DOI: 10.12442/j.issn.1002-185X.20240103

Study on the interface characteristics and evolution mechanism of W/CuCrZr in hot melt explosion welding

SUN Yuling[1,2], LIANG Hanliang[4], ZHU Jiansheng [2], MA Honghao[1,3], WANG Luqing[1,3], ZHANG Bingyuan[1], LUO Ning[1,4], SHEN Zhaowu[1]

([1] CAS Key Laboratory of Mechanical Behavior and Design of Materials, University of Science and Technology of China, Hefei 230026, China;
[2] PLA Army Academy of Artillery and Air Defense，Hefei 230031，China; [3] University of Science and Technology of China, Hefei 230026, China;
[4] School of Mechanics and Civil Engineering, China University of Mining and Technology, Xuzhou 221116, China

Abstract: In this paper, explosion welding is carried out on the basis of vacuum hot melt W/CuCrZr composite plate. Metallurgical microscopy, scanning electron microscopy (SEM) analysis and energy dispersive X-ray spectroscopy (EDS) analysis 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 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，with 3~8μ m cross-melting zone, but cracks developed on the W side; The numerical simulation reproduces the changes of combined interface pressure, stress, strain and internal energy in the process of hot melt explosion welding. The location of the crack generated by 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; Evolutionary mechanisms

Due to the fact that W and copper do not dissolve with each other or form intermetallic compounds, tungsten copper composite materials are called pseudo alloys [1]. Tungsten copper composite materials 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 uses a flat plate W/Cu deflector. Due to the fact that 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 methods. At present, the preparation methods of Tungsten copper composite materials include hot isostatic pressing, 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 technology 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

Foundation item:National Natural Science Foundation of China (No. 12072363,12272374,12372373); Special Fund for Fundamental Research of the Central Universities (WK2480000008, WK2480000007,WK2320000049), Anhui Provincial Science and Technology Major Project (202003A05020035).

Corresponding Author：Ma Honghao, Ph. D., associate professor, CAS Key Laboratory of Mechanical Behavior and Design of Materials, University of Science and Technology of China,He Fei,230026, E-mail:hhma@ustc.edu.cn.

explosion welding method to weld tungsten foil to copper plates. However, the thickness of tungsten foil is thin. Sun Yuling 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. It can be seen that the above methods have their own advantages and disadvantages. In order to obtain an ideal W/CuCrZr composite plate, in this paper, on the basis of vacuum hot melt welding, the hot melt explosion welding method is further used for composite. Combined with finite element calculations, the evolution mechanism of the hot-melt explosion W/CuCrZr composite plate interface is explored.

1 Experiment

1.1 Material parameters

The materials and parameters used in the experiment are the same as those in the article, such as the article[8] to fabricate the W/CuCrZr composite plate with a vacuum-cast dovetail groove structure.

The size of the tungsten plate: 100mm×50mm×3mm, 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 Figure 1（a、b）. A small sample of the vacuum casting dovetail groove structure W/CuCrZr composite plate was intercepted, it is covered with explosives, as shown in Figure 1(c), and placed in an explosive bunker for explosive welding. The size of CuCrZr plate is 100mm×50mm×6mm. 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.

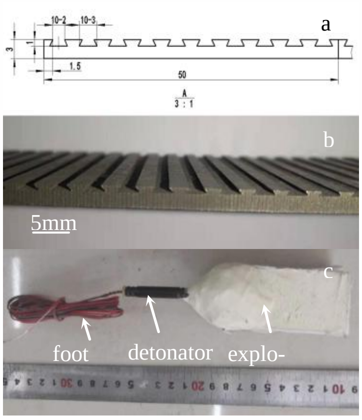

Fig.1 Dimensions and physical drawing of dovetail groove of tungsten plate,（a）Dimensions of dovetail groove ,（b）physical drawing of dovetail groove,（c）Diagram of an explosive device

Table 1 Content of Elements Other than Copper in CuCrZr

element	proportion	element	proportion
Al	0.1-0.25	Fe	0.5
Mg	0.1-0.25	Si	0.5
Cr	0.1-0.8	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.

1.2 Experimental process

Firstly, the W/CuCrZr composite plate with dovetail trough 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 trough 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 casting dovetail groove structure W/CuCrZr composite plate was further exploded and welded, and the sample was prepared. Metallurgical microscopy and scanning electron microscopy (SEM) energy dispersive X-ray spectroscopy (EDS) were used to analyse and study the interface microstructure of W/CuCrZr hot melt explosion composite panels. Meanwhile, the evolution mechanism of the interface between W/CuCrZr composite plates subjected to hot melt explosion was studied through numerical calculations.

2 Experimental results and analysis

2.1 Macroscopic morphology analysis

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

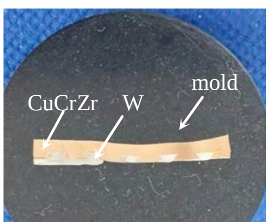

Fig. 2 Physical diagram of W/CuCrZr hot melt explosion welding composite board

2.2 Metallographic microscopic analysis

After grinding and polishing the composite plate samples, the interface bonding of the dovetail W/CuCrZr composite plate was observed by metallurgical microscope, and the ambient temperature was 23.9 ℃ and the relative humidity was 56.3%, and the test results are shown in Figure 4.

As can be seen from Figure 3, W and CuCrZr are still mainly straight combined, and cracks appear on the tungsten side. Especially in the dovetail groove of the dovetail there is a more obvious crack. It shows that under the explosive welding, W can not 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 chromium zirconium copper 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 binding of the W/CuCrZr composite plate has a thin layer of cross-melt zone, as shown in Figure 3(b). The width of the cross melting zone is approximately a few micrometers.

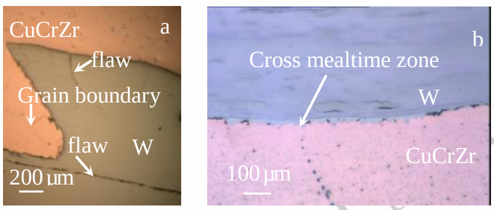

Fig.3 Metallographic structure of W/CuCrZr hot melt explosion welded composite plate

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 by scanning electron microscope and energy dispersive spectrometer. The test environment temperature is 20.4 ℃, the relative humidity is 56.3%, the test party is based on GB/T17359-201, the acceleration voltage is 15kV, the sample to be tested is plated with platinum (Pt) for 20 seconds and then directly put into the SEM vacuum chamber, and the morphology observation and composition analysis are carried out according to the standard process, the composition is semi-quantitative analysis, and the composition result is the mass percentage.

Fig. 4(a)shows the SEM morphology and the position of the surface scan at the interface of the W/CuCrZr hot melt explosion composite panel, Figure 4 (b~f) is the result of the area scan corresponding to the 1~5 area, and Table 3 shows the distribution of the main elements at the interface of the W/CuCrZr hot melt explosion composite panel. As can be seen from Figure 4 (a), there is a diffusion zone of about 3~8 μm, the tissues on the W side and CuCrZr side are dense, and the pores on the CuCrZr side are also eliminated. The main elements in pure W board include W element and some impurities, such as oxygen, carbon, boron, iron, copper and other elements. CuCrZr mainly contains elements such as 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 were tested for the five regions in Figure 4 (a).

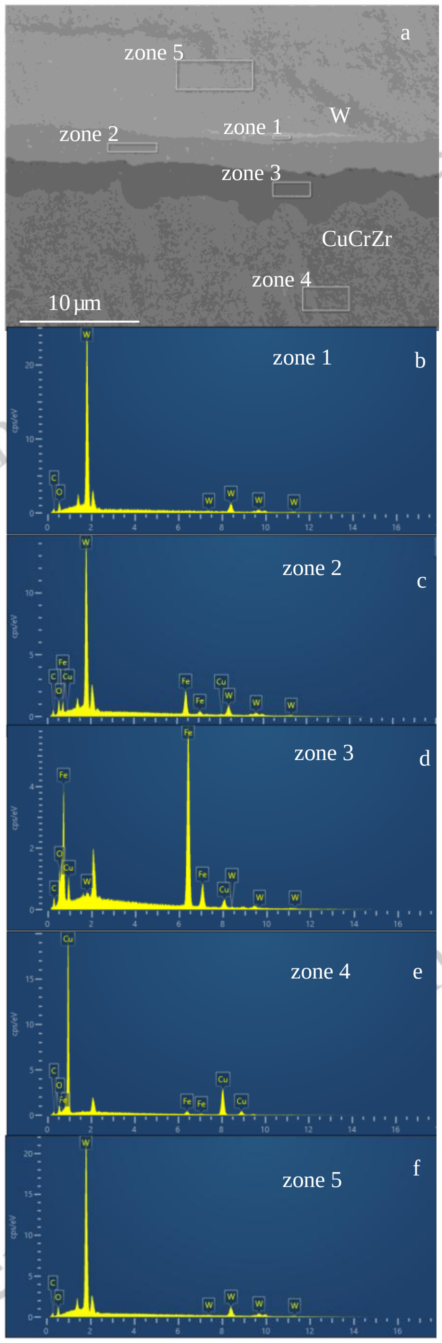

Fig. 4 (a) SEM topography of the interface and the location of the surface selection; (b~f) and (a) 1~5 districts should be the result of the scan

As can be seen from Fig. 4 and Table 3, zones 1 and 5 do not contain Cu and Fe, it is a pure tungsten side; zone 4 does not contain W, it's CuCrZr side; zones 2 and 3 are the cross-melting zones of W and CuCrZr, which shows 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 is caused by sample contamination, and its influence is ignored. From EDS analysis, it can be seen that Zone 5 and Zone 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.

Table.3 EDS composition analysis of W/CuCrZr hot melt explosive 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

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 using the 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 near 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 of 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 Tables 5 and 6[14].

3.3 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, and 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 Figure5.

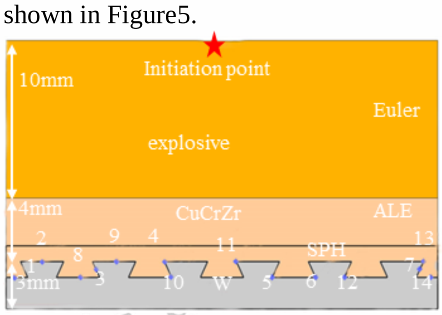

Fig. 5 Numerical calculation model diagram of W/CuCrZr explosion welding

The model heights of W and CuCrZr are 3 mm and 5 mm, the model length is 30 mm, the SPH particle size is 0.02 mm×0.02 mm, and the total number of particles is 299540. The size of the upper ALE grid of CuCrZr is 0.05 mm ×0.05 mm, and the number of grids is 36000. In order to be coupled with the ALE algorithm, the Euler model needs to wrap the

ALE model, so the height of the Euler model of explosives is set to 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 of 14 Gaussian points were set at the dovetail interface W and CuCrZr.

3.4 Numerical calculation results and analysis

Fig.6(a) is a contour of the pressure distribution at the W/CuCrZr explosion weld interface with dovetail groove, from which it can be seen that the pressure in the corner area of the dovetail trough structure is slightly higher than that in other regions, which is consistent with the crack 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. 6(b) shows the pressure curve at 14 Gaussian points at the dovetail trough bonding interface, and 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 trough structure. Therefore, high pressure is generated at the W/CuCrZr explosion welding bonding interface, with a duration of about 0.02ms, and high pressure is one of the important factors promoting the interface bonding.

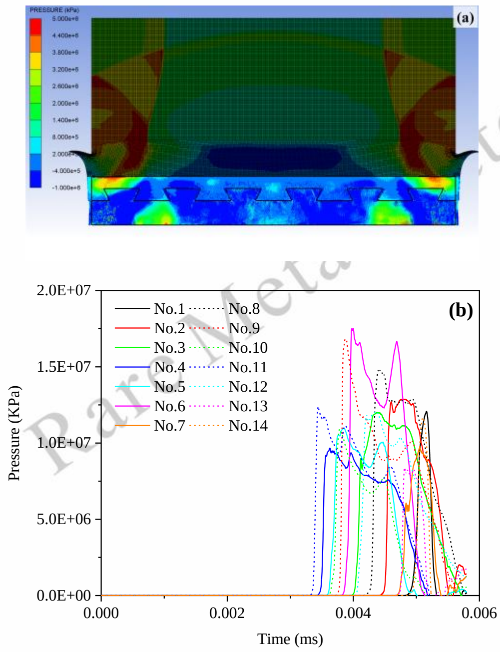

Fig.6 W/CuCrZr explosion welding combined with interface pressure change law: (a) pressure cloud diagram; (b) curve of pressure over time

Fig. 7(a) is the effective plastic strain distribution contour at the W/CuCrZr explosion welding interface with dovetail groove structure, and 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, and the impact load generated by the explosive detonation directly acts on CuCrZr, and 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. 7(b) shows the variation of the effective plastic strain at 14 Gaussian points at the dovetail groove bonding interface over time, with the Gaussian points No.1-No.7 on the W side and the No.8-No.14 Gaussian points on the CuCrZr side. It can be seen from the figure that the peak value of effective plastic strain occurs at the Gaussian point of No.13, and the peak value is about 0.6, and the effective plastic strain value of the Gaussian point on the CuCrZr side of No.8-No.14 is significantly higher than that of the Gaussian point on the W side of No.1-No.7

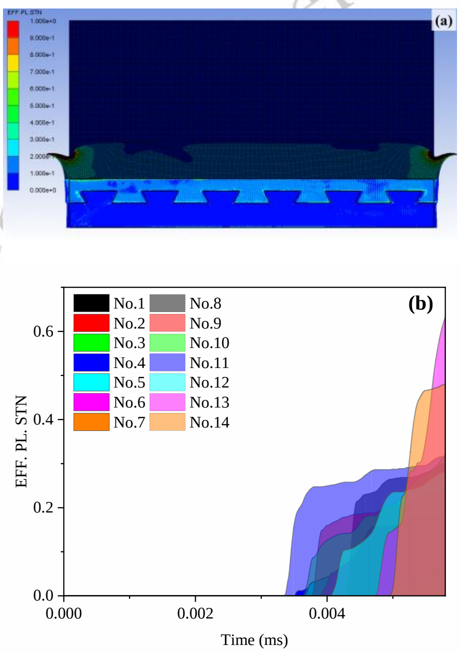

Fig. 7 W/CuCrZr explosion welding combined with effective plastic strain change law at the interface: (a) effective plastic strain cloud diagram; (b) effective plastic strain change curve with time

Fig. 8(a) is a contour of the internal energy distribution at the W/CuCrZr bond 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 temperature change trend at the bond interface to a certain extent. As can be seen from the figure, the internal energy at the edge of the dovetail groove structure of the W/CuCrZr binding interface is significantly higher than that in other regions, and the internal energy of the CuCrZr side is also slightly higher than that of the W side, which may be related to the properties of the material, the melting point of CuCrZr is 1070 ℃, while the melting point of W is 3410 ℃, and the melting 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. 9(b) The internal energy of the 14 Gaussian points at the dovetail trough interface is shown to be significantly higher than that of the No.1-No.7 Gaussian points on the W side, and the maximum value of the internal energy on the CuCrZr side is located at the No.9 Gaussian point, with a peak size of about 1.0×10^5 J/kg.

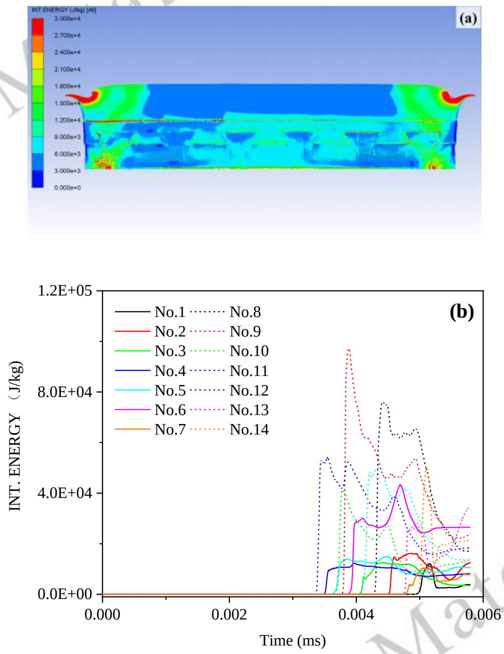

Fig.8 W/CuCrZr explosion welding combined with the internal energy change law:(a) internal energy distribution cloud; (b) graph of internal energy changes over time

Fig. 9 is the Mises stress distribution contour at the W/CuCrZr explosion weld interface with dovetail groove structure, and it can be seen that 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 it is not easy to have stress concentration 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 trough interface is higher than that on the inside of the substrate, which is mainly related to the structural characteristics of the interface, and the dovetail trough interface is more prone to stress concentration than the straight interface. The numerical results are in good agreement with the location of the experimental W break.

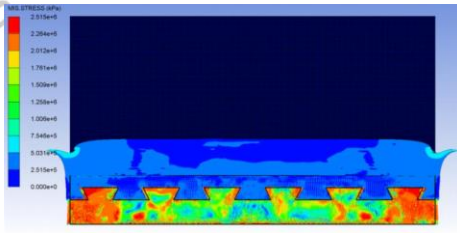

Fig. 9 W/CuCrZr explosion welding combined with interface Mises stress distribution cloud

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

4 Conclusion

W/CuCrZr was prepared by hot melt explosion welding. Metallographic display shows that the dovetail of the tungsten dovetail trough is fractured, and the interface bond has a thin layer of cross-melting zone. Scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS) analysis yielded: the thickness of the cross-melt zone is 3~8μ m, the tissues on both the W side and the CuCrZr side were dense, and the pores on the CuCrZr side were also eliminated. The variation of interfacial pressure, stress, strain and internal energy at 14 Gaussian points at different positions of the dovetail groove was traced by numerical simulation. The high pressure and high temperature near the interface further promote the bonding of the interface. The high strain also caused the formation of fractures on the W side, the location of fracture generation coincides with the position of high stress simulated numerically.

References

1 Wang Hui, Zhang Xiaoming, Wang Feng , et al. *Cemented Carbide*[J], 2014,31(05):322-326.

2 Chen Yuanyuan;Huang Yuan;Han Lu, et al. *Journal of Materials Research and Technology* [J], 2021,15:6260-6271.

3 Singh K P, Bhavsar R, Patel K, et al. *Fusion Engineering and Design* [J], 2017,121:272-281.

4 Chen Yuanyuan;Hou Haixue;Yao Gang, et al. *Materials Characterization*[J], 2021,184:111710.

5 Ren Junpeng(任俊鹏), Wang Yu(王毓) ,Zhao Jun(赵君), et al. *Rare Metals and Cemented Carbides* [J], 2020,48(04):17-23.

6 Chen Xiang(陈翔), Li Xiaojie(李晓杰), Yan Honghao(闫鸿浩),

et al. *Rare Metal Materials and Engineering*[J], 2018,47(03):968-971.

7 Tian Qichao, Sun Yuling, Ma Honghao, et al. *Fusion Engineering and Design* [J], 2021,172:112855.

8 Sun Yuling(孙玉玲), Ma Honghao(马宏昊), Shen Zhaowu(沈兆武),et al. *Rare Metal Materials and Engineering*[J], 2023,52(08):2844-2850.

9 Li Baoqiang(李保强). *Uniwersity of Chinese Academy of Sciences* [D], 2018.

10 XuXuan(徐玄), Dai Qin(戴琴), Ou Han(欧邯). *World Nonferrous Metals*[J], 2018(11):166-167.

11 Liu Zhenghong(刘政泓),Lu Yunzhuo(吕云卓), Lu Xing(陆兴). *Electrical Engineering Materials*[J], 2018(05):21-27.

12 Wang Zhiling, Bi Chenchen, Li Hongru. *Explosion and Shock Waves*[J], 2018,38(6):1419-1428.

13 Wu Xiaoming, Shi Changgen,Gao Li, et al.*Rare Metal Materials an Engineering*[J],2023,52(04):1272-1282.

14 Xin Chunliang et al. *China Machine Press*[M], 2019.

热熔爆炸焊接 W/CuCrZr 界面特征及其演化机理研究

孙玉玲[1,2]，梁汉良[4]，朱建生[2]，马宏昊[1,3]，王鲁庆[1,3]，张冰原[1]，罗宁[1,4]，沈兆武[1]

(1 中国科学技术大学中国科学院材料力学行为和设计重点实验室，安徽 合肥 230026;

2 中国人民解放军陆军炮兵防空兵学院，安徽 合肥 230031

3 中国科学技术大学，安徽 合肥 230026

4 中国矿业大学力学与土木工程学院力学与工程科学系，江苏 徐州 221116)

摘　要：本文在真空热熔 W/CuCrZr 复合板的基础上进行了爆炸焊接，采用金相显微镜、扫描电镜分析(SEM)分析及能量色散 X 射线光谱(EDS)分析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。研究结果表明：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、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

作者简介：孙玉玲，女，1980 年生，博士研究生，中国科学技术大学，安徽 合肥，230026，E-mail: ylsun16@mail.ustc.edu.cn；

通讯作者：马宏昊，男，1980 年生，博士生导师，中国科学技术大学，安徽 合肥，230026，E-mail: hhma@ustc.edu.cn。