Three-Dimensional Synchrotron X-Ray Imaging of Micro-Porosity in Aluminum Alloy Fusion Welding (Postprint)

Authors: Yu Cheng, Wu Shengchuan, Hu Yanan, Zhang Weihua, Fu Yanan

Date: 2023-03-19T00:00:00+00:00

Abstract

Based on synchrotron X-ray imaging technology, micropores within laser hybrid welded 7020-T651 aluminum alloy joints were investigated, and statistical analysis and fitting were performed on three-dimensional characteristic parameters including pore volume, roundness, flatness, and the distance from pore centroid to the free surface. The results indicate that micropores in aluminum alloy fusion welding are primarily near-spherical metallurgical pores with roundness values above 0.65, exhibiting approximately symmetric distribution about the weld centerline. Pores in the upper weld region are larger in size, whereas those in the heat-affected zone and lower region are denser and smaller. For pores with equivalent diameters within the 20 mm range, the frequencies in the upper and lower portions of the joint reach as high as 65% and 85%, respectively, while large-sized pores exceeding 100 mm are rarely observed. Additionally, due to the sagging tendency of the molten pool and rapid solidification, the liquid phase remaining within the interdendritic network leads to the formation of complex-shaped hot cracks in the lower weld region that are oriented perpendicular to the weld and distributed in a stacked manner. Interconnectivity exists among some pores and between pores and hot cracks, thereby reducing the average roundness of micropores in the lower region. Furthermore, higher welding speeds result in smaller pore volume fractions throughout the joint interior, but exhibit no significant influence on the distribution of pore morphology and location.

Full Text

ChinaXiv Partner Journal, Vol. 51

February 2015, No. 2, pp. 159-168

ACTA METALLURGICA SINICA

Three-Dimensional Imaging of Gas Pores in Fusion Welded Al Alloys by Synchrotron Radiation X-Ray Microtomography

YU Cheng[1], **WU Shengchuan**[1,3], **HU Yanan**[1], **ZHANG Weihua**[1], **FU Yanan**[2]

[1] State Key Laboratory of Traction Power, Southwest Jiaotong University, Chengdu 610031, China
[2] Shanghai Synchrotron Radiation Facility (SSRF), Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201204, China
[3] European Synchrotron Radiation Facility (ESRF), Grenoble F-38043, France

Correspondent: WU Shengchuan, associate professor, Tel: (028)87600868, E-mail: wusc@swjtu.cn

Supported by National Natural Science Foundation of China (No. 51005068), Fundamental Research Fund for the Central Universities (No. 2682013CX030), and Fundamental Joint Research Fund for the High Speed Railway of China (No. U1234208)

Manuscript received 2014-06-23, in revised form 2014-09-12

Abstract

Based on synchrotron radiation X-ray imaging technology, this study investigates micro-pores inside hybrid welded 7020-T651 aluminum alloy joints, with statistical analysis and fitting performed on three-dimensional characteristic parameters including pore volume, sphericity, flatness, and the distance from pore centroid to free surface. Results demonstrate that micro-pores in fusion welded aluminum alloys are primarily near-spherical metallurgical pores with sphericity above 0.65, distributed approximately symmetrically about the weld center. Pores in the upper weld region are larger in size, while those in the heat-affected zone and lower weld are denser and smaller. Pores with equivalent diameters within 20 m account for 65% and 85% of the total in the upper and lower weld regions, respectively, while large pores exceeding 100 m are rare. Furthermore, due to the collapse tendency of the molten pool and rapid solidification, residual liquid phase between dendrite networks leads to the formation of complex-shaped thermal cracks oriented perpendicular to the weld and distributed in layers in the lower weld region. Connectivity between some pores and between pores and thermal cracks reduces the average sphericity of lower weld micro-pores. Additionally, higher welding speeds decrease the overall pore volume fraction within the joint, but have minimal influence on pore morphology and spatial distribution.

Keywords: hybrid laser welding, aluminum alloy, gas pore, synchrotron radiation X-ray imaging

Introduction

With the increasingly extensive and in-depth application of medium- and high-strength aluminum alloys in high-speed trains, aerospace, and military industries, engineering accidents involving fatigue failure of welded structures have emerged repeatedly, causing significant losses to relevant industrial applications and research departments. During aluminum alloy fusion welding, numerous gas pores of varying sizes and complex distributions inevitably form, representing the primary defect that degrades welded structure performance and causes fatigue failure. Research indicates that pores in high-energy beam welded aluminum alloys can be classified into two types: process-related pores and metallurgical pores. The former, influenced by process stability, typically exhibit irregular spatial morphologies, such as pores formed by keyhole instability during laser deep penetration welding. The latter generally refer to spherical or near-spherical hydrogen pores resulting from supersaturated hydrogen precipitation—bulk defects that are difficult to eliminate completely.

Although these pores have minimal impact on static strength, they serve as stress concentration sites and plastic flow initiation points under fatigue loading, leading to crack nucleation. Alternatively, densely distributed pores directly reduce the load-bearing cross-section, making them a critical factor affecting the fatigue resistance of welded aluminum structures. Therefore, quantitative characterization and analysis of damage behavior and evolution in welded joints containing numerous micro-defects within large welded structures, and exploring the relationship between microstructural characteristics and macroscopic properties, have become important frontier fundamental topics for the safe service of welded structures.

Due to the small size and extremely complex distribution of pores in fusion welded joints, detection is very difficult (typically limited to macroscopic measurement on fracture surfaces). Consequently, scholars worldwide hold divergent views regarding pore distribution characteristics and their relationship with joint static and fatigue strength. For example, Rudy and Rupert proposed that micro-pores below 0.4 mm in diameter do not affect joint performance, while Shore and McCauley noted that numerous pores smaller than 0.4 mm account for approximately 50% of the total pore area fraction and thus cannot be ignored. Ma and Li similarly suggested that micro-pores under 0.5 mm have no obvious effect. In reality, pores in currently operational vehicle bodies are generally smaller than 0.4 mm and exist in large quantities. Ignoring their contribution to service performance could pose significant safety risks for high-speed train operation.

Constrained by technical limitations, previous research primarily examined pore effects on joint performance at the macroscopic phenomenological level. Moreover, when statistically analyzing pores on fracture surfaces or through X-ray detection, numerous micro-pores below 0.1 mm were overlooked. Conventional techniques cannot non-destructively determine internal pore distribution and morphological characteristics, leading to inconsistencies in some research conclusions. Currently, the exceptional characteristics of third-generation synchrotron radiation X-ray sources—high energy, high collimation, high brightness, and high resolution—enable researchers to penetrate metal interiors and non-destructively observe and quantitatively characterize microstructural features in real time.

Since the 1970s, the successful development and application of new joining technologies such as laser welding with lower heat input have made efficient and high-quality manufacturing of key structural components for high-speed train bodies possible. Compared with conventional arc welding, high-energy beam welding produces more aesthetically pleasing, smooth, continuous, and reliable aluminum welds, representing the most promising fusion welding technology for light alloys. Studies have found that pores also exist in high-energy beam welding, but their sizes are smaller than those in conventional arc welded joints.

To date, no reports have been published on investigating internal defect distribution in aluminum alloy welded joints and its influence on structural performance using high-resolution synchrotron radiation X-ray imaging. This work employs China’ s most advanced large scientific platform—the Shanghai Synchrotron Radiation Facility (SSRF) beamline 13W1—to conduct three-dimensional imaging studies of pores (or micro-voids) in hybrid laser welded 7020-T651 aluminum alloy joints used in next-generation high-speed train pantographs. Quantitative characterization of pore size, morphology, sphericity, and other distribution information provides critical foundational data support for subsequent research on pore-induced fatigue damage and offers theoretical guidance for material selection, welding process optimization, and service evaluation.

---

1. Experimental Methods

7020 medium-strength aluminum alloy rolled plates were selected as the base material, with main chemical composition (mass fraction, %) of: Zn 4.22, Mg 1.21, Cu 0.10, Fe 0.20, Cr 0.16, Zr 0.13, and Al balance. The plates were cut into 2 mm thin sheets with T651 heat treatment condition (solution treatment + artificial aging) and pre-stretched under T6 temper to reduce internal stresses. Fe is an impurity element, while Zr provides grain refinement. To compensate for Mg vaporization loss during welding, imported ER5356 filler wire with 1.2 mm diameter was selected, containing 4.8% Mg (mass fraction).

Butt welding was performed on a fiber laser-arc hybrid welding platform with pulsed arc mode. Prior to welding, plates were chemically cleaned and the weld surfaces were brushed with steel wire on-site. Optimized hybrid welding parameters were: laser power P = 3-3.5 kW, wavelength $\lambda = 1.07$ m, pulsed arc current I = 110-140 A, welding speed v = 6-9 m/min, defocus amount 0 mm, laser-wire distance 2 mm, Ar flow rate 1.5 L/min, and ambient humidity approximately 80%. Additionally, to prevent damage to the optical fiber from laser reflection off the aluminum surface, the laser beam was offset approximately 10° from the plate normal, with the arc at 75° to the plate normal.

Welds with continuous, smooth, and aesthetically pleasing appearance and without obvious pores or cracks were selected. The reinforcement was removed, and dog-bone specimens (total length 24 mm, thickness 1 mm) were cut perpendicular to the weld direction. Fourteen samples were prepared from two welded plates at different welding speeds, among which four were effective representative samples. Relevant parameters are listed in Table 1.

The characterization of three-dimensional morphology and distribution of micropores inside aluminum alloy fusion welded joints was completed through the following processing steps:

1. Due to beamtime limitations, X-ray microtomography was performed in two batches at SSRF beamline 13W1 to obtain tomographic projections. Main experimental parameters were: photon energy 21 keV, sample-to-detector distance 15 cm, 900 projections per scan, exposure time 2.0 s, spatial resolution 1.85 m, corresponding to voxel volume of approximately 6.33 m^3. Figure 1 [Figure 1: see original paper] shows the schematic of microtomography at beamline 13W1.
2. Phase retrieval, reconstruction, and grayscale conversion of projection images were performed using P3 and P3B software developed by SSRF to obtain 8-bit slice data for each specimen, approximately 4 GB per sample.
3. Pores in the slices were labeled, segmented, and measured for three-dimensional characteristic parameters using commercial software Amira and open-source software ImageJ. Measured parameters included pore volume V, surface area S, sphericity Y, ellipsoid fitting parameters (including longest semi-axis a and shortest semi-axis c of fitted ellipsoid), and straight-line distance D from pore centroid to specimen free surface. Sphericity Y indicates the degree of similarity to an ideal sphere, with lower values representing more irregular pores. Note that due to different sampling locations, for specimens B1 and B2, D represents the distance from pore centroid to the lower weld surface, while for specimens T1 and T2, it represents the distance to the upper weld surface.
4. The obtained pore morphological characteristics and distributions were identified and statistically analyzed. To reduce errors from grayscale noise in synchrotron radiation imaging and to focus on main distribution features, only micro-pores containing more than 21 voxels (approximately 21 × 6.33 m^3) were considered in the morphological statistical analysis.

2. Experimental Results and Analysis

Through the aforementioned experimental procedures and data processing methods, massive amounts of three-dimensional pore information were obtained from hybrid laser welded aluminum alloys. This work identifies and statistically characterizes pore spatial distribution, size, and morphology from multiple perspectives, explores their relationships, and classifies pores based on morphological characteristics. It should be noted that to ensure 1.85 m spatial resolution, the 2 mm thick weld was sectioned along the mid-plane into upper and lower 1 mm thick samples.

2.1 Pore Characteristics Description Figure 2 [Figure 2: see original paper] illustrates the three-dimensional pore morphology and distribution. Industrial X-ray inspection (with millimeter-level resolution) indicated that this weld met Class I standards. Pores are concentrated in the weld and heat-affected zone, distributed approximately symmetrically about the weld centerline. Combined with macroscopic metallographic observation, the symmetric pore distribution corresponds to regular weld morphology, indicating good alignment accuracy before welding. Larger pores are dispersed in the upper weld region, while smaller pores are densely distributed throughout the entire weld, particularly evident in the heat-affected zone. This distribution characteristic primarily results from solidification symmetry of the molten pool, which first solidifies at the cold base material on both sides, then rapidly advances toward the weld center, upper, and lower regions. This is the fundamental reason for the concentrated distribution of large pores in the upper weld. The small and dense micro-pores in the heat-affected zone mainly form because micro-pores generated from cold base material do not have sufficient time to grow, float, and escape before being trapped in the solidified weld.

Macroscopically, pores can be categorized into near-spherical pores and spatially flattened thermal cracks. These irregular thermal cracks form during weld solidification, generally attributed to residual liquid phase between dendrites under tensile stress. Most pores in specimens T1 and T2 are spherical, while specimens B1 and B2 contain a certain number of thermal cracks. Figure 3 [Figure 3: see original paper] shows the morphology of transverse thermal cracks in the lower weld region.

Research indicates that pores in aluminum alloy fusion welded joints are predominantly spherical or near-spherical hydrogen pores, also known as metallurgical pores. Under scanning electron microscopy, fracture surfaces of such pores typically exhibit dendritic crystallization with tightly and regularly arranged dendrite tips, smooth and clean inner walls without oxidation traces, as shown in Figure 4 [Figure 4: see original paper]. Notably, process-related shrinkage cavities also exist within the joints, suggesting that the laser keyhole is microscopically unstable—accounting for why pore distributions are not identical even under identical process parameters and material conditions. The laser keyhole refers to a small hole formed in the liquid molten pool when the laser beam is focused to a relatively small spot with high power density, causing metal vaporization in an extremely short time.

Figures 2b, d, f, and h also demonstrate the symmetric spatial distribution of pores. The area fraction plots for specimens T1 and B1 show only one major peak, while specimens B2 and T2 exhibit multiple major peaks, likely caused by laser keyhole instability during welding. This instability arises from various factors such as material inhomogeneity, shielding gas flow disturbance, and unstable droplet transfer, though the mechanism remains unclear.

Table 2 lists the statistical results of pore characteristic parameters for the four samples. The pore count and volume fraction in specimens B1 and B2 are higher than those in T1 and T2, indicating that the lower weld region tends to retain more and denser pores, while fewer pores float to the upper region and escape. Additionally, the average volume and maximum equivalent diameter of upper weld pores are generally larger than those in the lower region, demonstrating that pores grow and float during solidification but fail to escape the weld. Moreover, faster welding speeds (higher solidification rates) result in smaller average pore volume and area fraction, as well as smaller pores at corresponding locations. This suggests that increasing welding speed not only reduces pore size and quantity but also favors the formation of smaller molten pools and heat-affected zones.

The sphericity of pores in the upper weld region is higher than in the lower region, attributed to uniform pressure during floating and less liquid disturbance in the upper region compared to the molten pool front. The influence of welding speed on pore morphology distribution is not significant.

2.2 Three-Dimensional Characteristic Parameters of Micro-Pores As previously described, the equivalent diameter, morphology, and spatial distribution of micro-pores exhibit considerable scatter and complexity. This work employs statistical theory to quantitatively characterize pore equivalent diameter d, sphericity Y, and distance D, with distribution features fitted and analyzed.

Due to large pore scatter, direct application of conventional hypothesis testing methods yields statistically insignificant results. Therefore, data were first grouped (with bin widths of 4 m for d, 0.02 for Y, and 50 m for D) to obtain frequency histograms, after which optimal nonlinear functions were selected to fit the histogram envelopes. Note that the resulting fitted curves are not probability density functions but rather probability distribution curves of characteristic parameters within different bins.

The frequency histogram of d can be fitted with a lognormal curve expressed as:

$$wx \exp\left(-\frac{(\ln x - x_c)^2}{2w^2}\right)$$

After symmetry and translation about the vertical axis, the modified lognormal curve can fit the Y frequency histogram:

$$wx \exp\left(-\frac{\ln^2(x/x_0)}{2w^2}\right)$$

where x_0, y_0, x_c, w, and A are fitting parameters. Parameter w represents the shape parameter; smaller w values produce sharper peaks, indicating more concentrated distribution of the characteristic value.

For the D frequency histogram, the Voigt multi-peak fitting method commonly used in X-ray diffraction studies is applied:

$$y_b + \sum_i V_i(x)$$

where V_i represents the Voigt function for fitting the ith peak; fitting parameters A_i, WL_i, WG_i, xc_i, and y_b correspond to the area, Lorentzian component full width at half maximum (FWHM), Gaussian component FWHM, peak center position, and baseline for the ith peak, respectively; n is the number of fitted peaks.

Based on these fitting formulas, Figures 5 [Figure 5: see original paper]-7 [Figure 7: see original paper] present the distribution histograms and corresponding nonlinear curve fits for d, Y, and D of micro-pores inside the four welded specimens.

Figure 5 shows that pore frequency peaks in the 8-12 m bin, with right-skewed distributions indicating that pores with equivalent diameters above 15 m constitute a significant proportion. Pores within 20 m equivalent diameter are ubiquitous, accounting for 65% and 85% of the total in upper and lower weld regions, respectively, while large pores exceeding 100 m are rare. Regarding the shape parameter w from fitted curves, specimens B1 and B2 show significantly smaller values than T1 and T2, while no significant differences exist between B1 and B2 or between T1 and T2. This demonstrates that pore size distribution is more concentrated in the lower weld region. In summary, micro-pores in hybrid welded 7020-T651 aluminum alloy are extremely small, with few individual pores larger than 0.1 mm—a characteristic size unattainable by conventional testing techniques and the main reason for fewer detected micro-pores and larger reported pore sizes in previous studies. From the perspective of pore size alone, hybrid laser welding offers incomparable technical advantages over conventional arc welding.

Figure 6 [Figure 6: see original paper] reveals that the maximum Y frequency for specimens B1 and B2 occurs in the 0.64-0.66 bin, while for T1 and T2 it appears in the 0.66-0.68 bin, with left-skewed distributions. This confirms that upper weld pores are more spherical and that most pores in aluminum alloy welds are near-spherical, with few irregular solidification shrinkage cavities. Regarding fitting parameter w, specimens T1 and T2 show significantly smaller values than B1 and B2, while no significant differences exist between B1 and B2 or between T1 and T2. This indicates that sphericity distribution is more concentrated in the upper weld region, with welding speed having minimal influence on sphericity distribution.

It is well known that D is directly related to fatigue crack initiation—the closer the pore centroid is to the free surface, the easier it is for the pore to create stress concentration, plastic deformation, and slip, thereby initiating cracks. Figure 7 [Figure 7: see original paper] shows that the D frequency histograms for all four specimens exhibit several peaks, with fitted peak positions primarily near 100 m and 900 m from the free surface. This indicates that pores concentrate near the joint free surface and at the mid-thickness region. From the perspective of pore-crack initiation relationship, particular attention should be paid to pore distribution near free surfaces.

To investigate relationships among micro-pore size, spatial distribution, and morphological characteristics, scatter plots of Y versus d, Y versus D, and d versus D are presented in Figure 8 [Figure 8: see original paper].

Figure 8a shows that Y varies between 0.4–0.7, with d ranging from 10–40 m in the weld. Upper weld pores generally exhibit higher Y values than lower weld pores. For pores with $d > 30$ m in lower weld specimens B1 and B2, Y decreases with increasing d (larger micro-pores may be thermal cracks or process-related pores), with reduced scatter. In contrast, upper weld specimens T1 and T2 show increasing Y with d, confirming that larger micro-pores in the upper region are metallurgical pores that floated but failed to escape.

Figure 8b demonstrates that numerous near-spherical pores with $Y > 0.6$ exist throughout the weld from top to bottom. However, approaching the free surface, upper weld pores show decreasing Y scatter, while lower weld pores exhibit increasing Y scatter. This indicates that pore irregularity increases from the upper to lower surface. Additionally, due to the thin plate (2 mm) and high welding speed, the rapid cooling rate results in a short time interval from pore nucleation to floating to the upper surface, making differences in d and Y less pronounced.

Figure 8c further illustrates that larger pores mainly distribute near the subsurface region close to the free surface or at the mid-thickness region far from the free surface, with fewer pores in other locations. Overall, the upper weld region contains more pores than the lower region.

2.3 Micro-Pore Morphology Aluminum alloy fusion welded joints contain pores, thermal cracks, and process shrinkage cavities with distinct morphologies. Extensive experimental research and statistical analysis by the authors' group have shown that process shrinkage cavities rarely appear in stably performed hybrid laser welding and are therefore not considered further. Thermal cracks form primarily because the molten pool collapses while solidifying, causing separation along dendrite boundaries under gravity-induced tensile stress, as shown in Figure 3. Figure 9 [Figure 9: see original paper] presents typical pore and thermal crack morphologies in the specimens. Connectivity between a few pores reduces their sphericity, while thermal cracks often open to form larger pores or connect with pores, also exhibiting relatively high sphericity. Therefore, no clear sphericity threshold distinguishes pores from thermal cracks.

To characterize the complexity of different pore morphologies, flatness F is introduced, defined as the ratio of the longest semi-axis a to the shortest semi-axis c of the fitted ellipsoid. This parameter represents the degree of pore extension toward a particular plane. Figure 10 [Figure 10: see original paper] shows the relationship between Y and F for pores in all four specimens. Generally, pores with lower Y values exhibit larger F values with greater scatter, indicating that morphological differences increase as Y decreases. Moreover, the distribution ranges of Y and F in specimens B1 and B2 are significantly larger than those in T1 and T2, due to more frequent pore-pore and pore-thermal crack connections in these lower weld specimens, which reduce Y and increase F.

Conclusions

1. Micro-pores in hybrid welded 7020-T651 aluminum alloy are primarily near-spherical metallurgical pores with sphericity above 0.65. In high-quality joints, pores distribute approximately symmetrically about the weld centerline, with larger pores in the upper weld region and smaller, denser pores in the heat-affected zone and lower region.
2. The collapse tendency of the molten pool combined with rapid solidification forms dendritic networks, and tensile stress causes liquid film separation between dendrites. This is likely the main reason for layered transverse thermal cracks (perpendicular to the weld) in the lower weld region and a possible cause of connectivity between pores and between pores and thermal cracks.
3. Pores with equivalent diameters within 20 m are ubiquitous, accounting for 65% and 85% of the total in upper and lower weld regions, respectively, while large pores exceeding 100 m are rare. The average volume and maximum equivalent diameter of upper weld pores are generally larger than those in the lower region.
4. Higher welding speeds (lower linear heat input) tend to reduce pore equivalent diameter and volume fraction, but have minimal influence on pore morphology and spatial distribution.
5. The grouped probability distributions of pore equivalent diameter, sphericity, and centroid-to-free-surface distance are well-fitted by lognormal curves, modified lognormal curves, and Voigt multi-peak functions, respectively.

References

[1] Wu S C, Zhu Z T, Li X W. *Laser Welding of Aluminium Alloys and the Performance Evaluation*. Beijing: National Defense Industry Press, 2014: 234
[2] Gong S L, Yao W, Steve S. *Trans Chin Weld Inst*, 2009; 30(1): 60
[3] Mathers G. *The Welding of Aluminum and Its Alloys*. Cambridge: Woodhead Publishing Limited, 2002: 18
[4] Wu S C, Yu X, Zuo R Z, Zhang W H, Xie H L, Jiang J Z. *Weld J*, 2013; 92: 64
[5] Li X Y, Gong S L, Zhang J X. *J Mech Strength*, 2008; 30: 965
[6] Rudy J F, Rupert E J. *Weld J*, 1970; 49: 322
[7] Shore R J, McCauley R B. *Weld J*, 1970; 49: 311
[8] Ma J M, Li J Y. *Dev Appl Mater*, 2003; 18(6): 31
[9] Zhang M Y. Master Thesis, Southwest Jiaotong University, Chengdu, 2013
[10] Wang S G, Wang S C, Zhang L. *Acta Metall Sin*, 2013; 49: 897
[11] Yonetani H. *Weld Int*, 2008; 22: 701
[12] Wang Y J. *Welding Technique for Aluminum High-Speed Train Body*, 2nd Ed. Beijing: China Machine Press, 2011: 43
[13] Wang Y L, Chen H. *Aluminum Welding Technology of High Speed Train Body*. Chengdu: Southwest Jiaotong University Press, 2012: 81
[14] Mizutani M, Yamaguchi Y, Katayama S. *Weld Int*, 2008; 22: 705
[15] Andrew R C, Waring J. *Weld J*, 1974; 53: 85
[16] Wan Q, Zhao H D, Zou C. *Acta Metall Sin*, 2013; 49: 284
[17] Li Y J. *Quality Control of Microstructures and Performance for Welded Joints*. Beijing: Chemical Industry Press, 2005: 213
[18] Zhou W S, Yao J S. *Welding Aluminum and Its Alloy*. Beijing: China Machine Press, 2007: 48
[19] Zuo T C. *Laser Processing of High Strength Aluminum Alloys*, 2nd Ed. Beijing: National Defense Industry Press, 2008: 22
[20] Huang J L, Warnken N, Gebelin J C, Strangwood M, Reed R C. *Acta Mater*, 2012; 60: 3215
[21] Wu S C, Yu C, Zhang W H, Fu Y N, Helfen L. *Sci Technol Weld Join*, 2015; 20: 11
[22] Toda H, Masuda S, Batres R, Kobayashi M, Aoyama S, Onodera M, Furusawa R, Uesugi K, Takeuchi A, Suzuki Y. *Acta Mater*, 2011; 59: 4990
[23] Ma L D. *Modern X-ray Polycrystalline Diffraction: Experimental Technique and Data Analysis*. Beijing: Chemical Industry Press, 2004: 318
[24] Zhang Q L, Ding L H, Shao S F, Liu W P, Wang X M, Sun D L, Yin S T. *J Synth Cryst*, 2009; 38: 330
[25] Derek H. *Fractography: Observing, Measuring and Interpreting Fracture Surface Topography*. London: Cambridge University Press, 1999: 153
[26] Wu S C, Zhang W H, Jiao H S, Fu Y N. *Sci Sin Techologica*, 2013; 43: 785

Note: Figure translations are in progress. See original paper for figures.