of the steel are shown in Figs. 2 and 3 where the first welding parameter and second welding parameter are shown, respectively.

Ferrites and pearlites are main microstructure for the two welding parameters. The needle-like eutectoid ferrite dissolved along with the austenite grain boundary and the crystal are pearlite in the weld zone, see Figs. 2a,b and 3a,b. The microstructure size of the second layer is much larger than the first layer. For the fusion line microstructures, they are typically distributed just like Widmannstatten structure ferrite with slight decarburization from the center zone. However, the intra-crystalline are acicular ferrite (blue arrow) with pearlite (black arrow) from the left side of the Q235 steel. Widmannstatten structure ferrite develops intra-crystalline growth (red arrow). Moreover, it distributes the proeutectoid ferrite along with grain boundary however, the intra-crystalline are thin ferrite with less Widmannstatten structure ferrite, see Figs. 2c and 3c. The microstructure size of the HAZ zone is much larger than that of the base metals, distributed with less Widmannstatten structure ferrite and thin ferrite.

Optical micrographs of the sectioned area on the side of the TA2 are shown in Fig. 4.

The weld (Fig. 4a) is α-Ti with wattle and needle-like microstructure. The bulky columnar crystal of different growth direction and size do not have enough time to expand along the sides, during the solidification and crystallization of the rapid cooling speed of single laser welding. Moreover, this shows the needle-like microstructure. During the high-temperature region, the β-Ti bulky columnar microstructures change to α-Ti martensite and show wattle microstructure.

The fusion zone is composed of battle, needle-like and zigzag α ferrites as shown in Fig. 4b,c. The microstructures undergo phase recrystallization and the grains of the coarse-grained regions (CGR), near the weld region grow rapidly. However, the grains in the fine-grained regions (FGR) which are far away from the weld do not grow efficiently. The HAZ zone is zigzag α ferrites (Fig. 4d) with little larger grain size than that of the base metals and the microstructures changed to martensite, near the fusion line.

Figure 5 are the results of X-ray diffraction pattern of the selected areas near the bonding surface and close to the base layer(Q235), composite layer (TA2) respectively, which confirms the main occupying element near the base layer of the joint is α-Fe, and near the composite layer is α-Ti, and FeTi and Fe2Ti are the main ICs near the interface.

Phase distribution in the area close to the interface of joints made by the two welding parameters is shown in Fig. 6.

In case of first welding parameter, the Fe phase content is 46.5 wt%, where FeTi is 13.9%, Fe2Ti 17.7%, and brittle compounds are 31.6%, where Ti is 21.9%. For the second welding parameter, the Fe phase content is 45.3
wt%, where FeTi is 10.7%, Fe₂Ti 24.3% and brittle compounds are 35.0% with 24.3% Ti. The high content of brittle compounds is due to increased heat input which promotes the process of diffusion and metallurgy in the interface of the second welding parameter.

The grain size of the two-welding parameter is shown in Fig. 7. The mean grain size of α-Fe is 6.5 μm in the first welding parameter while it is 19.8 μm in the second welding parameter. About 35.4% grains size is distributed from 0 to 5 μm, 15.6% from 5 to 10 μm and some grains size...
nearly reached to about 30um. For the second welding parameter, the grains size is distributed from 5 to 20um and some grains size reach to 50 um. About 53.4% grains size of Ti is distributed from 0 to 5um, 22.6% grains size is distributed from 5 to 10um and a maximum size of 30um is reached for the first welding parameter. In case of second welding parameter, about 53.1% grains size is distributed from 5 to 10um. The mean grains size of α-Ti for the two welding parameters are 7.2 and 8.5um.

About 50.2% grains size of FeTi is distributed from 0 to 5um and some grains size reached to about 12um for the first parameter. However, 76.4% grains size is 6 to 14um and a maximum size of 40um is achieved for the second parameter.

The recrystallization distribution and volume statistics of different phases are shown in Fig. 8.

Figure 4. Microstructure of the TA2 side. (a) Weld, (b) fusion zone, (c) fusion zone and (d) HAZ zone.

Figure 5. X-ray diffraction pattern of the selected areas in joint: (a) close to the base layer (Q235), (b) Close to the base layer (TA2).
For the first and second parameters, the recrystallization volume ratio of Fe phase are 13.3 and 16.0%, for FeTi 10.7 and 25.4%, and for the Fe$_2$Ti phase are 76.2 and 84.4%, respectively. This data was calculated with the Channel 5 software. Fe$_2$Ti phase distributes with uniform equiaxial grains shape to about full recrystallization. Furthermore, the uniform grains turn into steady flow state at the true stress–strain curves where some extent of deformation exists, which shows the dynamic mode recrystallization mechanism of Fe$_2$Ti. On the other hand, in case of Fe and FeTi phases, the low angle boundary (boundary orientation difference ≤ 15°) decreased but...
high angle boundary (boundary orientation difference $\geq 15^\circ$) increased with the increase of heat input. This led us to conclude that the sub-boundary and dislocation density decreased and show static mode recrystallization mechanism of the Fe and FeTi.

From the calculation of HKL-Channel software, the Fe phase volume ratio (Fig. 9a–d) at 2° ~ 15° section is 7.4 and 6.9%, separately, while the mean orientation difference is 24 and 33.2%, separately. The volume ratio of Ti phase (Fig. 9a,b,e,f) at 2 ~ 15° section is 5.3 and 3.5%, separately, while the mean orientation difference are 28.2 and 34.7%, separately. In case of the peak value at 60° orientation difference will show crystalline or close-packed hexagonal structure of Ti The volume ratio of FeTi phase (Fig. 9a,b,g,h) at 2 ~ 15° section are 4.2 and 10.3% separately, while the mean orientation difference are 26 and 29.2%, separately. For the Fe2Ti phase (Fig. 9a,b,i,j), there exist high angle boundary and the volume ratio at low angle boundary are 0.51 and 0.33%, respectively and the mean orientation difference are 53.5 and 56.2%, respectively. It can be concluded that the change of welding parameters would promote different recrystallization extent which would change low angle boundary to high angle boundary at the sub-grain rotation, responsible for the disappearance of sub-grains. So, the density of dislocation defects decreased with the increase of heat input.

The kernel average misorientation (KAM) map in Fig. 10a,b shows that the local plastic strains of the joints in two parameters, the plastics strain is concentrated within the grain boundaries, and presenting an uneven "strip" type distribution. The mean residual strain of Fe phase (Fig. 10c) is 2.12 and 2.25 separately, the mean residual strain of FeTi (Fig. 10d) phase is 1.31 and 1.77 separately, the mean residual strain of Fe2Ti (Fig. 10e) is 0.86 and 1.20 separately, the mean residual strain of Ti (Fig. 10f) is 1.48 and 2.25 separately. The residual strain are mainly distributed in the inner of the grains with great inhomogeneity, the grains of larger residual strain interconnected with each other and showed inhomogeneity strip distribution.

**Discussions**

As can be seen from Fig. 11a, there are some favorable factors which form Ti (for TA2: more than 99wt% titanium and the fusion point is 1677 °C) and Fe (for Q235: more than 99 wt% Fe and the fusion point is 1537 °C) compounds. Both the α-Fe and α-Ti are evenly and non-directionally distributed (Fig. 11b). When the welding process is undergoing, the α-Fe diffuses into TA2 side and the α-Ti diffuses to Q235 side. With the chemical reaction of α-Fe with α-Ti, promoted by the reaction energy, generates high FeTi, Fe2Ti (Fig. 11c), and other brittle compounds. As the Fe2Ti (Fe ion is Fe$^{3+}$, Ti ion is Ti$^{4+}$) is more stable so, need more energy than that of FeTi (Fe ion is Fe$^{2+}$, Ti ion is Ti$^{3+}$). Finally, the volume ratio of Fe2Ti for the second welding parameter is higher than that of the first welding parameter.
Conclusions
In this work, we have employed laser arc welding and CMT welding technology for the fabrication joints of composite structures made of 2 mm-thick titanium and 10 mm-thick carbon steel. We have investigated the macrostructures, microstructures, phase distribution, grain morphology and size of the weld interface, recrystallization volume content and grains boundary orientation difference distribution in the sectioned welds, and thermal strain change process through EBSD technology. The following main conclusions are drawn:

1. With the help of appropriate laser arc welding parameter for TA2 and CMT for Q235 carbon steel, the structures of new titanium-carbon steel compounds can be well welded, the joints were fabricated successfully by control the heat input. The UTS of the joint in lower heat input (parameter 1) is 420 MPa, which is higher than the UTS (397 MPa) of the joint processed in parameter 2.

2. FeTi and Fe2Ti are the main ICs near the interface in welding zone, the content of ICs is lower and grain size is smaller in the joint processed in parameters with lower heat input, and which is the reasonable for the more excellent mechanical properties.

3. The fraction of recrystallization volume of α-Fe phase, FeTi phase and Fe2Ti phase are all added as the increase of heat input. The recrystallization percentage of Fe2Ti phase is significantly higher than that of α-Fe phase and FeTi phase, and even nearly complete recrystallization of grains. It suggested that the recrystallization mechanism of Fe2Ti phase may be different from that of Fe phase and FeTi phase.

4. Thermal strain reflected directly the residual stresses in the joints, the residual strain is smaller in the joint processed by the parameters with lower heat input, and which is mainly distributed around the grain boundaries of ICs (FeTi and Fe2Ti).

Methods
The titanium-steel compound plates are used for the application (Fig. 12a,b) of natural gas transmission, from the west to east, made of single laser arc and CMT process. The carbon steel layer was first made from TPS-4000 CMT welding technology in two layers and the welding wire is ER50-6. After that the titanium layer TA2 was made from a TruDisk 10002 continuous wave disc type laser and a Transpuls Synergic 4000 welding machine (Fig. 12c,d) and 2 KW power was used (welding speed: 30 mm/s, laser angle: 90, gas flow speed:40 L/min). The welding wire is ERTi-2. "V" shaped grooves with 0.5 mm gaps were used with an angle of about 40° – 60°. The CMT welding parameters of the carbon steel were divided into two systems. The detailed parameters are listed in Table 1.

Optical macroscopy, microscopy, phase distribution, grain morphology and size, recrystallization volume content, and grains boundary orientation difference distribution were carried out for microstructure analysis. The samples used for optical microscopy were prepared according to the standard procedure and etched via
Figure 10. Plastic strain change of different phases: (a) Grain boundary diagram of the first parameter (b) Grain boundary diagram of the second parameter (c) plastic strain of phase Fe (d) plastic strain of phase FeTi (e) plastic strain of phase Fe2Ti (f) plastic strain of phase Ti.
different reagent. In case of carbon steel, the reagent was 4% volume content nitric acid alcohol while for the titanium, the reagent was 3 mL HF + 10 mL HNO₃ + 87 mL H₂O.

Phase distribution, grain morphology and size of the weld interface, recrystallization volume content and grains boundary orientation difference distribution in the sectioned welds were analyzed via electron

Figure 11. Schematics representation of formation process of FeTi and Fe₂Ti compounds. (a) PHASE diagram of Ti-Fe and their compounds. (b) Final elements distribution of Titanium and carbon steel compound welded joints. (c) Magnification of (b) at the marked zone.

Figure 12. Schematic design for the investigation of titanium alloys with carbon steel compound plates. (a,b) From west to east natural gas transmission and the titanium alloys with carbon steel compound plates. (c) LAW equipment. (d) CMT equipment. (e) Schematic of LAHW process and location of sample cutting.
back-scattered diffraction (EBSD) on an SEM (FEM 6500). The thermal strain change process was also analyzed. The EBSD samples were electrolytically polished in 5% perchloric acid–ethanol solution for 45 s.

The cutting of sample for microstructure analysis was located as shown in Fig. 12e.

Data availability
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Table 1. Parameters for CMT welding Q235 carbon steel.

| Parameters | Position | Welding current (A) | Welding voltage (V) | Welding speed (mm/s) | Wire feeding speed (mm/s) |
|------------|----------|---------------------|---------------------|----------------------|--------------------------|
| Parameters 1 | Pass one | 265 | 20 | 5.0 | 167 |
| Parameters 1 | Pass two | 250 | 20 | 4.0 | 150 |
| Parameters 2 | Pass one | 265 | 20 | 3.7 | 167 |
| Parameters 2 | Pass two | 250 | 20 | 4.0 | 150 |
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Author contributions
Z.Y.Z., G.Q.G. and W.G. designed the research project; Y.L.L., J.C. made the joints; Z.Y.Z. and G.Q.G. analyzed the data; Z.Y.Z. and Y.L.L. wrote this paper.

Competing interests
The authors declare no competing interests.

Additional information
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