Microstructure evolution and grain refinement mechanism of Inconel 601H alloy welded joints under compound physical fields of vibration and rapid cooling

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Abstract
The method and mechanism of suppressing grain growth and microstructure coarsening in nickel-based alloy welded joints were studied herein. First, sodium thiosulfate was used to simulate the crystallization processes of the welding pool. Then, on this basis, the compound physical fields of low-frequency mechanical vibration and rapid cooling on the microstructure of the Inconel 601H alloy welded joint were investigated. Finally, the joint grain refinement behavior and mechanism were analyzed based on the experimental and physical simulation results. The experimental results indicate that only the low-frequency mechanical vibration acting in the welding process caused the center of the weld to be mostly composed of equiaxed grains. The epitaxial solidification phenomenon near the fusion line disappeared, but there were still many fine columnar grains in the upper part of the weld edge. The heat-affected zone (HAZ) morphology was eventually dominated by coarse grains, and the width of the HAZ increased. However, with the compound physical fields, the weld was mainly composed of equiaxed grains, and the grain size and width of the HAZ decreased. Thus, an increased hardness distribution was also achieved. Moreover, the $\gamma'$ phase exhibited a dispersed distribution and the alloy elements were very uniformly distributed in the $\gamma'$ phase, which helped to prevent the initiation of hot cracking of the weld comprising nickel-based alloys. In addition, the results demonstrated that the generation of additional crystal nuclei and the increase in the cooling rate from the compound physical fields were the main mechanisms for the grain refinement.

1. Introduction
Nickel-based alloys have a number of excellent properties, such as hot corrosion resistance, creep resistance, and microstructure stability, that make them particularly attractive in various applications, such as aerospace engines and industrial gas turbines [1]. However, the welded joints of nickel-based alloys are prone to severe segregation, grain coarsening, and hot cracking under conventional welding processes [2]. Fine and uniform grains can reduce the extent of segregation concentration and improve grain boundary strength, thereby reducing susceptibility of the welded joints to hot cracking. A great deal of research has been carried out to find improved methods to produce fine grains and a homogeneous structure in the weld joints comprising nickel-based alloys. Traditionally, fine and uniform microstructures can be acquired by two different approaches, such as chemical stimulation and an external physical field [3–5]. For the chemical stimulation method, the addition of chemical elements can reduce the grain size. However, this technique is not without the adverse effects that are associated with the introduction of impurities, floating and agglomeration in the weld [6]. The chemical simulation method may cause degradation of high-temperature mechanical properties. Therefore, physical refinement could be used as an alternative to overcome the aforementioned problems.
The physical refinement methods include mechanical vibration, ultrasonic treatment, pulsed magnetic field, and rapid cooling. Tewari et al. [7] applied a longitudinal vibration to significantly increase the mechanical properties of a joint during the welding process. Kuo et al. [8] applied vibration during the welding of 304 stainless steel and found that the vibration reduced the degree of supercooling and increased the nucleation rate of δ-ferrite to refine the grain. Jariyaboon et al. [9] found that carbon dioxide cooling reduced the width of the HAZ in an AA2024-T351 aluminum alloy welded joint. Amuda and Mridha et al. [10, 11] performed liquid nitrogen cooling during the welding of ferritic stainless steel. The size of the weld and HAZ were reduced, and the grains were refined. It is obvious that the external physical fields can significantly refine the grains of the welded joint [12–15].

Our previous studies an Inconel 601H alloy showed that a low-frequency mechanical vibration refined the grains of the weld center, but there were additional columnar grains in the upper part of the weld edge, the width of the HAZ increased and the HAZ morphology was dominated by coarse grains [16]. Moreover, we found that rapid cooling can improve the above situation. Zhao et al. [17] demonstrated that a low-temperature gas can promote nucleation and refine the grains of Inconel 601H alloy welded joints. The weld was composed of very fine equiaxed grains, and the width of the HAZ decreased by approximately 50%.

In conclusion, in a single vibration, coarse grains appeared in the upper part of the weld edge, and the HAZ morphology was eventually dominated by coarse grains. The width of the HAZ increased, and the rapid cooling method can effectively improve the morphology of the welded joint. Therefore, a novel method of compound physical fields may have the potential to further improve the properties of welded joints. Articles have studied combinations of the techniques [18, 19]. However, the compound physical fields mainly cause the grain refinement during the alloy casting process. In this paper, the grain refinement of joints comprising nickel-based alloys that were welded by a combination of mechanical vibration and rapid cooling was investigated, and the refinement mechanism was analyzed by combining the date with physical simulation.

2. Experimental

2.1. Welding equipment

The schematic view of the welding equipment is consisted of an exciter and a forced cooling source as shown in figure 1. In the welding experiment, a mechanical vibration motor with a vibration frequency of 50 Hz and a maximum exciting force of 1.96 kN was used as the exciter. During the vibration process, the output power was approximately 250 W. The exciter generates periodic excitation force by rotating the eccentric block, causing the weldments on the platform to produce vertical vibration (V-vib) in the vertical direction of the weld. The platform is composed of two sections, both of which are 300 mm × 100 mm × 15 mm. The platform material is 16MnR. Before welding, the vibration amplitude of the weld is detected by a vibration meter, and according to previous studies, the amplitude was maintained at approximately 0.2 mm [16]. The configuration of the liquid nitrogen cooling device is shown in figure 1. The forced cooling source is fixed under the weldments, and the cooling effect was obtained by the spraying liquid nitrogen through 10 holes, with diameters of 1 mm and an interval of 10 mm, drilled in a copper pipe. Moreover, the wall thickness of the copper pipe is 1 mm, the inner diameter is 10 mm, and the length of the copper pipe is 100 mm. The forced cooling source locates on back side of weld, and d is the distance between the forced cooling source centerline and the weld centerline. The cooling

Figure 1. Schematic drawing of the welding equipment.
The transparent crystal used in the physical simulation was sodium thiosulfate (Na₂S₂O₃·5H₂O). In the physical simulation, sodium thiosulfate crystals were placed in a beaker and heated using an alcohol lamp. When sodium thiosulfate was heated to 52 °C (4 °C above the liquidus temperature) and completely turned into a liquid, the liquid was poured into a culture dish having a diameter of 60 mm, and the liquid depth is 3 mm. Moreover, the culture dish is fixed on the experimental platform. Then, the natural crystallization, V-vib assisted crystallization (vib crystallization), and combination of V-vib and rapid cooling on assisted crystallization (vib-cooling crystallization) were performed respectively. A digital camera was used to record the liquid crystallization process in the culture dish.

Solid-solution-strengthened alloy Inconel 601H sheets of 3 mm thick were used as weldments of which the chemical composition of the weldments is given in table 1. The weldments were sheared into dimensions of 50 mm × 80 mm. The weldments were brushed with a stainless steel wire brush and cleaned with acetone prior to welding.

In the assisted welding process, automatic gas tungsten arc welding (GTAW) without filler metal was used. Welding experiments were carried out in conventional GTAW, V-vib assisted GTAW (vib GTAW), and combination of V-vib and rapid cooling on assisted GTAW (vib-cooling GTAW), respectively. Welding parameters is shown in table 2.

The specimens along the across section of welded joints were cut by electro-discharge machining for metallographic analysis. The specimens were ground using SiC paper and cleaned afterwards by means of an ultrasonic cleaner. Then the sections were polished to obtain a mirror-like finish by adopting standard metallographic procedures and etched in a solution of 0.5 g CuCl₂, 10 ml HCl and 10 ml C₂H₆O, the etching time was 10–15 s. A Leica DM2700 optical microscope and a HITACHI S-4800 scanning electron microscope (SEM) equipped with an Energy dispersive analysis of x-rays (EDAX) energy-dispersive spectroscopy (EDS) apparatus were used to analyze the microstructure and segregation. X-ray diffraction (XRD) of Bruker D8 Discover type was used to analyze the phase composition. This XRD equipment uses a Cu x-ray tube. The voltage, current and power of test are 40 kV, 40 mA and 1600 W, respectively. The step size is 0.2°, the scanning speed is 10°/min, and the scanning angle is 30–90°. Shimadzu HMV-2T Vickers hardness tester was used to measure the hardness under a test load of 50 g for a dwell time of 10 s, and the interval of micro hardness testing was 250 μm.

3. Results and discussion

3.1. Microstructure

3.1.1. Micrographic examinations

The microstructure of the Inconel 601H alloy welded joints under different conditions are shown in figures 2–4. As shown in figure 2(a), in the conventional GTAW, the HAZ is dominated by coarse grains. According to the liner intercept method, mean grain sizes of 50 μm and 196 μm are obtained for the base metal and HAZ of the conventional GTAW welded joint, respectively. Moreover, the average width of the HAZ is about 525 μm. However, after the vib GTAW, as shown in figure 2(b), the grain size of the HAZ is increased to 230 μm, and the average width of the HAZ is increased to 620 μm. By contrast, in the vib-cooling GTAW, as shown in figure 2(c), the grain size of the HAZ is decreased to 156 μm, which is about 20% and 32% lower than that of conventional GTAW and vib GTAW, respectively. The width of the HAZ is decreased to 317 μm, which is significantly lower

| Table 1. The chemical composition of Inconel 601H alloy (wt%). |
|-----------------|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Ni | Cr | Fe | Ti* | Al | Mn | C | Cu | Si | P* | S |
| 58.0–63.0 | 22–24 | Bal. | 0.3–0.6 | 1.1–1.6 | ≤0.6 | ≤0.1 | ≤0.5 | ≤0.5 | ≤0.02 | ≤0.01 |

Note: *—not specified in ASTM.

| Table 2. Welding parameters. |
|-----------------------------|-----------------|-----------------|-----------------|-----------------|
| Welding current /A | Arc voltage /V | Travel speed /(mm-min⁻¹) | Argon flow rate /(L-min⁻¹) |
| 140 | 12 | 120 | 12 |
than conventional GTAW and vib GTAW. According to relevant research, the HAZ liquation cracking has a great relationship with the width and grain size of HAZ. The HAZ liquation cracking was easy to occur in many nickel-based alloys during welding [20–22]. Idowu [23] showed a significant relationship between liquation...
cracking and grain size. Lippold [24] reported that a narrower width of the HAZ was beneficial to reduce liquation cracking susceptibility. Therefore, the vib-cooling GTAW can effectively inhibit the initiation of liquation cracking in the HAZ of Inconel 601H alloy.

As shown in figures 3(a) and 4(a), in the conventional GTAW, coarse columnar grains existed throughout the weld, and the phenomenon of epitaxial solidification is clearly near the fusion line. After the vib GTAW, as shown in figure 3(b), the weld grains are refined, and the microstructure of the weld center is mainly composed of fine equiaxed grains. However, as shown in figure 4(b), there are still many fine columnar grains in the upper part of the weld edge. In addition, in the vib-cooling GTAW, as shown in figure 3(c), the grain size at the center of the weld is further reduced. Moreover, figure 4(c) shows that the grain near the fusion line are significantly refined, and figure 4(d) displays a high magnification microstructure photomicrography of region A, which can confirm the possibility that the vib-cooling GTAW can refine the grain size in the upper part of the weld edge.

In summary, in the conventional GTAW, the crystallization of liquid metal present in the welding pool has a phenomenon of epitaxial solidification, which means the crystallization starts from the partial melting grains at the fusion line, and grows toward the center of the welding pool in the direction of the substantially vertical fusion line. Therefore, the weld morphology is eventually dominated by coarse columnar grains. In the vib GTAW, the increase degree of supercooling could improves the number of crystal nuclei in the welding pool. The grains of the weld are refined. But the crystal nuclei at the upper part of the weld edge remelt and disappear under the acting of the high-temperature liquid metal present in the center of the welding pool. Thus, the refinement effect is poor and columnar grains exist in this region. In addition, the vibration accelerates the convention of the liquid metal present in the welding pool and the heat exchange in sufficient. Thus, the HAZ morphology is dominated by coarse grains, and the width of the HAZ significantly increased.

However, in the vib-cooling GTAW, the welding pool is rapidly cooling, the degree of supercooling of the liquid metal is significantly increased, and additional crystal nuclei appear in the welding pool. Moreover, the weld edge is less suffered by the high-temperature liquid metal, thereby additional crystal nuclei can be remained, so the grains in the upper part of the weld edge are significantly refined. In addition, the HAZ is less suffered by the heat of the welding pool, so the width and grain size of the HAZ are reduced.

3.1.2. Precipitation phase distribution and element segregation
The XRD pattern of Inconel 601H weld is shown in figure 5. It is revealed that the XRD pattern of Inconel 601H alloy is similar under different external physical fields. This indicates that Inconel 601H weld have the same
crystal structure. The main constituent phases of Inconel 601H nickel-based alloy welds are $\gamma$ and $\gamma'$ phases. The $\gamma'$ phase is an strengthening phase in nickel-based alloys; the main component is Ni$_3$(Al, Ti)$_{25}$, and combined with EDS analysis result is shown in figure 6. In the conventional GTAW, the diffraction peak of the (111) crystal plane is obvious, indicating that there is a preferred orientation in the $\langle 111 \rangle$ crystal orientation in the weld. In the vib GTAW, the diffraction peak of the (111) and (200) crystal plane are higher, while the diffraction peak of the (220) plane is lower, which indicates that vib GTAW may inhibit the preferential growth of grains in the $\langle 111 \rangle$ crystal orientation. However, in the vib-cooling GTAW, the intensity of the three diffraction peaks changed, and the diffraction peak of the (200) crystal plane increases significantly, which indicates that the preferential growth can be significantly inhibited by the vib-cooling GTAW. In addition, the application of vibration during welding, the weld grains are refined. Therefore, compared with conventional GTAW, the diffraction peaks are broadened. Furthermore, in the vib-cooling GTAW, the diffraction peaks are further broadened, which may be related to the finer grains in the weld.

The SEM image for precipitated phase distribution in the weld is shown in figure 7. The difference observed in the size and distribution of $\gamma'$ phase could attribute to the different solidification microstructures shown in figures 3 and 4 and the relevant external physical fields. In the conventional GTAW welding as shown in figures 7(a) and (d), the $\gamma'$ phase nucleates and coarsens along coarse columnar grains. In contrast, in the vib
GTAW, as shown in figures 7(b) and (e), the vibration promotes nucleation, so that the solute is uniform, the γ′ phase is refined and distributed homogeneously at the upper part of the weld edge and the weld center. The precipitation phases are not distributed along their growth direction [26]. In addition, as shown in figures 7(c) and (f), in the vib-cooling GTAW allows the welding pool cooling more rapidly, and more γ′ phase is dissolved into the matrix more adequately. Thus, the number of γ′ phase is reduced. However, the finer equiaxed grains in the weld provide well-separated interdendritic regions for the formation of more dispersed and refined γ′ phase, which can effectively hinder the movement of dislocations and further improve the mechanical properties of the material at high temperatures [27, 28].

Figure 8 displays the SEM image of the precipitated distribution in the HAZ. Inconel 601H base metal on both sides of the weld is subjected to welding thermal cycling to form a HAZ. The precipitation phase is solid-dissolved in the matrix during temperature rise stage and these phases re-precipitate during the temperature drop stage. Thus, the number of precipitation phase in HAZ is different due to different external physical fields during temperature drop stage. As shown in figure 8(b), the vibration accelerates the convection of liquid metal present in the welding pool, which improves the thermal conductivity of the liquid metal, so the HAZ grains get coarser after being heated. At the same time, the cooling rate of liquid metal is also increased in the welding pool. Therefore, compared with conventional GTAW, more precipitation phase is dissolved into the matrix without precipitation. The number of precipitation phase in the HAZ is reduced. In the vib-cooling GTAW, liquid nitrogen accelerates the heat dissipation rate and significantly increases the cooling rate. As shown in figure 8(c), there are a few precipitation phase in the HAZ. Therefore, the external physical fields can change the size and the distribution of the precipitation phase of the HAZ.

Ti element could constantly segregate to liquid phase during solidification process because of the low equilibrium distribution coefficient $k$, and this eventually precipitate in the form of γ′ phase. In this paper, the vib-cooling GTAW can significantly refine the microstructure of the upper part of the weld edge and promote the fine and uniform distribution of γ′ phase. Thus, the segregation of Ti element can be effectively reduced [29]. Figure 9 demonstrates the Ti element line mapping in the upper part of the weld edge under different external physical fields, in the conventional GTAW, the content of Ti element changes obviously in different region near the fusion line, and the segregation of Ti element is most serious. In the vib GTAW, columnar crystals exist in the

Figure 7. Precipitation of weld center and edge: (a), (d) conventional GTAW; (b), (e) vib GTAW; (c), (f) vib-cooling GTAW.

Figure 8. Precipitation of HAZ: (a) conventional GTAW; (b) vib GTAW; (c) vib-cooling GTAW.
upper part of the weld edge. However, the $\gamma'$ phase is finer and more uniform, as shown in figure 7(e). Therefore, the segregation of Ti element in this region is reduced, and the range of the content change is reduced. In the vib-cooling GTAW, the content of Ti in the upper part of the weld edge is stable and the segregation is significantly reduced, which may be related to the fine and uniform distribution of the $\gamma'$ phase. Therefore, the vib-cooling GTAW reduce Ti element segregation, which is also helpful to suppress the generation of hot cracking of Inconel 601H alloy.

3.2. The mechanism of grain refinement

The vib-cooling GTAW can effectively refine the grains in the upper part of the weld edge, and reduce the grain size and width of the HAZ. The crystal nucleation process and refinement mechanism of the welding pool under a single external physical field have been studied by scholars [15–17]. However, the mechanism of refining the grains of welded joint in the compound physical fields has not been studied. In this paper, by the means of physical simulation, the crystallization process of liquid metal at welding pool in the vib-cooling GTAW is analyzed.

3.2.1. Physical simulation of crystallization process

Figure 10 shows the sodium thiosulfate crystallization results of the physical simulation in the natural crystallization and vib crystallization. As evident in figure 10(a), the crystal nuclei is formed at the wall of the culture dish at the beginning of natural crystallization, and the crystal nuclei grows mainly in the form of columnar grains in the direction perpendicular to the wall toward the center of the dish, whereas the center of the culture dish grows in the form of equiaxed grains due to the uniform temperature in this region and the same heat dissipation condition all directions of the grains. Finally, the crystal morphology mainly composed of coarse columnar grains and equiaxed grains, as shown in figure 10(b). In the vib crystallization, as shown in figure 10(c), the increase in degree of supercooling cause many fine crystal nuclei to appear in the culture dish, these fine crystal nuclei move to the edge of the culture dish in the action of vibration. Thus, the fine grains growth at the wall is inhibited the growth of columnar grains, so that the sodium thiosulfate crystal is mainly composed of equiaxed grains, as shown in figure 10(d).

Figure 11 shows the physical simulation results in the vib-cooling crystallization. At the beginning of crystallization, the crystal nuclei appear at the center and wall of the culture dish as shown in figure 11(a). In the action of vibration makes the central crystal nuclei move toward to the wall, as shown in figure 11(b). Moreover, the degree of supercooling of the nucleation is significantly increased due to the application of a cooling source. Therefore, there are more crystal nuclei in the center of the culture dish, which continuously moves to the edge of the wall in the action of vibration. Thus, many fine crystal nuclei appears at the center and edge of the culture dish, which inhibits the growth of the columnar crystal at the edge of the wall, as show in figure 11(c). Therefore, the crystal morphology is mainly composed of fine uniform equiaxed grains, as shown in figure 11(d). Physical simulation has found that the vib-cooling crystallization can refine the grains and significantly improve the crystal morphology.

3.2.2. Effect of compound physical fields on crystal nuclei

During the crystallization of liquid metal present in the welding pool, the vib-cooling GTAW influences the final microstructure in two aspects: nucleation and growth process [30].
According to the thermodynamic conditions of crystallization, the relationship between the change in free energy per unit volume and the degree of supercooling can be expressed as:

\[
D = -\frac{\Delta H_f \Delta T}{T_m V_f m}
\]

where \(\Delta T\) is the degree of supercooling, \(\Delta H_f\) is the latent heat of melting and \(T_m\) is the theoretical crystallization temperature. Equation (1) shows that the larger the degree of supercooling is, the larger the difference in the free energy of the solid and liquid phases; that is, the larger phase change driving force is, the faster crystallization rate.

During crystallization, groups of short-range ordered atoms that constantly appear in liquid metal are called phase fluctuations. These phase fluctuations are the embryos. An embryo with a size equal to or greater than a
certain critical size can exist stably and grow spontaneously. At this time, an embryo is a crystal nucleus. From
the analysis of the energy changes during nucleation, the critical nucleus radius can be expressed as:

\[ r_N = \frac{2\gamma T_m}{\Delta H_f \Delta T} \]  

(2)

where \(\gamma\) is the surface energy per unit area. Equation (2) shows that a large degree of supercooling reduces the
critical nucleus radius. Furthermore, nucleation work is required to form a critical nucleus. The relationship
between the nucleation work and the degree of supercooling can be obtained with the following equation:

\[ \Delta G_k = \frac{16\pi\sigma^3T_m^3}{3\Delta H_f^2} \frac{1}{\Delta T^2} \]  

(3)

Equation (3) shows that an increased degree of supercooling can reduce the critical nucleation work, which
enables the appearance of additional crystal nuclei in the welding pool.

When stable crystal nuclei appear in the welding pool, they immediately enter the growth stage. The grain
size depends on the nucleation rate and growth rate of the crystal nuclei. The number of grains per unit volume
can be calculated by:

\[ Z_v = 0.9 \left( \frac{N}{G} \right)^{3/4} \]  

(4)

where \(\dot{N}\) is the nucleation rate and \(G\) is the growth rate of crystal nuclei. Equation (4) shows that the grains can
be refined by promoting the nucleation rate and inhibiting the grain growth. In a certain range of supercooling,
as the degree of supercooling increases, the \(\dot{N}/G\) ratio increases, so the weld grains are refined.

In conclusion, during the formation and growth of crystal nuclei, with the addition of a cooling source, the
phase change driving force increases, and the crystallization rate of the liquid metal accelerates, eventually
leading to an increase in the degree of supercooling during crystallization. Furthermore, the vibrations enhance
the convection of the liquid metal. The temperature field of the molten pool is uniform, and the temperature
gradient is reduced, which inhibits the preferential growth; and the degree of supercooling of liquid metal is also
increased. Consequently, the phase fluctuation and energy fluctuation required for nucleation are reduced; that
is, the critical nucleus radius and nucleation work are significantly reduced, which enables the appearance of
additional crystal nuclei in the welding pool. In addition, the nucleation rate can be improved and the nuclei
growth can be effectively inhibited. Therefore, it is easy to obtain refined grains in the vib-cooling GTAW, which
further increase the comprehensive performance of the welded joint.

3.2.3. Effect of compound physical fields on convection
Marangoni convection is driven by surface tension during the natural crystallization of liquid metal present in
the welding pool, as shown in figure 12. The warmer liquid metal in the center of pool surface has a lower surface
tension, while the cooler liquid metal in the pool edge has a higher surface tension, as shown in figure 12(a). The
liquid metal flows from the center of the pool surface to the pool edge under the surface tension gradient, and
returns to the bottom of the welding pool to form convection, as shown in figures 12(b)–(c).

Through further comparison, the physical simulation shows that the sodium thiosulfate liquid is naturally

crystallized and has a lower liquidus temperature, which leads to the smaller temperature difference and the
weaker convection in the culture dish. Therefore, the motion of the crystal nuclei is mainly caused by vibration.
The results of the vib-cooling crystallization show that the growth of the columnar grains at the edge of the wall
is inhibited, and the grains in the center of the dish are refined. The sodium thiosulfate crystal morphology is
mainly composed of fine and uniform equiaxed grains, which is more refined than natural crystallization and vib

![Figure 12. The Marangoni convection of the weld pool.](image-url)
crystallization. Therefore, it is believed that vibration and rapid cooling have a significant effect on the convection of the liquid.

In the vib GTAW, the welding pool is subjected to up and down reciprocating motion perpendicular to the platform. Therefore, with the combined action of vibration and convection, the high-temperature liquid in the center of the welding pool accelerates to the pool surface. At the same time, the high-temperature liquid at the pool surface moves to the pool edge under the action of surface tension, causing the crystal nuclei at the pool edge can be remelt and disappear at high temperature, and the nucleation sites are reduced. Finally, more columnar grains are formed in the upper part of the weld edge, as shown in figure 13(a). However, in the vib-cooling GTAW, the increase in degree of supercooling can significantly reduce the critical nucleation radius and critical nucleation work; thus, the nucleation rate is increased, and additional crystal nuclei can generate in the welding pool. Moreover, compared with vib GTAW, the vib-cooling GTAW significantly increase the cooling rate of liquid metal present in the welding pool. The weld edge is less affected by the high-temperature liquid and additional crystal nuclei can be remained. Therefore, as shown in figure 13(b), the upper part of the weld edge is mostly composed of equiaxed grains.

In addition, the formation of equiaxed grains is related to the temperature gradient (\(G/R\)) ratio. The vib-cooling GTAW makes the temperature distribution in the welding pool more uniform and lower \(G/R\) ratio promotes constitutional supercooling. These factors lead to the formation of more fine and uniform equiaxed grains in the weld.

Moreover, the base metal on both sides of the weld is subjected to welding thermal cycling. The vibration accelerates the convection of the welding pool, which improves the thermal conductivity of the liquid metal. So the heat exchange is sufficient, and more heat is transferred to the base metal. Moreover, the thermal conductivity of Inconel 601H alloy is 11.3 W·m⁻¹·K⁻¹, which is relatively low. Therefore, the maximum heating temperature (\(T_m\)) of the metal at HAZ zone increases significantly. Eventually, the HAZ morphology is dominated by coarse grains and the width of the HAZ is increased. In the vib-cooling GTAW, the rapidly cooling of welding pool lower the \(T_m\) and reduce the heat affected time of the base metal, so the width and grain size of the HAZ are reduced.

In summary, substantial grain refinement was achieved in Inconel 601H alloy welded joint in vib-cooling GTAW. The main mechanism of grain refinement is that the vib-cooling GTAW not only increase the degree of supercooling of the liquid metal present in the welding pool, which increases the crystal nuclei in the welding pool; but also accelerate the cooling rate of the liquid metal present in the welding pool, which lead to remaining more crystal nuclei in the upper part of the weld edge and becoming nucleation sites. Furthermore, the HAZ is less affected by the heat of the welding pool. Eventually, the grains of the welded joint are refined.

3.3. Hardness distribution

The hardness distribution in the upper part of the welded joint is shown in figure 14. On the whole, the lowest HAZ hardness is attributed to the formation of coarse grains and the dissolution of the precipitates phase into the matrix at high temperature. In the conventional GTAW and vib-cooling GTAW, the hardness near the weld centerline are lower than that near the fusion line in the weld, and this is due to the formation of coarse grain in the weld center. This trend is most obvious in the conventional GTAW process. Additionally, in the conventional GTAW, the base metal hardness is highest, and the hardness value fluctuates greatly in the weld.

In the vib GTAW, the grains in the center of the weld are refined, which leads to an increase in hardness and makes the hardness distribution more homogeneous. Moreover, the hardness near the fusion line in the weld is
reduced, which may be related to the formation of columnar crystals in this zone. The HAZ has coarse grains and fewer precipitation phases, and the hardness of this zone is reduced.

However, in the vib-cooling GTAW, the microstructure is significantly refined and homogeneously distributed in the weld. The hardness is further increased. The hardness distribution of the weld is steady. Furthermore, the grain size and width of HAZ become smaller, the HAZ hardness is improved. In addition, figure 14 shows that the width of the weld is lowered due to the application of the cooling source.

Therefore, despite the different precipitates phase distribution and its size shown in figures 7 and 8 under different external physical fields, the hardness value and its distribution in the welded joint seem to be more closely related to the refined grains. Moreover, the hardness of the welded joint abruptly changes in the conventional GTAW, which can lead to stress concentration and the cracking initiation. In the vib-cooling GTAW can effectively solve this problem and further improve the mechanical properties of the welded joint.

4. Conclusions

(1) During vib-cooling GTAW, the grains in the upper part of the weld edge are significantly refined. Moreover, the weld center and the HAZ grains are also refined, and the width of the HAZ is reduced.

(2) In terms of the grain refinement mechanism during vib-cooling GTAW, the degree of supercooling is increased, which promotes the formation of additional crystal nuclei in the welding pool. Moreover, the cooling rate is also increased in the liquid metal present in the welding pool, additional crystal nuclei remain in the upper part of the weld edge, and the nuclei growth can be effectively inhibited. Also, the base metal on both sides of the weld is less affected by the heat of the welding pool.

(3) The refined equiaxed grains and uniform $\gamma'$ phase in the weld reduce element segregation and increase grain the boundary strength of the alloy, which effectively inhibit the generation of hot cracking during the welding process of nickel-base alloys.

(4) During vib-cooling GTAW, the weld width is reduced, the weld hardness value is increased and the distribution is stable. Furthermore, the grain size and width of the HAZ decrease, and the HAZ hardness is improved, which improves the hot cracking susceptibility of the HAZ.

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