Effect of Reversed Austenite on Mechanical Properties of ZG06Cr13Ni4Mo Repair Welded Joint

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Abstract: In this work, gas tungsten arc welding (GTAW) was used to repair ZG06Cr13Ni4Mo martensitic stainless steel. Repair welding occurred either once or twice. The changes in the microstructure and properties of the repair welded joints were characterized by optical microscope (OM), scanning electron microscope (SEM), electron backscattering diffraction (EBSD), tensile and impact tests. The effects of reversed austenite in repair welded joints on microstructure and mechanical properties were studied. The results show that the microstructure of the welded joint after repair welding consists of a large amount of martensite (M) and a small amount of reversed austenite (A), and the reversed austenite is distributed at the boundary of martensite lath in fine strips. With the increase in the number of welding repairs, the content of reversed austenite in the welded joint increases. The microstructure in the repair welded joints is gradually refined, the microstructure in the once and twice repaired joints is 45.2% and 65.1% finer than that in the casting base metal, respectively. The reversed austenite presented in the repair welded joints decreases the tensile strength by 4.8% and 6.7%, increases the yield strength by 21.3% and 26.4%, and increases the elongation by 25% and 56%, respectively, compared with the casting base metal. In addition, the reversed austenite mainly nucleates and grows at the boundary of lath martensite. The refinement of the martensite structure was due to the generation of reversed austenite and the refinement of original austenite grain by the welding thermal cycle. After repair welding, the reverse austenite appeared in the repair welded joints and the tensile strength decreased slightly, but the plastic toughness was significantly improved, which was conducive to the subsequent service process.

Keywords: super martensitic stainless steel; repair welding; reversed austenite; mechanical properties; EBSD

1. Introduction

ZG06Cr13Ni4Mo is a super martensitic stainless steel. It has numerous applications in hydropower, nuclear power and petrochemical industries [1]. It originated in the late 1950s, when Swiss scientists reduced the carbon content to less than 0.07%, while adding nickel (ω = 4%–6%) and molybdenum (ω ≤ 2.5%). This steel not only improves the weldability, but also overcomes the shortage of plasticity and toughness of traditional martensitic stainless steel, the difficulty of cold processing and forming. Thus, this steel has good weldability, strength and toughness and corrosion resistance [2–4]. Since the 1980s, low-carbon martensitic stainless steel material ZG06Cr13Ni4Mo has been successfully developed in China. Compared with CA6MN stainless steel in ASTM standard, it has higher hardness, better corrosion fatigue strength, better static fracture toughness and excellent weldability at room temperature and low temperature [5]. The ZG06Cr13Ni4Mo low-carbon martensitic stainless steel also has excellent casting, forging, welding and machining properties [6].
The impeller is usually manufactured by casting. The defects such as air holes and inclusions are usually in the casting process, leading to safety hazards in the process of equipment service. Re-melting and re-casting cause great economic losses and cannot completely rectify the defects. Therefore, the defective parts need to be welded and repaired before they can be put into use. Because the carbon content is very low, multi-pass welding is usually used in the process of remanufacturing and repair of such steels, which reduces the loss of toughness after each welding and the generation of residual tensile stress [7–9]. However, due to the uneven heating of the repair welded joints, the microstructure and mechanical properties of the repair welded joints will be changed or even discarded because they cannot meet the requirements of use. Ahmad et al. studied 30CrMnSiA steel after multiple GTAW welding repair, quenching and tempering [10]. It was observed that the tensile strength and corrosion resistance of the specimens decreased, while the elongation and impact energy increased slightly. Carrouge [11] and Enerhaug [12] et al. used the arc welding process to produce a large heat-affected zone in the super martensitic stainless steel weldment and to influence its mechanical properties. During the repair welding process, the resulting welding heat cycle is equivalent to heat treatment of a small local area. Jiang Wen studied the microstructure transformation of super martensitic stainless steel during tempering, the mechanism of producing reversed austenite and its influence on properties [13]. Mirakhorli et al. studied the post-weld tempering microstructure of CA6NM stainless steel by hybrid laser-arc welding. They analyzed the microstructure evolution from the fusion zone to the base metal and characterized the distribution of reversed austenite in different heat-affected areas by EBSD [14]. Wang Pei and others have studied the phase transition of ZGCr13Ni4Mo low-carbon martensitic stainless steel during the tempering process, which shows that different tempering temperatures and times have significant effects on the content, microstructure and morphology of reversed austenite [15]. Mohsen et al. studied the distribution of microstructure and hardness of 13Cr4Ni steel after multi-pass welding and pointed out that there is a tempering zone and a double quenching zone in the heat-affected zone [16]. Da-Kun Xu et al. studied the refinement of martensite slabs in 00Cr13Ni5Mo2 super martensitic stainless steel during tempering at sub-temperature and considered that the reversal of martensite to austenite was the main reason for refinement [17]. Yang et al. studied the crack propagation law of the heat-affected zone of P91 steel welded joint under repair heat load, and pointed out that under the action of the repair heat cycle, the crack in the affected zone propagates perpendicular to the surface and deflects towards the weld [18]. Mohammad et al. repaired X20Cr13 martensitic stainless steel by gas shielded metal arc welding many times. During 0–9 repairs, they observed no adverse effect on microstructure and mechanical properties, improved heat-affected zone (HAZ) impact toughness and promoted ductile fracture [19]. Zhang pointed out that abnormal grain coarsening occurred during solution treatment of the repair joint in the research of post-weld heat treatment of GTAW repair weld joint of sand casting Mg-Y-RE-Zr alloy [20]. Carpenter K. R. et al. performed multiple weld repairs and Gleeble heat-affected zone simulations to describe the effects of repeated thermal cycles on the microstructure and toughness of different heat affected zone [21]. At present, there is no specific research on the properties of ZG06Cr13Ni4Mo martensitic stainless steel after several repair welding and the microstructure transformation in the repair welded joints. Especially, what effects the reversed austenite generated during the repair welding process will have on the microstructure and properties remain to be further studied. The influence of reversed austenite formed during repair welding on the microstructure and properties of welded joints also needs to be studied. Therefore, in this paper, we study the change in microstructure and mechanical properties of ZG06Cr13Ni4Mo martensitic stainless steel welded joint under different numbers of welding repairs, and we explore the relationship between the number of welding repairs, the content of reversed austenite and mechanical properties to provide corresponding theoretical guidance for production practice.
2. Materials and Methods

In this experiment, a ZG06Cr13Ni4Mo martensitic stainless steel plate was welded by GTAW. The planer was used to slot and prefabricate the welding groove on the steel plate. The groove diagram of the repair welding test plate is shown in Figure 1a. The model of the welding equipment was Panasonic YC-400TX4 (Panasonic, Osaka, Japan), the electrode type was DC positive connection, the diameter of tungsten electrode was 2.4 mm, the geometry of tungsten electrode tip was 45°–50°, the shielding gas was pure argon, the gas flow was 8–10 L/min, the current range was 180–200 A, the voltage range was 17–20 V and manual welding was adopted. The composition of the base metal and welding wire are shown in Table 1. The first repair welding was to open a V-groove on the casting and then weld it. The second repair welding was to plan the thickness of the weld with a planer to a margin of about 5 mm based on one repair welding, and then continue repair welding under the same process. Penetrant testing (PT) and radiographic testing (RT) were checked and qualified after the welding. When the test results met the requirements (RT II and PT I), the sample was machined according to the diagram in Figure 1b. Pictures of the specimen for the twice repair welding, tensile test and impact test were shown in Figure 1c,d.

Table 1. Chemical compositions of ZG06Cr13Ni4Mo cast steel and ER410NiMo (mass fraction, wt.%).

| Sample         | C    | Si   | Cr   | Ni   | Mn   | Mo   | S    | P    |
|----------------|------|------|------|------|------|------|------|------|
| ZG06Cr13Ni4Mo  | 0.04 | 0.58 | 13.6 | 4.10 | 0.60 | 0.55 | 0.01 | 0.02 |
| ER410NiMo      | 0.02 | 0.40 | 12.1 | 4.61 | 0.60 | 0.47 | 0.002| 0.021|

The metallographic specimens of the welded joints were cut and polished. Then, Kalling’s No. 1 corrosive agent (1.5 g CuCl₂, 33 mL HCL, 33 mL C₂H₅OH, 33 mL H₂O) was prepared to corrode at room temperature. The microstructure was observed under the metallographic microscope of OMLPUSBX-6 (Olympus, Tokyo, Japan). The X-ray diffraction (XRD) instrument XRD-Shimadzu7000 (Shimadzu, Kyoto, Japan) was used to detect the phase of the welded joints. For the detection parameters, CuKα ray, 2θ was 2° to 90° and the scan speed was 2°/min. The tensile and impact fracture of the specimens were observed by field emission scanning electron microscopy (Carl Zeiss, Oberkochen, Germany) with the Gemini SEM model. The phase content and grain size were identified by electron backscattering diffraction (EBSD). The strength and toughness of the welded joints were tested using...
the WAW-300C tension tester (Xin Sansi, Shanghai, China) and the JB-300B impact tester (Hengda Huifeng, Jinan, China) as specified in ASME-SA370-2015.

3. Results
3.1. Microstructure of Repair Welded Joint
3.1.1. XRD Phase Detection and Analysis

As can be seen from Figure 2, the phase composition of the original casting is a single martensite phase. The austenite phase is formed in both the once and twice repair weld metal (WM) and heat-affected zone (HAZ) and the microstructure consists of martensite and austenite. Austenite phases are present in the WM and HAZ. During the cycle of repair welding, the weld heat treats the HAZ and the second layer of bead to the previous layer of the weld. The temperature increase is just enough to produce some austenite particles and temper the new martensite matrix [22]. The WM and HAZ suffer an uneven heat cycle of welding. When the temperature exceeds the critical temperature for transformation from martensite to austenite, the reversal transformation from martensite to austenite will take place; Bilmes et al.’s research also points out this change [23]. Austenite formed by the reversal transformation which will be preserved at room temperature is called reversed austenite.

![X-ray diffraction patterns of casting and repair welding joint.](image)

Figure 2. X-ray diffraction patterns of casting and repair welding joint.

3.1.2. Metallographic Microscopic Analysis

Figure 3 shows the microstructures of the original castings. From the optical microscope (OM), it can be seen that the original austenite grains are divided into several martensite packets with a similar orientation, each of which contains several martensite blocks composed of roughly parallel, unequal strip widths. Figure 3b is the microstructure diagram under the scanning electron microscope (SEM). It shows that each martensite block consists of densely arranged thin laths of different lengths. No other phases except martensite laths are found in the diagram, which is the same as the XRD analysis of the original casting in Figure 2.

![Microstructure of original casting. (a) OM, (b) SEM.](image)

Figure 3. Microstructure of original casting. (a) OM, (b) SEM.
In Figure 4, the microstructures of different areas of the once and twice welded joints are shown. Figure 4a,b is the fusion zones of welded joints. It is clear that the welded joints consist of three parts: WM, HAZ and base metal (BM). From the macro view of the welded joints, it is obvious that the microstructure of the welded joints decreases gradually from the BM to the WM. The base metal in the once and twice repair welded joints is typical lath martensite, as shown in Figure 4c,i. The martensite substructure maps of Figure 4f,l are obtained by SEM. The blocks in the maps consist of many parallel martensite laths, often with black and white lath distributions. In Figure 4j,m is HAZ in once and twice repair welded joints. Their microstructures are typical tempered martensite microstructure. Compared with Figure 4f,i, the HAZ is significantly refined. In Figure 4g,m, the martensite laths decrease significantly, becoming shorter and finer, and the block becomes more dense. In addition, there is a lot of bright white aggregation at the martensitic block boundary. Figure 4e,k represents WM in once and twice welded joints. The fine equiaxed martensite microstructure is observed in the metallographic microstructure. Because the microstructure is small, it is observed and analyzed under the SEM, as shown in Figure 4l,n. Due to the latter weld bead having the effect of heat treatment on the weld microstructure of the previous layer during the repairing process of multi-pass, multi-layer welding, the microstructure in the weld also appears as a tempered martensite microstructure. In the SEM diagram, it is also observed that the approximately equiaxed martensite blocks become finer, and more fine and dense martensite laths are formed in the welded joints. There are many bright white particles and fine strip component segregation zones in the once and twice welded joints.

In order to explore the composition changes in the bright white segregation zone in WM and HAZ during repair welding, the content of Cr and Ni in martensite in original casting (Figure 4f,l), bright white zone in once and twice repair welding HAZ (Figure 4g,m) and WM(Figure 4h,n) were tested by energy spectrum analysis. The results are shown in Table 2. From Table 2, it can be seen that the content of Cr and Ni elements in the original casting is equivalent to that of the casting, but the Ni-enriched and chromium-depleted elements are present in the bright white areas in the HAZ and the WM. Nickel enrichment is generally considered to be the main reason for the stabilization of reversed austenite, as the Ni element significantly reduces the starting temperature of martensite transformation and promotes an increase in the amount remaining at room temperature [24]. In combination with the austenite diffraction peaks in the XRD diffraction analysis of Figure 2, the reversal of martensite (M) to austenite (A) occurs in CA6NM steel at temperatures higher than the critical tempering temperature, resulting in the formation of reversed austenite at the martensite block boundary; this is similar to the findings of Bilmes et al. [23]. In the medium-temperature HAZ of multi-layer and multi-pass welding, the increase in the welding heat cycle temperature was just enough to produce some austenitic particles and temper the new martensite matrix, similar to Thibault’s research [22]. Therefore, we can infer that reversed austenite is formed in the bright white areas of the HAZ and the WM area after repair welding.

Because the reversed austenite is too small, its morphology cannot be observed under OM and 2000× magnification SEM; instead, electron backscattering diffraction (EBSD) was used, and the results are shown in Figure 5. In Figure 5, the red represents martensite, the yellow represents reversed austenite and the black line represents the grain boundary. We found that in the original casting with all-martensite microstructure and no detected austenite phase, the reversed austenite generated during repair welding is distributed at the grain boundary of the original austenite and the boundary of the martensite laths. The aggregation and segregation of elements in the defective areas such as the boundary of packets, blocks or laths of martensite will decrease the temperature point at which austenite begins to form. These reactions will make the reversed austenite easy to form in its position and increase the content of the reversed austenite; similar phenomena have been observed in other studies [25].
Figure 4. Microstructure of once and twice repair welded joints. (a) Once repair welded joint; (b) twice repair welded joint; (c,f) once repair welding BM; (d,g) twice repair welding BM; (e,h) once repair welding HAZ; (i,l) twice repair welding HAZ; (j,m) once repair welding WM; (k,n) twice repair welding WM.

Table 2. Changes in Ni and Cr element contents in different regions (mass fraction, wt.%).

| Element | P1   | P2   | P3   | P4   | P5   | P6   |
|---------|------|------|------|------|------|------|
| Cr/wt.% | 12.69| 12.79| 11.05| 11.14| 11.95| 11.69|
| Ni/wt.% | 4.48 | 4.25 | 6.41 | 6.16 | 6.38 | 6.39 |

Figure 6 shows the contents of martensite and reversed austenite in welded joints for once and twice repair welded joints. The content of reversed austenite at room temperature depends on the stability of the reversed austenite [11]. It can be seen from Figure 6 that the reversed austenite content in the WM is 9.3%, which is slightly higher than 8.86% of the HAZ. This is due to the normalization of the first layer of WM and HAZ by the second layer of the weld during multi-layer and multi-pass repair welding. Where the temperature is at $M \rightarrow A$ above the critical transition temperature, the reversed austenite nucleates and grows at the martensite boundary of the lath. Moreover, because the inhomogeneous welding heat cycle temperature in the HAZ is much higher than that in the WM, the reversed austenite will remelt when the temperature is higher than the stable temperature of the reversed austenite. Segregation of Ni elements becomes homogeneous, which decreases its stability, and subsequent cooling causes the transformation of reversed austenite into new martensite, which in turn causes the content of reversed austenite in the HAZ to be lower than that in the WM. During the twice repair welding, the temperature and time of the WM and HAZ above the critical transformation temperature from $M \rightarrow A$ are higher.
than that of once repair welding. Thus, the content of reversed austenite in the twice repair welded joint is higher than that in the once repair welded joint.

![Figure 5](image)

**Figure 5.** Phase content and grain boundary distribution diagram. (a) Original casting; (b) once repair welding WM; (c) once repair welding HAZ; (d) twice repair welding WM; (e) twice repair welding HAZ.

![Figure 6](image)

**Figure 6.** Contents of martensite and reversed austenite in once and twice repair welded joints.

The grain sizes of martensite and reversed austenite of the original casting and WM and HAZ in the once and twice repair welded joints were calculated by Channel 5 software (version 5.12.74.0); the results are shown in Figure 7. It can be seen from Figure 7 that the microstructure of the repair welded joint is significantly finer than the average grain size of the original casting (about 1.691 μm). The average martensite microstructure size of the WM in once repair welded joint is nearly twice as large as the reversed austenite produced. Due to this, the weld pool metal tissue solidifies faster during the welding process, which will refine the tissue in the weld. Moreover, during the multi-layer and multi-pass repair welding process, the normalizing effect on the HAZ and the upper layer of the weld bead will refine the HAZ as-cast microstructure and WM. The reverse transformation in
a process above the critical tempering temperature-produced austenite followed generally by the refinement of martensitic laths at room temperature, which is consistent with the refinement of 13Cr-nimo super martensitic stainless steel reported by Bilmes et al. [23]. Considering that the specimen was martensitic with refinement observed when it was subjected to a non-uniform welding heat cycle treatment, it is reasonable to infer that the reversed austenite produced at above the austenite start transition temperature resulted in martensitic laths refinement. Even at a high temperature, more reversed austenites were produced, and because the unstable reversed austenite transformed into new martensite again during cooling, the martensite was finally refined. The microstructure changes in the twice welded joint were similar to once repair welded joint, with further refinement in both martensitic and reversed austenite of WM and HAZ. In particular, two normalizing heat treatments were performed for the HAZ, and their martensitic and reverse austenites were significantly refined, which can play a great role in improving the HAZ of weak mechanical properties.

Figure 7. Average grain size distribution of martensite and reversed austenite in different areas with repair welding once and twice.

3.2. Mechanical Properties of the Welded Joint Area
3.2.1. Tensile Test

The tensile test is one of the important means for quality inspection of welded joints of metal samples. The indices of tensile strength, yield strength and elongation section shrinkage provide an important basis for product design and process verification [26]. The performance indices of repair welded joints under different times are tested and the data obtained are sorted and shown in Figure 8.

The results of tensile strength and yield strength are shown in Figure 8a. It can be seen that the tensile strength of the original casting is 975.7 MPa. The tensile strength of the once welded joint is 928.6 and 910 MPa for the twice welded joint. The yield strength increases with the number of repairs and the yield-strength ratio increases, so the material is more resistant to deformation and less prone to plastic deformation. The section shrinkage and elongation increase with the number of welding repairs in Figure 8b. The reason is that reversed austenite significantly improves its plasticity and toughness, which, contained in the welded joint, undergoes a martensitic transformation during tension. In conclusion, after once repair welding and twice repair welding, the tensile strength decreases slightly, the yield strength increases significantly compared with the original casting and the section shrinkage and elongation of the plastic index increase gradually.
The number of repair welding


twice once

Grain Size (μm)

|          | WM-M | WM-A | HAZ-M | HAZ-A |
|----------|------|------|-------|-------|
| Original casting | 0.927 | 0.591 | 0.452 | 0.288 |
| Once      | 1.423 | 1.192 | 0.907 | 0.509 |
| Twice     | 1.691 | 0.0   | 0.0   | 0.0   |

Figure 7. Average grain size distribution of martensite and reversed austenite in different areas with repair welding once and twice.

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Figure 8. Relationship between tensile properties and number of repairs. (a) Tensile strength, yield strength, yield strength ratio. (b) The shrinkage and elongation of sections.

After the tensile test, the fracture positions of the three groups of specimens appear in the HAZ of the welded joint. From the macroscopic view, all the specimens present cup cone-type fractures. Obvious necking can be observed and there are obvious shear lips, radiation areas and fiber areas on the fracture surfaces. Figure 9 displays the micro-morphology of the fracture for further observation. The tensile fracture of the original casting contains small and dense dimples and a small number of slip surfaces, shown in Figure 9a. Figure 9b,c is the fracture diagrams of once and twice welded joints, respectively, and show that there are a lot of equiaxed dimples. Compared with Figure 9a, the dimples are large and deep, and there are small dimples with large dimples, all of which are good for plastics. When the larger dimples in Figure 9b,c cause large plastic deformation at their edges, the grains restrain each other and the slip takes place along several slip systems, resulting in serpentine sliding, ripple, and extension zone characteristics on the dimple wall, as shown by the white arrow in Figure 9. The white ridge line at the edge of dimple is the tear edge, which is the slip line left by the growth and unstable expansion of microcracks between dimples under the action of larger external forces, indicating that they have undergone large plastic deformation. During the stretching process, when the specimen necks due to loading, in the area of large deformation, the interface of the metal matrix will be broken and separated, and many small holes will be formed, which become the core of the microcrack source. With the increase in external force, the voids grow and form larger dimples. When the dimples are connected with each other through the tear edges, the crack propagates forward and eventually leads to fracture.
The results of tensile strength and yield strength are shown in Figure 8a. It can be seen from Figure 10 that the impact energy of the WM and HAZ after repair welding is higher than that of the original casting, and the impact energy value of the twice repair welded joint is higher than that of the once repair welded joint. Particularly, in the once and twice repaired WM, the impact energy is significantly increased, which shows that the joints have better impact toughness after the repair welding.

![Figure 9](image_url)

**Figure 9.** Tensile fracture morphology under different repair welding times. (a) Original casting; (b) once repair welded joint; (c) twice repair welded joint.

3.2.2. Impact Test

The impact toughness of WM and HAZ of the repair welded joints at 25, 0, −20, −40, and −60 °C were tested to determine the influence of the number of welding repairs on impact toughness of welded joint; the results are shown in Figure 10. It can be seen from Figure 10 that the impact energy of the WM and HAZ after repair welding is higher than that of the original casting, and the impact energy value of the twice repair welded joint is higher than that of the once repair welded joint. Particularly, in the once and twice repaired WM, the impact energy is significantly increased, which shows that the joints have better impact toughness after the repair welding.

![Figure 10](image_url)

**Figure 10.** Impact energy in different areas of welded joints.

In Figure 10, the impact energy curve has an obvious inflection point at −20 °C; the corresponding impact fractures are shown in Figure 11. The impact fracture of the original casting is shown in Figure 11a. From the macrofracture view, there are three typical areas: fiber zone, radiation zone and shear lip. From the microfracture view, the fracture morphology is a quasi-dissociation fracture. There are cleavage surfaces and slip bands in the figure. In the local area, dimple bands are formed due to micropore accumulation during the tearing process. Figure 11b,d shows the impact fractures in once and twice repaired WM. The fibers on the fracture represent the position of certain instantaneous crack
front in the fracture process, arranged in rows. The radiation zone cannot be found, which indicates suitable plasticity and toughness. The fiber zone and the shear lip can be found in the microfracture, which shows typical tough fracture. In addition, some secondary cracks formed by micropore aggregation can also be found, which are formed by plastic tears under the action of external forces. Figure 11c,e shows impact fractures in the HAZ of once and twice repair welding. From the macroscopic view, compared with the fracture in the WM, the areas of the fiber zone decrease and the toughness decreases. Further analysis of the microfracture structure is a mixed fracture of toughness and quasi-cleavage. The dimple bands in the figure are formed when large plastic deformation occurs and when the hidden crack sources micropore aggregate to form dimples. When plastic deformation continues to increase, dimple bands are formed, as shown by the arrows in the figure. After the occurrence of cleavage cracks in different areas, they grow continuously under the action of force, and finally tear the remaining connecting parts in a plastic way. The cleavage cracks develop into cleavage planes, while part of plastic tearing is shown as tearing ribs, dimples or dimple bands.

Figure 11. Impact fracture morphology. (a) Original casting; (b) once repair welding WM; (c) once repair welding HAZ; (d) twice repair welding WM; (e) twice repair welding HAZ.

Material toughness is determined by two main factors: the type of microstructure and the grain size of the microstructure [27]. Based on the analysis of microstructure and grain size, a large amount of fine reversed austenite is dispersed at the boundary of martensite laths in the welded joint. Reversed austenite has a significant toughening effect. When plastic deformation occurs during impact, the reversed austenite absorbs deformation power and transforms into martensite; this plastic-induced phase transformation can significantly improve the material toughness [15,28]. Zackay [29] et al. pointed out that when reversed austenite transforms into martensite through plastic-induced phase transformation, it absorbs about six times the energy absorbed by plastic deformation of stable austenite grains. It can be seen that the impact toughness of the repaired welded joint can be improved significantly. Local Ni-rich, reversed austenite remains stable at room temperature and its presence in multi-pass welding is advantageous, in agreement with
The presence of reversed austenite can alleviate stress concentration, hinder the formation and propagation of cracks and reduce crack sensitivity. In combination with Figure 7, it can be seen that the grain sizes in the once and twice repair welded joints are also significantly refined, which plays an active role in improving the strength and toughness. Fine martensite laths result in an increase in hardness/strength by introducing more boundaries that prevent dislocation movement.

4. Discussion

The transformation-induced plasticity of reversed austenite generated in the repair welding area will occur under the external load, which transforms the reversed austenite into martensite and improves the plasticity and toughness of the material. EBSD was used to detect the necking zone of the fracture of the once and twice repair welded tensile specimens. Figure 12 is a band contrast and phase diagram of the necking zone at the fracture of the once and twice welded tensile specimens. The deformation of martensitic laths is elongated, and it is difficult to confirm the existence of reversed austenite. At 2000× magnification, the splitting step is 0.09 μm under the parameter and the contents of reversed austenite in the necking zones of tensile fractures are 0.02% and 0.04%, respectively. Compared with the content of reversed austenite in pre-tension weld joint area, the content of reversed austenite in the repair weld area is basically zero after tension deformation. The reversed austenite formed in the repair welding area completely transformed into martensite after tension. During the transformation process, a large amount of energy is absorbed and the plasticity is improved. Similarly, in the process of impact, the impact toughness will be improved because the transformation-induced plasticity of reversed austenite absorbs a lot of energy.

![Figure 12. Band contrast and phase diagram of the necking zone at the fracture. (a) Once repair welding; (b) twice repair welding.](image-url)

In the process of GTAW repair welding, when the temperature is higher than the critical transition temperature from M → A, it will undergo reverse transformation and form reversed austenite. The mechanism of its transformation is shown in Figure 13. When the critical transition temperature from martensite to austenite is reached, the martensite begins to form within a prior-austenite grain, including several martensite packets, as shown in Figure 13a. The martensite packets consist of martensite blocks with approximately parallel orientations, and within martensite blocks, there are many martensite laths with similar orientations closely arranged, as shown in Figure 13b. When the temperature of the welding heat cycle is higher than the critical transition temperature from martensite to austenite, enrichment of Ni and barrenness of Cr elements are formed at the boundary of the martensite laths during the repair welding process. These zones then become reversed austenite at the nucleation location shown in Figure 13c, and the reversed austenite will grow as the temperature continues to increase. During the growth of reversed austenite, one side is close to and parallel to the boundary of the martensite laths and the other side is embedded in the matrix of the martensite laths, as shown in Figure 13d.
When the temperature is higher than the solution temperature of austenite, the enriched Ni element is homogenized due to diffusion, which decreases the stability of reversed austenite. Reversed austenite is dissolved and metastable reversed austenite is re-transformed into new martensite (M') or the previously wider slab martensite is divided into two or several pieces; thus, the martensite laths are refined. Therefore, the formation of reversed austenite is the main reason for martensite refinement.

During the process of repair welding, the martensite blocks are refined due to the heat treatment effect of the welding heat cycle on the HAZ and the previous WM. The schematic diagram is shown in Figure 14. When the heat cycling temperature is higher than the critical transition temperature of \( M \rightarrow A \), the Ni element enriches at the boundary of martensitic laths and becomes the nucleation point of reversed austenite. With the subsequent temperature changes, there are two ways for the reversed austenite to change. The first is Path A: when the heat cycling temperature is slightly higher than the critical transition temperature of \( M \rightarrow A \), the reversed austenite grows up and occupies part of the matrix of martensite laths, the width of remaining martensite laths will be narrowed and martensite laths will be refined. In Path B, when the heat cycle is much higher than the critical transition temperature of \( M \rightarrow A \), the reversed austenites that have nucleated at the martensitic lath boundary gradually grow. When the temperature is higher than the solution temperature of austenite, the enriched Ni element is homogenized due to diffusion, which decreases the stability of reversed austenite. Reversed austenite is dissolved and metastable reversed austenite is re-transformed into new martensite (M') or the previously wider slab martensite is divided into two or several pieces; thus, the martensite laths are refined. Therefore, the formation of reversed austenite is the main reason for martensite refinement.

In addition, the large angle grain boundary area (primary austenite grain boundary, martensite packet boundary and martensite block boundary) within the austenite grain boundary of the original casting will become the nucleation position of austenite and change a large primary austenite grain into several small austenite grains due to the heat cycle of the repair welding heating in the area of the repair welding joint [31]. During subsequent cooling, the transformation of fine austenite grains into lath martensite will refine the martensite microstructure, as shown in Figure 15.
During the process of repair welding, the martensite blocks are refined due to the heat treatment effect of the welding heat cycle on the HAZ and the previous WM. The change a large primary austenite grain into several small austenite grains due to the heat boundary of the original casting will become the nucleation position of austenite and martensite laths. In Path B, when the heat cycle is much higher than the solution temperature of austenite, the enriched Ni element is homogenized due to diffusion at the martensitic lath boundary gradually grow. When the temperature is higher than the critical transition temperature of $M_c$, martensite refinement. In Path A, the reversed austenite grows up and occupies part of the WM increases by 88% and 120% compared with HAZ, respectively.

5. Conclusions

1. After repair welding of ZG06Cr13Ni4Mo, the phase composition of the welded joint changes from martensite alone to martensite and a small amount of reversed austenite. Reversed austenite distributes at the martensite boundary of a block in a fine strip shape and increases with the number of welding repairs. The content of reversed austenite in twice repair welding is larger than that in once repair welding, and the WM is larger than that in the HAZ.

2. Within the test range, repair welding can refine the microstructure of the welded joint. The microstructure of a twice repair welding joint is finer than that of a once repair welding joint and finer than that of the original casting (compared with the original casting, the martensite in the WM is refined by 45.2% and 65.1%, respectively). The microstructure of the WM is thinner than that of the HAZ (in once and twice repair welded joints, the microstructure size of the WM is 63.7% and 73.3% of the HAZ, respectively). Reversed austenite is finer than martensite (in WM, reversed austenite is about 50% of martensite size).

3. In the test range, the production of reversed austenite plays a positive role in plasticity and toughness. The yield strength, elongation and reduction of the area gradually increased. The impact energy of the twice repair welding is greater than that of the once repair welding (the WM impact energy increases by about 30 J at the same temperature), and the impact energy of the WM is greater than that of the HAZ (at $-20^\circ C$, the WM increases by 88% and 120% compared with HAZ, respectively).

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