Microstructure and fatigue damage mechanism of 6082-T6 aluminium alloy welded joint

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Abstract

In this paper, 6mm thick 6082-T6 high-strength aluminium alloy is taken as the research object, and CLOOS ROMAT-3500 industrial robot MIG welder is used for welding. High-cycle fatigue test is carried out on welded joint and 6082-T6 base metal. Microstructure, microhardness, tensile properties and fatigue properties are studied, and fatigue fracture is observed and analyzed. The test results show that: equiaxed crystals exist in the center of the weld. Broken equiaxed crystals are found in the weld due to stirring in the molten pool, a large number of pore and columnar crystal layers are found at the junction of the two beads. A small amount of pore and cellular dendrite are found in the fusion zone. A softening zone with a minimum hardness of 65.5HV exists in the heat affected zone (HAZ). The conditional fatigue limits for base metal and weld specimens are 77.26MPa and 48.69MPa at the set target cycle of 10^7 respectively. In fatigue fracture, there are a lot of cleavage fracture characteristics and ductile fracture characteristics. The crack initiation is quasi-cleavage fracture characteristic. In the past studies, I have studied the fatigue life of joints, but as the research progresses, I believe that the fatigue behavior and fatigue damage mechanism plays an important role in fatigue life. In this paper, Fatigue fracture process is analyzed by correlation calculation of stress intensity factor. Two crack initiation modes are proposed based on the welding process. The first is fatigue crack initiation caused by stress concentration at the grain boundary where hydrogen elements converged, the second is fatigue crack initiation caused by the gap between equiaxed and columnar crystals inside and outside the central pore of the weld.

1. Introduction

6082 aluminum alloy has good mechanical properties, low density, excellent corrosion resistance, good processability [1], excellent welding performance and mechanical properties, etc [2-4]. It can be used as a light new material to meet various requirements through different metal processing technology in transportation, automobile manufacturing, aerospace and other occasions [5-7].

Melting inert gas arc welding (MIG) uses welding wire as one electrode and workpiece as the other, under inert gas protection, the welding wire acts as arc initiation, arc stabilization and metal filling into the molten pool. Although the current range used for MIG welding is large, due to the low energy density and insufficient concentration of MIG welding, the penetration is very limited when welding aluminium alloys with very high thermal conductivity [8]. If high penetration is to be pursued, a higher heat input and a lower welding speed are required. However, this will lead to coarse structure and poor mechanical properties of the welded joint. At present, although many advanced welding technologies have appeared, MIG welding is still the most widely used welding technology for high-speed train body joints, numerous studies have shown that there are softening zones in the heat affected zone where the yield strength is significantly reduced by about 40%, which have a great negative impact on the safety and reliability of high-speed trains.

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Fatigue fracture is a common failure mode of metal components, it has been found in numerous studies [9–11] that the stress corresponding to the fatigue life limit of many materials is often lower than its own strength and even the stress corresponding to the fatigue life limit of a few materials is lower than its yield strength. Therefore, fatigue fracture is a very dangerous failure behavior. At present, the high-speed trains with speeds over 500 km h\(^{-1}\) have entered the test stage, and the increase of speed has increased the impact load of each state of the trains which puts forward higher requirements for service fatigue life safety of welded joints [12–14]. The welded parts of the train body are often the weakest link, so the fatigue life of the welded joints largely determines the safety and reliability of the train operation. In conclusion, the research on MIG welding technology, microstructure and mechanical properties of 6082 large-scale wide heat treatment strengthening high-strength aluminium alloy has a profound influence on the reliability of high-speed train long-term operation and the development of manufacturing technology.

Although there is a lot of literature on fatigue properties of 6000 series aluminium alloys, the influence on fatigue behavior and damage mechanism of joints has not been studied in depth. High cycle fatigue tests on 6082-T6 aluminium alloy base metal and welded joints are carried out in this paper. Deformation structure and fracture characteristics of cyclically failed fatigue specimens were studied in detail under given stress amplitudes. The purpose of this study is to gain a more comprehensive understanding of the fatigue behavior of 6082-T6 aluminum alloy base metal and welded joints, and to reveal the fatigue damage mechanism and the evolution process of fatigue crack growth.

### 2. Experiment

#### 2.1. Experimental materials

The test material is 6 mm thick 6082 aluminium alloy plate, which is treated by solution and artificial aging. This heat treatment process is T6. In the following, 6082-T6 is used to represent the state of the base metal. ER5356 with diameter of 1.2 mm is used as welding wire and its chemical composition is shown in table 1 [15].

#### 2.2. Welding process

The base metal is welded by automatic MIG welding method. The base metal is welded by German CLOOS ROMAT-3500 industrial robot MIG welder. The plate thickness is 6 mm, the joint type is 70° single V butt joint, the shielding gas is 99.999% high purity argon. The welding process parameters are shown in table 2, in which bead 1 is backing weld and bead 3 is cosmetic weld.

#### 2.3. Microscopic analysis

Welding produces different microstructural areas in the joint. As the surface of the polished metal sample is bright as a mirror, it is white under the microscope. In order to show the true and clear structure, the metal sample is corroded by Keller reagent and the microstructure of different areas is observed after corrosion. The microstructure of BM, HAZ and WZ are observed with VHX-600 optical microscope. The micro-hardness of the welded joint is tested with HX-1000 Vickers hardness tester. The loading force is 100 g and the holding time is 15 s. The fatigue test fracture is observed and analyzed with S-3400 SEM.

#### 2.4. Mechanical properties test

Mechanical properties tests include tensile and fatigue tests. As shown in figure 1(a), the tensile test is carried out on a Zwick-HB250 testing machine at room temperature, the tensile rate is 360 N s\(^{-1}\). The fatigue properties test

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**Table 1.** The chemical composition of the 6082-T6 and the filler material (wt.%).

| Material | Si   | Mg  | Zn  | Fe  | Ti  | Cu  | Mn  | Al   |
|----------|------|-----|-----|-----|-----|-----|-----|------|
| 6082     | 0.97 | 1.02| 0.06| 0.37| 0.01| 0.07| 0.67| Balance |
| ER5356   | 0.18 | 5.10| 0.06| 0.25| 0.11| 0.09| 0.08| Balance |

**Table 2.** Welding process parameters.

| Bead | Welding current/A | Arc voltage /V | Welding speed/(mm·s\(^{-1}\)) | Shielding gas flow/(L·min\(^{-1}\)) | Heat Input/(J·mm\(^{-1}\)) |
|------|------------------|----------------|-------------------------------|-------------------------------------|-----------------------------|
| 1    | 180              | 23             | 4                             | 15                                  | 724.5                       |
| 2    | 210              | 23.5           | 3                             | 15                                  | 1151.5                      |
| 3    | 210              | 24             | 4                             | 15                                  | 882                         |

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is carried out on Zwick-HB250 experimental machine, axial sinusoidal cyclic load with stress ratio \( R = 0.1 \) on the specimen, the frequency is about 100Hz, the specified number of cycles is \( 10^7 \). Tensile specimen and fatigue specimen are made according to GB/T3075-2008 standard, as shown in figure 1(c), and the thickness is 6 mm, The tensile specimen and fatigue specimen are shown in figure 1(b). According to the size of the sample, the maximum stress is calculated, and the test is carried out from 70% of the tensile strength. In order to eliminate the influence of surface defects on the experiment, the samples are polished with 400#, 800#, 1000#, and the fatigue fracture is observed by JSM-6700F SEM.

3. Experimental results and analysis

3.1. Microstructure analysis

During MIG welding, there are base metal grains at the melting boundary, which correspond to the matrix required for nucleation, the liquid metal is in direct contact with the matrix particles, in which the crystal cell can easily nucleate on the matrix grains. As shown in figure 2(a), when the boundary of the molten pool begins to crystallize, The molten pool crystallizes in the form of columnar crystals from the partially melted BM surface to the weld center. There are many different orientations of grains in the early stage of growth on the side near the weld. However, the grains growing along the direction of temperature gradient compete to grow, and the grains growing along other directions are restrained and stop growing, thus forming cellular crystals, because of the increase of undercooling, most of the cellular crystals in the weld area deviating from the fusion zone grow laterally and transform into columnar crystals, which are oriented towards the weld center. Because this direction has the largest temperature gradient. At the same time, there are obvious epitaxial solidification at the fusion line. Figure 2(b) shows the microstructure of the weld center, where the undercooling increases continuously, because the molten metal has very little restraining force during the crystallization process and the core temperature gradient is very small, it can nucleate from inside the liquid phase, equiaxed crystals with a diameter of about 50μm are formed. The center of the weld is snowflake like equiaxed crystal with a small amount of cellular dendrites. Figure 2(c) shows the microstructure at the joint of the two beads. Pore defects are first found at the joint of the two beads, which is mainly caused by insufficient liquid metal flow during welding. Two areas separated by cylindrical crystals are also found in the welded area of the cosmetic welding, this is due to the fact that the grain of the first bead is remelted and the grain of the second bead epitaxies on the grain of the first bead, the heat input of the second bead promotes the secondary growth of the regional structure; The grain size of the first pass is larger than that of the cosmetic welding bead. This is not caused by a single factor of the thermal action of the rear weld bead, but by the fact that there are fewer heterogeneous nucleations during the
welding of the rear weld bead, while the basic reason for the heterogeneous nucleation is the insufficient flow of the molten pool during the welding.

3.2. Microhardness analysis

Figure 3 shows the measured microhardness curve of the welded joint 4 h after welding. As can be seen in figure 3, the microhardness distribution from the center of the weld to the base metal is uneven. From the edge of the HAZ (about 150 °C) to the center of the weld (about 680 °C), an area with a large difference in the type and distribution of precipitated phases is formed, which is also the reason for the uneven microhardness. Previous studies [16] have determined the dissolution temperatures of each precipitated phase from the GP zone to the steady state $\beta$ phase, with the following temperature ranges:

- GP zone dissolution around 30–150 °C
- $\beta'$ precipitation around 240/250 °C
- $\beta'$ precipitation from 250 up to 320 °C
- $\beta$ precipitation around 450 °C
- $\beta$ dissolution around 550 °C

In the HAZ high temperature quenching zone close to the fusion line, there is a hardness rise with the highest value of 95.2HV. Due to the higher heating temperature of thermal cycle, the strengthening phase dissolves more fully, and the $\beta'$ and $\beta''$ strengthening phases precipitate again in the subsequent natural aging process. The structure of $\beta''$ phase is different from matrix. Compared with GP zone, the coherent strain around $\beta'$ phase is larger, which leads to greater strengthening effect. $\beta'$ is also considered to be the main strengthening phase in Al-M-Si alloy system. The reprecipitation of $\beta''$ phase makes the strength and hardness of quenched zone increase to a great extent. Due to the microhardness distribution of 4 h after welding, the hardness has not reached a high level. It is estimated that the aging hardness will reach the peak after a longer period of time. With the distance from the weld center, the peak temperature of thermal cycle is lower than that of quenching zone, the reprecipitation of transition strengthening phase is reduced after welding due to insufficient re solution of
strengthening phase, and part of undissolved $\beta'$ phase is transformed into stable $\beta$ phase, the strengthening effect is greatly reduced, the softening zone is formed, and the hardness reaches the lowest value of 65.4HV. In the lower temperature zone far away from the weld, only MgSi clusters and GP zone redissolve, which has little effect on $\beta'$ and $\beta''$, and its hardness is not different from that of the base metal.

3.3. Tensile properties analysis

In order to study the mechanical properties of welded joint, the tensile test of 6082-T6 aluminum alloy MIG welded joint is carried out, and the tensile results are compared with that of 6082-T6 base metal. The results are shown in table 3. The tensile stress-strain curve of weld and base metal is shown in figure 4(a), since no sharp yield point is found in the two curves, the yield strength is estimated from the stress value of 0.2% plastic strain, and the yield strength of the two samples are 295.3MPa and 204.2MPa respectively. Compared with BM, TS and YS of WJ decreased significantly. The elongation of WJ is 6.3%. In these two kinds of local specimens, the low tensile strength of the welded joint and the existence of defects make the local stress concentration and large deformation of the welded joint. As shown in figure 4(b), in most cases there are more or less defects in the welded joints. Non-uniform stress distribution occurs at the defect section, where the maximum stress at the root of the defect exceeds the load applied in real time, resulting in micro-cracks at the edge of the defect. Under uniaxial tensile stress, small voids form in the local area of the sample, which reduce the toughness of the material, resulting in a lower elongation of WJ than that of BM. As shown in figure 4(b), the macro-fracture surface consists of countless small cup cones, which indicate that microcracks are propagating and interconnecting during plastic deformation. The color of the fracture surface is darkened and the color of the fracture is the result of light reflection from the fracture surface. The color darkening of the fiber ports is due to the poor reflection of light from the port surface and is characteristic of ductile fracture. The fracture surfaces of both specimens show 45° with the tensile axis and necking occurs. During the tensile process of the sample, the center of the sample first produces micro-cracks perpendicular to the tensile direction. When the crack body tip is loaded, a large amount of slip occurs in the plastic zone of the crack tip, forming an extension zone as shown in figure 4(c); When the dimple surface is perpendicular to the direction of the principal stress, the higher stress will result in a new slip on the free surface of the dimple, with sharp initial slip marks as shown in figure 4(d); As the load increases, the elongation region grows to a critical value, Formation of microvoids in the second phase of the ligament in front of the crack leading to the nucleation of the microcrack. As the load continues to increase,
microcracks propagate along one of the 45° planes, for the shape of test specimen specified in national standard GB/T228.1-2010, the shear stress of these two planes is the largest. When the crack propagates to a certain extent, the heat generated by the plastic deformation of the metal causes the local softening of the joint, coupled with the effect of continuously increasing load, and finally shears away along the 45° direction of the tensile axis.

3.4. Fatigue test

3.4.1. Fatigue life results analysis

The failure of structural parts during service is mostly caused by fatigue due to alternating loads, especially in stress concentrated parts of components. Fatigue test of 6082-T6 aluminium alloy weld joint specimens is carried out at room temperature according to national standard GB/T3075-2008. The cantilever fatigue test is carried out with an electro-hydraulic servo fatigue tester with actuating cylinder on the upper cross member. The test waveform is an equal amplitude sine curve. The applied force follows the longitudinal axis of the sample and passes through the axis of the cross section of each sample. The S-N curve of weld joint and base metal is shown in figure 5. Samples not broken after the target cycle are indicated by arrows and it is obvious from the diagram that the SN curves of the base metal and the joint show similar trends.

For the study of fatigue properties of welded structures, the fatigue life curves are generally expressed by stress amplitude $S_a = (S_{max} - S_{min})/2$ and number of cycles $N$ [17]:

$$C = N^k S_a^k$$ (1)

Where $N$ is the number of cycles, $S_a$ is the stress amplitude, $C$ is the fatigue strength coefficient defined when the number of cycles is 1, and $k$ is the fatigue strength coefficient. According to the description of S-N curve in national standard GB/T3075-2008, logarithmic coordinate is used for cycle number and linear or logarithmic coordinate for stress amplitude coordinate axes. In this paper, logarithmic coordinate axes are used for stress amplitude coordinate axes and logarithms are taken for both sides of equation (1):

$$\log C = \log N + k \log S_a$$ (2)

The linear relationship between $\log N$ and $\log S_a$ can be clearly seen from equation (2). The fitting formulas of weld joint and base metal can be obtained by Origin software fitting.
The fitting formula obtained above shows that the absolute value of $k$ in 6082-T6 aluminium alloy base material is slightly lower than that of $k$ in welding joint, which indicates that the fatigue life of welded joints decreases more rapidly during the same cycle load increase than that of the base metal. Formula (3) and Formula (4) can be used to estimate the fatigue limits of the base metal and the welded joint, which are 77.26MPa and 48.69MPa respectively. The fatigue life of the welded joint reaches about 63% of that of the base metal (stress amplitude under target cycle $10^7$).

### 3.4.2 Fatigue damage mechanism analysis

In fatigue tests, all specimens break at the weld, which indicates that the weld is the weakest link in the welded joint. Figure 6 is a SEM photograph of the fatigue fracture specimen of the 6082-T6 aluminium alloy welded joint. As can be seen from figure 6(a), the crack initiation is pore. Pore is a common defect in the welding process. The gas in the molten pool does not have time to over flow and stay in the weld. The appearance of pore will cause insufficient initial mechanical strength and structural defects. The fatigue crack initiated at the pore and propagated under long-time cyclic load, which eventually became the cause of fracture. A large number of tearing edges are found near the pores, which radiate around the pores. This large number of high-density short and curved tearing edges are similar to the river pattern in which the point cracks radiate from the center to the surrounding. The growth area presents a typical fan-shaped distribution, which can be inferred as a quasi cleavage fracture type. The stable fatigue growth area is characterized by cleavage fracture. Figure 6(b) is an enlarged view of the area circled by the square dotted line in figure 6(a), and obvious river pattern is found, this pattern is due to the fact that the crack growth is not limited to a single plane, followed by a series of parallel and simultaneously growing cracks, these cracks are interconnected by the disconnection of metal strips between them. When one of the tributaries is magnified, as shown in figure 6(c), it is found that there is a secondary crack with Z-shaped propagation characteristics at the edge of the tributary converging into the mainstream, and the crack closure effect, which Liu has analyzed in this paper [18]. Figure 6(d) shows the characteristics of fatigue striations in the stable growth stage of fatigue cracks. It can be seen from the figure that the secondary cracks existing together with the fatigue striations in the stable growth stage of fatigue cracks are parallel to the fatigue striations. There are large and small second phase particles between the striations, and the small particles have no effect on the fatigue striations. In the figure, it can be found that some second phase particles are cut, and the cracks are often hindered when they encounter large particles. Moreover, due to the dislocation reciprocating through the large second phase particles, dislocation accumulation will occur around the particles, which result in stress concentration and cracks on both sides of the particles. Figure 6(e) shows the instantaneous fracture area of welded joint fatigue fracture. There are a lot of dimples in this area, and the second phase particles are found at the bottom of most dimples. Figure 6(f) is an enlarged view of the dotted circle in figure 6(e). In the figure, it is obvious that the secondary crack passes through the grain and fatigue striations are found on the inner surface of the dimple. According to the dislocation theory, there are dislocation loops around the second phase particles. When the applied tensile stress is large enough and the elastic strain energy accumulated at the front edge of the dislocation loop is enough to overcome the interfacial bonding force between the second phase particles and the matrix to form a new surface, the microvoid will be formed. The microvoid will grow and gather until fracture. Therefore, we can know that there are a lot of cleavage fracture characteristics and ductile fracture characteristics in the fatigue fracture of welded joint, and the quasi cleavage fracture characteristics are at the crack stable growth area, which indicates that the fatigue fracture of welded joint is a mixed fracture of toughness and brittleness.
4. Discussion

The fatigue failure mechanism of 6082-T6 aluminum alloy welded joint includes three stages, as shown in figure 7. The first stage is crack initiation, and microcrack nucleation is caused by welding defects inside the joint. After microcrack nucleation, due to the influence of microstructure, the crack growth is still a slow and irregular process. However, after some microcracks propagate away from the nucleation point, more regular growth is observed. Under cyclic loading, the microcracks radiate around, which is the stage of low growth rate of microcracks; in the second stage of fatigue fracture, macroscopic stable crack growth. The third stage is instantaneous fracture. After the local damage propagation in the first and second stages, the third stage can be divided into fatigue crack instability propagation and instantaneous fracture. Due to the instability, the crack growth rate accelerates again on the basis of the second stage and finally fracture.

4.1. Evaluation of stress intensity factor

The fatigue fracture process of 6082-T6 aluminum alloy welded joint is analyzed by the calculation of stress intensity factor. According to the fracture morphology, the fracture diagram of internal failure is shown in figure 9. Vidit Gaur [19] has found that crack initiation due to defects accounts for the majority of cases at high
stress ratios ($R \geq 0.1$). This change is due to local cyclic plasticity caused by stress concentration factors associated with them. As mentioned above, in the first stage of crack initiation, the crack nucleates and spreads radially around under the action of cyclic loading. Under the action of axial load, the growing crack tends to

Figure 7. Stages of fatigue failure.

Figure 8. Analysis of fracture surfaces under tensile mean stress ($R = 0.1$) with Maximum stress 110MPa: (a) overall fracture surface, (b) brittle fatigue striation in stable crack growth area (point 1), (c) & (d) unstable crack growth area (point 2 and 3).
expand into a semi ellipse with uniform driving force at all points of the crack tip, which can be regarded as a circular embedded crack in an infinite solid. In this case, the range of the relative stress intensity factor $\Delta k$ of the specimen under tension can be expressed by formula (5) [20]:

$$\Delta k = \beta \Delta \sigma \sqrt{\pi d}$$  \hspace{1cm} (5)

Where the dimensionless parameter $\beta$ is the correction factor related to the geometry and configuration of the crack and specimen [21], $d$ is the depth of the crack or defect. Sagar Sarkar [22] has found that unstable crack growth can be attributed to the presence of mean tensile stress during low cycle fatigue tests with different stress ratios. Figure 8 shows a fatigue fracture with a maximum stress of 110 MPa. It can be seen from the diagram that the unstable spreading area is small. Sagar Sarkar found that when the load amplitude decreases, the area of stable expansion area becomes larger and the area of unstable expansion area becomes smaller. For a given stress ratio $R = 0.1$, the load amplitude decreases and the load decreases accordingly. The unstable spreading zones exhibit mixed fracture characteristics of quasi-cleavage and dimples (see figure 8(c) and (d)), which confirms Hao’s findings [23]. When a crack transits from a stable growth zone to an unstable growth zone, the material changes from brittleness to ductility (see comparison of fatigue bands in figure 8(b) and (d)). The diagram of crack source area, stable crack growth area and unstable crack growth area is shown in figure 9. The corresponding stress intensity factors are $\Delta k_{CIA}$ and $\Delta k_{CSGA}$, and the corresponding formula is as follows:

$$\Delta k_{CIA} = \beta \Delta \sigma \sqrt{\pi d_{CIA}}$$  \hspace{1cm} (6)

$$\Delta k_{CSGA} = \beta \Delta \sigma \sqrt{\pi d_{CSGA}}$$  \hspace{1cm} (7)

In formulas (6) and (7), $d_{CIA}$ and $d_{CSGA}$ represent the depth of these two regions respectively, and $\Delta \sigma$ is the range of applied stress, according to the previous study [21], the value of $\Delta k_{CIA}$ remains basically constant at each stress ratio, so $\Delta k_{CIA}$ is also considered as the threshold controlling the growth of macrocracks on stable surfaces.

According to the above analysis, the fatigue failure process of 6082-T6 aluminum alloy welded joints can be divided into:

1. Microcrack nucleation in CIA area.
2. The microcracks grow stably outside the CIA area and in the CSGA area, and are controlled by $\Delta k_{CIA}$. Outside the CSGA area, unstable microcrack growth is controlled by $\Delta k_{CSGA}$.
3. Final instantaneous fracture.

### 4.2. Mechanism of crack initiation model

Two kinds of crack initiation mechanisms are described in figure 10, and the microscopic characteristics and propagation modes of the three stages of the fatigue failure process are described respectively. Figure 10(a) shows the model of crack initiation caused by hydrogen. In the welding process of aluminum alloy, hydrogen can cause...
pores, because the solubility of hydrogen in liquid aluminum is much higher than that in solid aluminum. With the advance of solid-liquid interface, hydrogen is restrained in the molten pool. Due to the tensile stress of cyclic loading will intensify the penetration of hydrogen, and because there are not a large number of internal dislocations hindering hydrogen atoms, under the action of tensile stress of external loading, a large number of hydrogen atoms are easy to gather at the grain boundary, the stress concentration at the grain boundary results in crack initiation, as shown in Figure 10(c). Figure 10(b) shows another way of initiation, in the solidification process of molten pool, hydrogen atoms are adsorbed in the impenetrable oxide film and grow to form bubbles. The impenetrable air is moved into the bubbles by heat. After the molten pool is cooled, a pore without welding

Figure 10. Microscopic characteristics and expansion modes of the three stages of fatigue failure process: (a) Model of crack initiation caused by hydrogen, (b) Model of crack initiation caused by grain gaps in pores, (c) Crack initiation caused by grain boundary stress concentration, (d) Fatigue-crack initiation mechanism at pore.
is formed. Because the pores are located in the center of the weld, the edge and interior of the pores are surrounded by a large number of equiaxed grains and a small number of columnar grains, as shown in figure 10(d), There will be gaps between these dendrites, which some scholars also think is a kind of pore [24], which is caused by solidification shrinkage. The gap of equiaxed grains is smaller than that of columnar grains, and the gap can increase the stress concentration factor, which is related to the size of the gap [25]. Under the double action of tensile stress and large stress intensity factor, the crack initiates at the red point in the figure and produces microcracks of large and small size, under cyclic loading, some microcracks stop propagating due to the crack closure effect, some microcracks pass through the grains to form transgranular cracks, some microcracks continue to expand and converge into the main cracks, and then extend to the second stage.

5. Conclusions

(1) The results show that there are equiaxed grains in the weld center of 6082-T6 MIG welding joint. The equiaxed grains are broken due to the effect of molten pool stirring. There are cellular dendrites growing towards the weld center near the fusion zone, and there are a lot of pores in the fusion zone. Columnar crystal delamination is found at the junction of the two beads, and there are more pores than other places in the weld center.

(2) The hardness distribution of the joint is uneven. There is a 95.2HV rise at the weld toe. There is a softening zone with the lowest hardness of 65.5HV in the HAZ. The hardness is low, but the fatigue and tensile tests all break the weld. This shows that the weld is the weakest link of the joint. A large number of river like patterns are found at the crack source of fatigue fracture, Z-type cracks and crack closure effect are found at the stable and growth stages of fatigue cracks, secondary cracks are found between fatigue bands, and crack growth behavior of larger second phase between fatigue bands is found.

(3) For the average tensile stress, the fatigue fracture process of 6082-T6 MIG welded joints can be divided into: 1. Microcrack nucleation in CIA area. 2. The microcracks grow stably outside the CIA area and in the CSGA area, and are controlled by $\Delta k_{\text{CIA}}$. 3. Outside the CSGA area, unstable microcrack growth is controlled by $\Delta k_{\text{CSGA}}$, the unstable crack growth zone can be attributed to the presence of mean stress. 4. Final instantaneous fracture.

(4) Due to the tensile stress of cyclic loading will increase the penetration of hydrogen, and there is no large number of internal dislocations to hinder hydrogen atoms, a large number of hydrogen atoms are easy to gather at the grain boundary under the tensile stress of external loading, resulting in stress concentration at the grain boundary, resulting in crack initiation; Under the action of tensile stress and larger stress intensity factor, the pores generated by hydrogen atom adsorption initiate cracks and show different propagation modes.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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