Effect of DT4 Interlayer on Properties of Hot-roll Bonding TA2/Q235B Plate

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Abstract. In this paper, a Q235B/TA2/DT4/Q235B plate was bonded by hot-rolling in a vacuum, and the effect of including a DT4 interlayer within the TA2/Q235B plate was studied. The microstructure and properties of the composite plate at different reduction ratios were investigated by scanning electron microscopy, as well as tensile-shear, bending and tensile tests. The results show that when the reduction ratio is below 18%, the shear strength of the interface is higher with the DT4 interlayer than without it. At 35% reduction, the shear strength is similar in both cases. At a reduction ratio of 68%, with the DT4 interlayer, fracture of the bonding interface occurs on the TA2 side, whereas without the DT4 interlayer, fracture occurs on both the TA2 side and the compound layer on the interface. Including the DT4 interlayer improves the bending and tensile properties of the TA2/Q235B plate appreciably.

1. Introduction
Titanium clad steel plates are not only have the corrosion resistant of titanium but also have the weldability, formability and thermal conductivity of carbon steel, and it also saves precious titanium metals. Due to these characteristics, titanium clad steel plates are widely used in the petrochemical, shipbuilding, and marine industries, among others [1-2]. Currently, several methods have been used to manufacture titanium clad steel plates, such as explosive welding, explosive-rolling bonding and rolling bonding. Each method has its own advantages, compared with the explosive cladding and explosive-rolling bonding methods, the rolling bonding method can produce large-sized and thin titanium clad steel plates with high production efficiency, low pollution and low energy consumption [3].

While producing dissimilar metals composite plates, intermetallic compounds are easily formed on the interface, and they have a great influence on the properties of the composite plates. Many studies have improved the mechanical properties of composite plates by using an intermediate layer. In the production of titanium clad steel plates, the formation of brittle compounds such as TiC, FeTi and Fe₂Ti on the interface may cause the degradation of mechanical properties [4]. To prevent the formation of brittle compounds that reduce the bonding strength, some studies have used niobium, copper, silver and nickel as the interlayer [4-7], however, because of high costs, these materials are not widely used in the production of titanium clad steel plates. C. Yu [8] used DT4 interlayer to hot-roll bonding TA2/Q235B plate with the single pass reduction ratio of 25%, the TA2 and Q235B could be bonded well at heating temperature of 850 °C. However, in the industrial production, in order to obtain a large wide composite plate, it often requires multi pass rolling, therefore, on the basis of study on
literature [8], this paper uses DT4 as interlayer, to study the effect of DT4 on properties of hot-roll bonding TA2/Q235B plate after multi pass rolling.

2. Experimental
The assembly pattern is shown in Figure 1, in which the thicknesses from top to bottom are 6 mm, 3.7 mm, 1 mm and 5 mm. Because the phase transition temperature of titanium is 882 °C, the mechanical properties of the titanium change radically near this temperature. Above 882 °C, Fe readily dissolves in titanium to form Fe₂Ti and FeTi compounds. Therefore, in order to stabilize the mechanical properties of TA2 during rolling, the heating temperature of the billet was chosen to be 850 °C to limit both the deformation resistance during rolling and the formation of Fe₂Ti and FeTi compounds. The billets were heated in a furnace for 2 h, rolled at a speed of 50 mm/s, and cooled to room temperature in air. The rolling reduction ratios were 8%, 18%, 35%, 54% and 68%, the first 3 of which were single pass rolling reductions, and the last 2 were cumulative reduction ratios based on the prior reduction. The surface temperature of the plate after 68% rolling reduction was approximately 553.3 °C.

![Figure 1. Assemble pattern.](image)

The tensile-shear, bending and tensile tests were carried out using an Inspekt Table 100 kN instrument. The speed was 1 mm/min. The tension-shear test samples are shown schematically in Figure 2. The morphology of the fracture surface was investigated using scanning electron microscopy (SEM, Zeiss Sigma 500). The distribution of elements across the interface was examined by SEM equipped with an energy dispersive spectrometer (EDS).

![Figure 2. Schematic of the tension-shear samples: (a) measuring the tension-shear strength of the side without the DT4, (b) measuring the tension-shear strength of the side with the DT4.](image)

3. Results and discussion

3.1. Macroscopic bonding property test of the clad plates
The effect of the rolling reduction ratio on the interfacial shear strength of titanium clad steel plate with and without the DT4 interlayer is shown in Figure 3. When the reduction ratio is between 8%~68%, the shear strength of the interface increases with increasing reduction ratio: without a DT4 interlayer, the shear strength increased from 66.9 MPa to 271.2 MPa, and with a DT4 interlayer, the shear strength increased from 144.8 MPa to 262.8 MPa. When the reduction ratio is less than 18%, the shear strength is much higher with the DT4 interlayer than without it. When the reduction ratio is greater than 35%, the shear strengths on both sides are similar. The shear strength of the interface reaches the standard value of 140 MPa from the GB/T 8547-2006 type 1 titanium clad steel plate when the reduction ratio is 18% without the DT4 interlayer and 8% with it. The shear strength reaches the standard value of 196 MPa from the type 0 titanium clad steel plate when the reduction ratio is 35% without the DT4 interlayer and 18% with it. It can be concluded that the addition of the DT4 interlayer...
improves the shear strength of the composite plate at small reduction ratios. When the reduction ratio is large, the shear strength of the interface on both sides is close to the shear strength of the titanium matrix, meaning the effect of the DT4 interlayer on the shear strength is not as obvious.

Figure 3. Effect of reduction ratio on the shear strength of titanium clad steel plates.

3.2. Interfacial structure of TA2/Q235 clad plates

Figure 4 and Figure 5 show secondary electron images and element surface scanning analysis images of the fracture surface on the Q235 side and the DT4 side, respectively, at a 68% reduction. As shown in Figure 4 (b) and (c), there is a large amount of Ti and a smaller amount of Fe distributed on the fracture surface. The microstructures of these two main element distribution regions are respectively shown in Figure 4(d) and (e). Figure 4 (d) reveals brittle fracture characteristics on the surface, indicating that brittle intermetallic compounds have been formed there. Figure 4 (e) presents obvious ductile fracture features with many dimples. Figure 6 shows that fractures occur mainly on the Ti side, though some occur in the brittle region at the interface. From Figure 5 (a) and Figure 5 (b), the fracture surface is full of Ti, and as shown in Figure 5 (c), there is a large number of dimples distributed along the fracture surface, which is characteristic of plastic fracture. This indicates that the fracture absolutely occurs on the TA2 side, where the bonding strength between DT4 and TA2 is high.
**Figure 4.** SEM and element surface scanning analysis of the fracture surface on the Q235 side at a reduction ratio of 68%: (a) overall morphology, (b) Fe distribution on Fig. 4 (a), (c) Ti distribution on fig. 4 (a), (d) and (e) microstructure of areas selected from Fig. 4 (a).

**Figure 5.** SEM and element surface scanning analysis of the fracture surface on the DT4 side at a reduction ratio of 68%: (a) overall morphology, (b) Fe distribution on Fig. 5 (a), (c) microstructure of the fracture surface.

Figure 6 shows the element distribution profiles across the interface at a bonding reduction ratio of 68%. The Ti and Fe diffusion distances are similar for both interfaces and are approximately 1.5 μm. Comparing the intensity of C across the interface between Figure 6 (a) and (b), it can be seen that, without the DT4, the C is concentrated near the interface. Conversely, with the DT4, such concentration is not as obvious. This shows that adding the DT4 interlayer can effectively reduce C diffusion to the interface from Q235, thus reducing the formation of brittle compounds such as TiC on the interface.

**Figure 6.** Element distribution profiles across the interface (a) between Q235 and TA2, (b) between TA2 and DT4.

### 3.3. Mechanical properties of TA2/Q235 clad plates

Figure 7 shows macroscale photographs of a bent specimen at a reduction ratio of 68%. Whether the DT4 is on the interior or the exterior, there are no cracks after bending. An optical specimen was taken from the bent specimen to observe the microstructure, which is shown in Figure 8. Without the DT4, there are some microcracks on the TA2 side whether the DT4 is on the interior or the exterior. Because the amount of deformation is greater on the outside than the inside, there are more cracks on the outside. With the DT4, no microcracks were found on the interface. Therefore, when TA2 and Q235 are compositied by rolling, brittle compounds are easily formed on the interface. The poor plasticity of such compounds results in the formation of microcracks during bonding. This suggest that the addition of a DT4 interlayer can effectively inhibit the generation of compounds, thereby improving the bending performance of the composite plate.
Figure 7. Macro photographs of bent specimen: (a) DT4 at interior, (b) DT4 at outside.

Figure 8. Optical micrograph of bent specimen: (a) DT4 at interior, (b) DT4 at outside.

Tensile specimens were taken along the rolling direction of the composite plate with 68% reduction ratio, and the tensile test results are shown in Figure 9. Without the DT4, when the strain was 0.356, Q235 and TA2 became separated, resulting in the invalid. With the DT4, when the strain was 0.386, the DT4 and TA2 became separated, and when the strain was 0.397, the composite plate underwent overall fracture. This indicates that since adding a DT4 interlayer can effectively reduce the formation of brittle compounds, crack sources are reduced on the interface during tensile deformation. Therefore, with the DT4 interlayer, the tensile properties are improved, and the fracture invalid is relieved.

Figure 9. Tensile test results.

4. Conclusions
(1) A Q235B/TA2/DT4/Q235B plate was bonded by hot-rolling in a vacuum to compare the effect of the DT4 interlayer on the TA2/Q235B plate. When the heating temperature is 850 °C and the rolling speed is 50 mm/s, the shear strength of the interface increases with reduction ratio on both sides with or without DT4. When the reduction ratio is below 18%, with the DT4 interlayer, the shear strength of the interface is higher than without it. After 35% reduction, the shear strengths of the interfaces on both sides are similar.

(2) When the reduction ratio is 68%, with the DT4 interlayer, shear fracture occurs on the TA2 side. Without the DT4 interlayer, the fracture occurs mainly on the Ti side, though some also occur at the brittle region near the interface.

(3) With a DT4 interlayer, the bending and tensile properties of the TA2/Q235B plate can be improved.

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