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ARTICLE

Interface Characteristics and Evolution Mechanism of W/CuCrZr in Hot Melt Explosion Welding

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Abstract: Explosion welding was carried out on the basis of vacuum hot melt W/CuCrZr composite plate. Metallurgical microscope, scanning electron microscope and energy dispersive X-ray spectroscope were used to observe the microscopic morphology of the bonding interface. At the same time, combined with finite element calculations, the evolution mechanism of the interface of the hot melt explosion welded W/CuCrZr composite plate was explored. The results show that the interface bonding of the hot melt explosion welded W/CuCrZr composite plate is good and there is a cross-melting zone with 3–8 μm in thickness, but cracks are developed on the W side. The numerical simulation reproduces the changes of pressure, stress, strain and internal energy at the bonding interface in the process of hot melt explosion welding. The location of the crack generated in the experiment coincides with the high stress position calculated by numerical simulation. The high pressure and high temperature near the hot melt explosion welding interface further promote the bonding of the interface.

Key words: hot melt explosion welding; W/CuCrZr; interface characteristics; numerical simulation; evolution mechanisms

Since tungsten and copper do not dissolve with each other or form intermetallic compounds, tungsten copper composite materials are called pseudo alloys[1]. Tungsten copper composite mater-ials combine the excellent properties of tungsten and copper, which makes them have a very broad application prospect in electrical, electronic, nuclear energy and military fields. For example, the deflector on the first wall of the fusion energy experimental reactor BEST is a flat plate W/Cu deflector. Because tungsten and copper are immiscible with each other and have large differences in properties, it is difficult to prepare dense tungsten copper composites by traditional meth-ods. At present, the preparation methods of tungsten copper composite materials include hot isostatic pressing (HIP), diffusion welding[2–4], fusion casting[5], explosion composite[6–7], vacuum hot melt welding[8], plasma[9-10], laser manufacturing[11], etc. The production process of HIP technique is complex, the cost is high, and the interfacial bonding strength is low. Diffusion welding has high welding accuracy and small deformation, but it has strict requirements for the welding joint surface and low production efficiency. Tian et al[7] used a crack-free high-wave impedance confined explosion welding method to weld tungsten foil and copper plates. However, the thickness of tungsten foil is thin. Sun et al[8] prepared W/CuCrZr composite panels with dovetail groove structure by vacuum hot melt welding, but there are partial holes on the side of CuCrZr. The above methods have their own advantages and disadvantages. In order to obtain an ideal W/CuCrZr composite plate, in this study, on the basis of vacuum hot melt welding, the hot melt explosion welding method was further used for composite. Combined with finite element cal-culations, the evolution mechanism of the hot melt explosion welded W/CuCrZr composite plate interface was explored.

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1 Experiment

1.1 Material parameters

The materials and parameters used in the experiment were the same as those in Ref. [8], by which the W/CuCrZr composite plate with a vacuum-cast dovetail groove structure was fabricated.

The size of the tungsten plate was 100 mm×50 mm×3 mm, and the size of the prefabricated dovetail groove on the surface of the tungsten plate and the physical drawing of the tungsten plate after slotting are shown in Fig. 1a and 1b, respectively. A small sample of the vacuum-cast dovetail groove structure W/CuCrZr composite plate was intercepted, which was covered with explosives, as shown in Fig. 1c, and placed in an explosive bunker for explosive welding. The size of CuCrZr plate was 100 mm×50 mm×6 mm. The main elements of CuCrZr include chromium, zirconium, copper, and small amounts of iron, aluminum, magnesium, silicon, etc. The content of elements other than copper in CuCrZr is shown in Table 1. The physical and mechanical properties of CuCrZr and W are shown in Table 2.

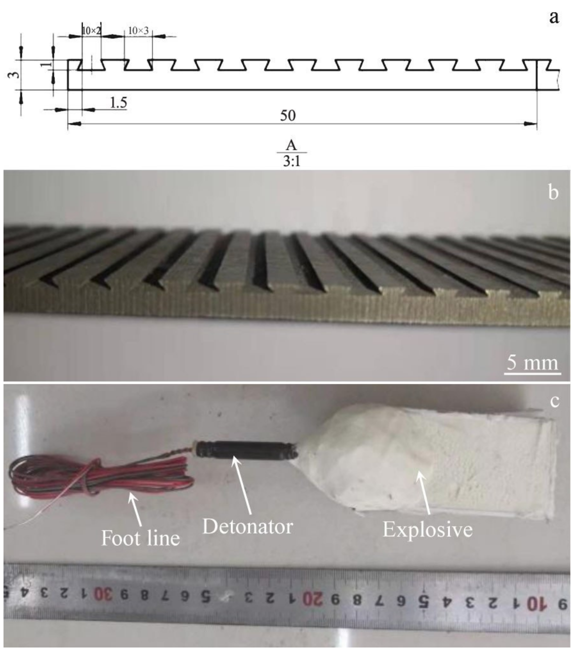

Fig.1 Dimension (a) and physical drawing (b) of dovetail groove of tungsten plate; diagram of explosive device (c)

Table 1 Content of elements except copper in CuCrZr

Element	Proportion
Al	0.1–0.25
Mg	0.1–0.25
Cr	0.1–0.8
Fe	0.5
Si	0.5
Zr	0.1–0.6

Table 2 Physical and mechanical properties of CuCrZr and W

Material	ρ/kg·m^{-3}	T/°C	HV/MPa	C/m·s^{-1}
CuCrZr	8900	1083	1100	4674
W	19350	3422	3410	5334

Note: ρ is density; T is melt point; HV is Vickers hardness; C is speed of sound through different substances

1.2 Experimental process

Firstly, the W/CuCrZr composite plate with dovetail groove structure was prepared by vacuum casting method[8]. The results show that there are some holes on the copper side of the W/CuCrZr composite plate of the vacuum-cast dovetail groove structure[8], which has a certain impact on the composite panel. In order to improve the quality of the composite panels, the hot melt explosion welding method was used for further processing, in order to obtain high-quality W/CuCrZr composite panels.

The vacuum-cast dovetail groove structure of W/CuCrZr composite plate was further exploded and welded, and the sample was prepared. Metallurgical microscope, scanning electron microscope (SEM) and energy dispersive X-ray spectroscope (EDS) were used to analyze the interface microstructure of hot melt explosion welded composite panels W/CuCrZr. Meanwhile, the evolution mechanism of the interface between W/CuCrZr composite plates subjected to hot melt explosion welding was studied through numerical calculations.

2 Experimental Results

2.1 Macroscopic morphology

After the explosion welding, it is found that part of the tungsten block on the W side is broken, only a thin layer of W left is connected with CuCrZr, and the fracture is not at the interface. The sample is embedded in the mold for metallographic observation, as shown in Fig.2.

2.2 Metallographic microscopic

After grinding and polishing for the composite plate samples, the interface bonding of the dovetail composite plate W/CuCrZr is observed by metallurgical microscope at the ambient temperature of 23.9 °C and the relative humidity of

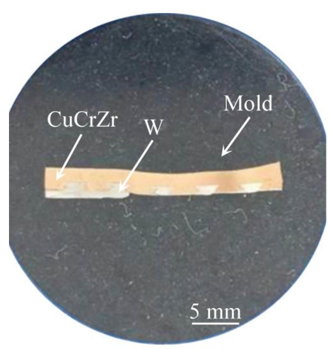

Fig.2 Appearance of hot melt explosion welded composite plate W/CuCrZr

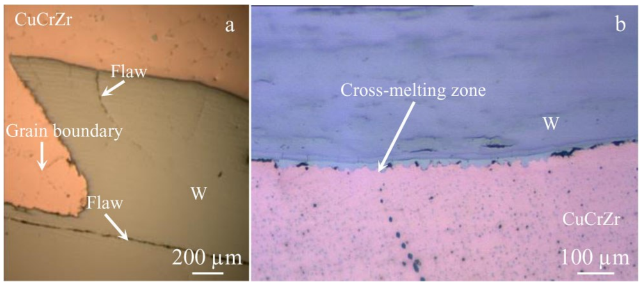

Fig.3 Metallographic structure of hot melt explosion welded composite plate W/CuCrZr

56.3%, and the test results are shown in Fig.3. It can be seen that W and CuCrZr are still mainly straight combined, and cracks appear on the tungsten side. Specifically, in the dovetail groove, there is a more obvious crack. It shows that under the explosive welding, W cannot withstand the strong impact, and the stress concentration appears, resulting in cracks. On the CuCrZr side, grain boundaries of copper grains can be observed. Grain size is one of the important factors affecting the mechanical properties and deformation behavior of chromium zirconium copper. The effect of CuCrZr grains on deformation is mainly manifested in inhibiting grain recrystallization, improving the fracture behavior of the alloy, and increasing fatigue life. From the metallographic diagram, it can be seen that the interfacial bonding of the W/CuCrZr composite plate has a thin layer of cross-melting zone, as shown in Fig. 3b. The width of the cross-melting zone is approximately a few micrometers.

2.3 SEM and EDS detection

The microscopic morphology and chemical elements of the interface of W/CuCrZr hot melt explosive welded composite panels were measured. The test environment temperature was 20.4 °C, the relative humidity was 56.3%, the test party was based on GB/T17359-201 and the acceleration voltage was 15 kV. The sample to be tested was plated with platinum (Pt) for 20 s and then directly put into the SEM vacuum chamber, the morphology observation and composition analysis were carried out according to the standard process, and the composition was semi-quantitatively analyzed.

Fig. 4a shows SEM morphology and the position of the surface scan at the interface of the W/CuCrZr hot melt explosion welded composite plate. Fig.4b–4f show the result of EDS element scanning corresponding to zone 1 – 5 in Fig.4a, respectively, and Table 3 shows the distribution of the main elements at the interface of the W/CuCrZr hot melt explosion welded composite plate. As can be seen from Fig.4a, there is a diffusion zone with 3–8 μm in thickness, the structures on the W side and CuCrZr side are dense, and the pores on the CuCrZr side are also eliminated. The main

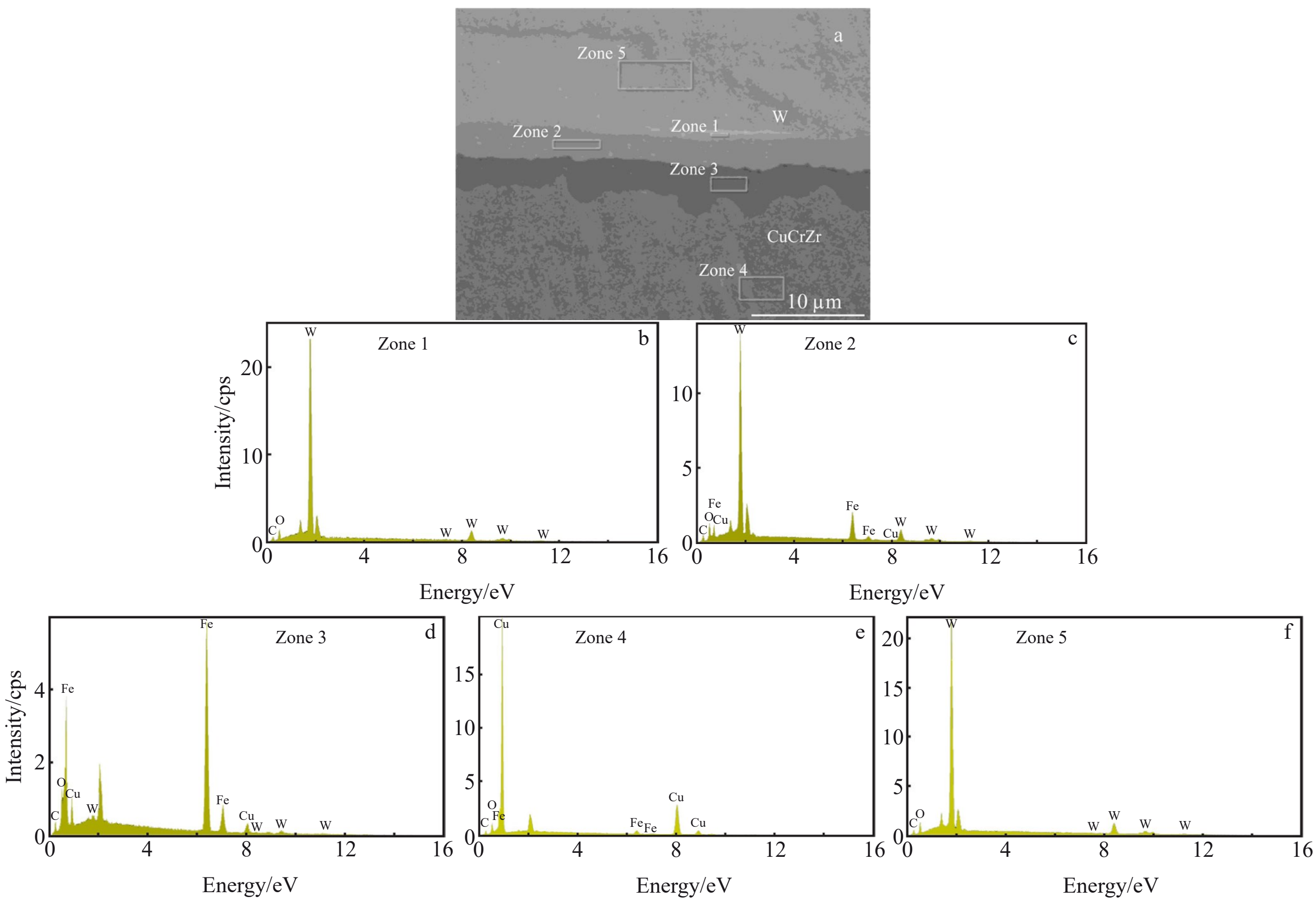

Fig.4 SEM image of the interface (a) and EDS results corresponding to zone 1–5 marked in Fig.4a (b–f)

elements in pure W board include W and some impurities, such as oxygen, carbon, boron, iron and copper. CuCrZr mainly contains elements including copper, chromium, zirconium, magnesium, aluminum, iron, silicon, etc. High purity tungsten ingots contain very little iron and copper elements. The contents of carbon, oxygen, iron, copper and tungsten in zones 1–5 in Fig.4a were tested.

As can be seen from Fig. 4 and Table 3, zones 1 and 5 do not contain Cu and Fe, indicating pure tungsten side; zone 4 does not contain W, indicating CuCrZr side; zones 2 and 3 are the cross-melting zones of W and CuCrZr, indicating that W and CuCrZr have achieved metallurgical bonding. The iron content in both W and CuCrZr in W/CuCrZr composite plates is very low, and a large amount of iron appears at the composite interface. It can be concluded that the iron element in this area comes from sample contamination, and its influence is ignored. From EDS analysis, it can be seen that zones 5 and 1 are located on the W side, with high W content and almost no Cu present. Zone 4 is located on the CuCrZr side, with high Cu content but no W present. Zones 2 and 3 are fusion zones, with W and Cu present, forming a metallurgical zone that meets the experimental purpose.

3 Numerical Simulation and Interface Mechanism

3.1 Selection of simulation methods, constitutive equations and equations of state

The two-dimensional numerical calculation model of W/CuCrZr dovetail groove explosion welding was established by the finite element method-smoothed particle hydrodynamics (FEM-SPH, Euler-ALE-SPH) coupling algorithm. The SPH method can reproduce the waveform formation and vortex structure in the explosion welding process, solve the problem caused by the large distortion and deformation, demonstrate the whole dynamic welding process, and reveal the evolution mechanism of the explosion welding interface under different conditions, but the SPH method has lower calculation efficiency than the traditional FEM (finite element method) numerical algorithm. In order to make up for the shortcomings of SPH, the FEM-SPH coupling method is proposed, that is, FEM modeling is used in the small deformation area and SPH modeling is used in the large deformation area. This can not only avoid mesh distortion in large deformation areas, but also reduce the computational domain of SPH, thus greatly improving the computational efficiency[12–13]. Therefore, for the W/CuCrZr hot melt explosion welding experiment, the Euler method was used to model the explosive region far away from the W/CuCrZr interface, the ALE method was used to model the CuCrZr region far away from the interface, and the SPH model was used to model the W/CuCrZr interface.

Based on the W/CuCrZr hot melt explosion welding experiment, the W/CuCrZr hot melt explosion welding was numerically simulated. The changes in pressure and strain during the explosion welding process of W/CuCrZr with the dovetail structure were obtained. The Johnson-Cook model was used for the material constitutive model for the numerical simulation of W/CuCrZr hot melt explosion welding, the Mie-Grüneisen equation was used for the equation of state of the material, and the parameters of the Johnson-Cook model and the Mie-Grüneisen equation of state for W and CuCrZr are shown in Table 4 and Table 5, respectively[14].

3.2 Physical model establishment

Based on the ANSYS/AUTODYN numerical calculation software, a two-dimensional numerical calculation model of the explosion welding of the small-size W/CuCrZr dovetail groove was established by the Euler-ALE-SPH coupling algorithm, the variation laws of pressure and effective plastic strain at the interface of the W/CuCrZr dovetail groove under explosive loading were explored, and the schematic diagram of the numerical calculation model is shown in Fig.5.

The model heights of W and CuCrZr are 3 and 5 mm, respectively, the model length is 30 mm, the SPH particle size is 0.02 mm×0.02 mm, and the total number of particles is 299 540. The size of the upper ALE grid of CuCrZr is 0.05 mm×0.05 mm, and the number of grids is 36 000. In order to be coupled with the ALE algorithm, the Euler model needs to

Table 3 EDS analysis results of W/CuCrZr hot melt explosive welded composite plate interface (wt%)

Element	Zone 1	Zone 2	Zone 3	Zone 4	Zone 5
C	5.21	5.48	5.50	7.83	5.47
O	5.14	5.17	3.00	4.28	5.53
Fe	-	21.29	80.36	4.69	-
Cu	-	0.53	9.24	83.20	-
W	89.65	67.54	1.89	-	89.00
Total	100	100	100	100	100

Table 4 Johnson-Cook model parameters for W and CuCrZr

Parameter	W	CuCrZr
A/MPa	1093	235
B/MPa	1270	340
C	0.0188	0.048
m	0.78	1.831
n	0.42	0.708
T_0/K	298	298
T_m/K	3695	1343

Table 5 Parameters of Mie-Grüneisen equation of state for W and CuCrZr

Parameter	W	CuCrZr
γ_0	2.96	1.99
c_0/m·s^{-1}	4 030	3 940
ρ_0/kg·m^{-3}	18 600	8 890
C_v/J·(kg·K)$^{-1}$	134	383
S_1	1.24	1.489
S_2	0	0
S_3	0	0

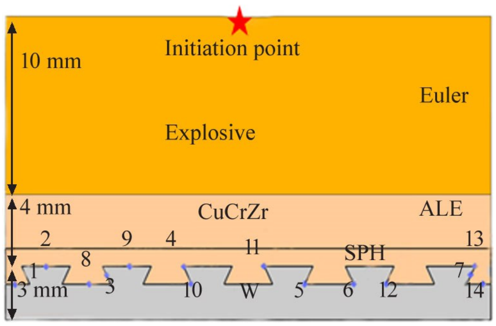

Fig.5 Numerical calculation model diagram of W/CuCrZr explosion welding

wrap the ALE model, so the height of the Euler model of explosives is set as 10 mm, the mesh size is 0.05 mm×0.05 mm, and the number of grids is 156 000. In order to analyze the pressure and strain of the dovetail interface during explosive welding, a total number of 14 Gaussian points were set at the dovetail interface between W and CuCrZr.

3.3 Numerical calculation results and analysis

Fig. 6a is a contour of the pressure distribution at the W/CuCrZr explosion weld interface with dovetail groove structure, from which it can be seen that the pressure in the corner area of the dovetail groove structure is slightly higher than that in other regions, which is consistent with the fact that crack appears on the ground near the corner of the dovetail groove, and the pressure on the CuCrZr side is also significantly higher than that on the W side.

Fig. 6b shows the pressure curve of 14 Gaussian points at the dovetail groove bonding interface. It can be seen that the highest pressure value occurs at the No.6 Gaussian point, and the peak pressure is about 17 GPa, which is located at the corner of the dovetail groove structure. Therefore, high pressure is generated at the W/CuCrZr explosion welding bonding interface, with a duration about 0.02 ms, and high pressure is one of the important factors promoting the interface bonding.

Fig. 7a is the effective plastic strain distribution contour at the W/CuCrZr explosion welding interface with dovetail groove structure. It can be seen that the effective plastic strain on the CuCrZr side is significantly higher than that on the W side, which is mainly due to the fact that CuCrZr is in direct contact with the explosive as a composite plate, the impact load generated by the explosive detonation directly acts on CuCrZr, the hardness of CuCrZr itself is less than that of W, and the CuCrZr and W plate are deformed compared with the initial model. The deformation of CuCrZr plate is slightly larger than that of W plate. In the CuCrZr plate, the effective plastic deformation near the dovetail groove structure is significantly higher than that in other areas of the plate. Fig.7b shows the variation of the effective plastic strain at 14 Gaussian points at the dovetail groove bonding interface over time, in which the Gaussian points No.1–No.7 are located on the W side and the Gaussian points No.8–No.14 are located on the CuCrZr side. It can be seen that the peak value (about 0.6) of effective plastic strain appears at the Gaussian point of No. 13, and the effective plastic strain value of the Gaussian points No.8–No.14 on the CuCrZr side is significantly higher than that of the Gaussian points No.1–No.7 on the W side.

Fig.8a is a contour of the internal energy distribution at the W/CuCrZr bonding interface with dovetail groove structure, and the change of the internal energy at the explosion weld interface is related to the temperature change of the material at the bonding interface, which can effectively reflect the

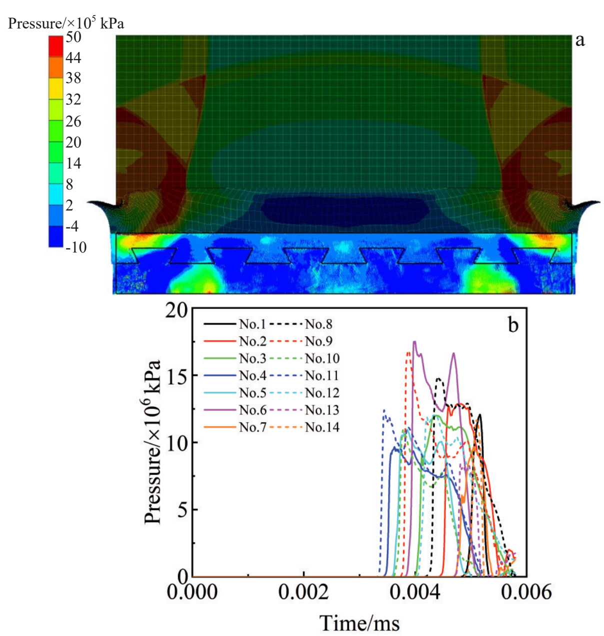

Fig.6 Pressure cloud diagram (a) and curves of interface pressure over time (b) for W/CuCrZr explosion welding

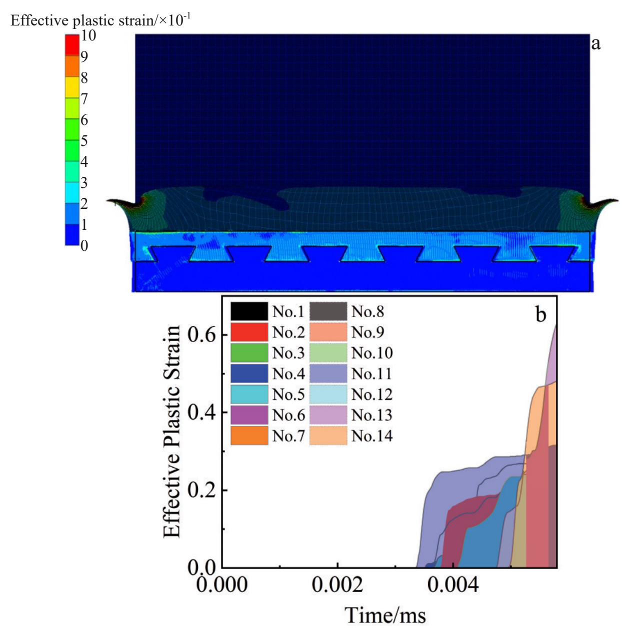

Fig.7 Effective plastic strain cloud diagram (a) and curves of effective plastic strain change with time at interface (b) for W/CuCrZr explosion welding

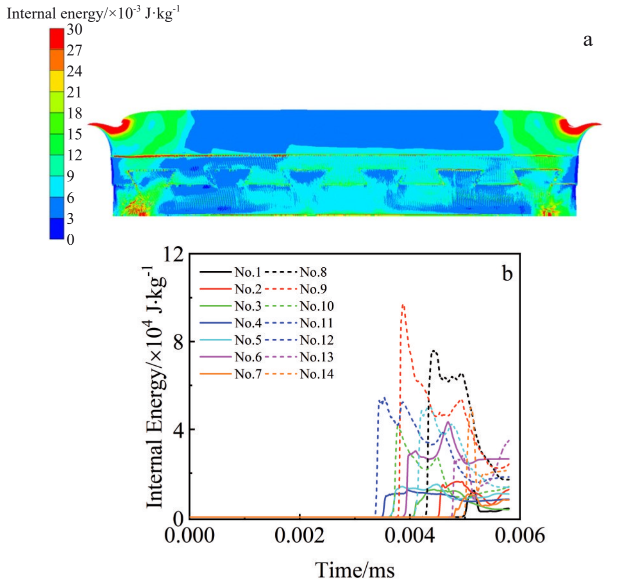

Fig.8 W/CuCrZr explosion welding combined with the internal energy change law: (a) internal energy distribution cloud; (b) graph of internal energy changes over time

temperature change trend at the bonding interface to a certain extent. The internal energy at the edge of the dovetail groove structure of the W/CuCrZr bonding interface is significantly higher than that in other regions, and the internal energy on the CuCrZr side is also slightly higher than that on the W side, which may be related to the properties of the material, i. e., the melt point of CuCrZr is 1083 °C, the melt point of W is 3422 °C, and the melt point of W is much higher than that of CuCrZr. Therefore, for the composite of W material and conventional metal material, it is often necessary to preheat W material to make it easier to form a molten state, so as to facilitate the effective composite between metals. Fig. 8b shows that the internal energy of the No. 14 Gaussian point at the dovetail groove interface is significantly higher than that of the Gaussian points No. 1 – No. 7 on the W side, and the maximum value of the internal energy on the CuCrZr side is located at the Gaussian point No. 9, with a peak size of about 1.0×10^5 J/kg.

Fig. 9 is the Mises stress distribution contour at the W/CuCrZr explosion weld interface with dovetail groove

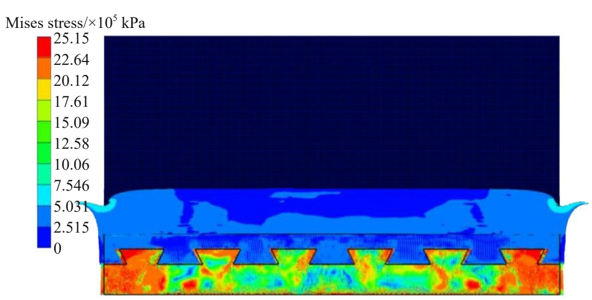

Fig.9 Interface Mises stress distribution cloud of W/CuCrZr explosion welding

structure. The Mises stress on the W side of the substrate is significantly higher than that on the CuCrZr side of the composite plate, and the maximum stress value is about 2.5 GPa. In addition, the Mises stress value at the dovetail groove structure on the W side of the substrate is also significantly higher than that in the internal area of the W plate. Compared with W, CuCrZr has a stronger plastic deformation ability, so stress concentration is not easy to occur in the explosion welding process, while the plasticity of W is relatively poor, so the stress on the W side is higher than that on the CuCrZr side. The stress distribution at the dovetail groove interface is higher than that in the inside of the substrate, which is mainly related to the structural characteristics of the interface, and the dovetail groove interface is more prone to stress concentration than the straight interface. The numerical results are in good agreement with the location of the W break in experiment.

In summary, the hot melt explosion welding process is reproduced by numerical simulation, including the laws of pressure, stress, strain and internal energy changes at interface in the hot melt explosion welding process. The high pressure and high temperature near the interface promote the further combination of the interface, and high strain also causes cracks on the W side. Numerical simulation and experiments have better coincidence.

4 Conclusions

1) W/CuCrZr was prepared by hot melt explosion welding. Metallographic results display that the tungsten dovetail groove structure is fractured, and the interface bonding has a thin layer of cross-melting zone, which is 3 – 8 μm in thickness. The structures on both the W side and the CuCrZr side are dense, and the pores on the CuCrZr side are also eliminated.

2) The variation of interfacial pressure, stress, strain and internal energy at 14 Gaussian points of different positions of the dovetail groove is traced by numerical simulation. The high pressure and high temperature near the interface further promote the bonding of the interface. The high strain also causes the fractures on the W side, and the location of fracture coincides with the numerically simulated high stress position.

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热熔爆炸焊接W/CuCrZr界面特征及其演化机理

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摘　要：在真空热熔W/CuCrZr复合板的基础上进行了爆炸焊接，采用金相显微镜、扫描电镜及能量色散X射线光谱对结合界面进行微观形貌观察，同时结合有限元计算探索了热熔爆炸W/CuCrZr复合板界面的演化机制。结果表明：热熔爆炸焊接W/CuCrZr复合板的界面结合良好，具有3~8 μm交叉熔融区，但W侧产生了裂纹。数值模拟再现了热熔爆炸焊接过程中结合界面压力、应力、应变及内能变化规律，实验产生裂纹的位置和数值模拟计算的高应力位置吻合，热熔爆炸焊接界面附近的高压、高温进一步促进了界面的结合。

关键词：热熔爆炸焊接；W/CuCrZr；界面特征；数值模拟；演化机制

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