Rare Metal Materials and Engineering
Volume 48, Issue 12, December 2019
Available online at www.rmme.ac.cn

Science Press

Cite this article as: Rare Metal Materials and Engineering, 2019, 48(12): 3876-3882.

ARTICLE

Niobium-316L Stainless Steel Transition Joints for Superconducting Radiofrequency Cavities by Explosive Welding

Wang Ruoxu[1,2,3], He Yuan[3], Tan Teng[3], Guo Xuepeng[4], Song Jian[4], Ren Junshuai[4], Zhang Shenghu[3], Zhang Xingyi[1,2]

[1] College of Civil Engineering and Mechanics, Lanzhou University, Lanzhou 730000, China; [2] Key Laboratory of Mechanics on Disaster and Environment in Western China, Ministry of Education, Lanzhou University, Lanzhou 730000, China; [3] Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China; [4] Northwest Institute for Nonferrous Metal Research, Xi'an 710016, China

Abstract: 316L stainless steel and niobium composite plates were jointed by explosive welding technique. Microstructure and mechanical properties of the composite plates were investigated both immediately after explosive welding and after heat treatment processes. The investigation of microstructure demonstrates that no brittle intermetallic layer forms and no diffusion phenomenon is observed after heat treatment processes. Mechanical tests including tensile tests, shear tests and bending tests were conducted both at room temperature and cryogenic temperature. At cryogenic temperature, the composite plates hold higher strength than those at the room temperature. In cryogenic tensile tests, we observed that the niobium section of the composite plate breaks in layers when the sample reaches yielding strength. Beside the raw material, transition joints with Nb-SS adapters were designed and fabricated. The leak check shows the joints' leak rates meet project requirements and indicates explosively bonded Nb-SS is a viable way to fabricate stainless steel helium vessel for SRF cavities.

Key words: explosive welding; niobium; stainless steel; transition joint; liquid helium

In order to solve the problem of safe disposal of nuclear waste, the research of the China initiative Accelerator Driven System (CiADS) is conducted at the Chinese Academy of Sciences, which consists of three parts: a linear accelerator, a spallation target and a reactor[1]. With the characteristics of superconducting properties, the metal niobium is used for fabrication of the RF (radiofrequency) cavities, which have small wall loss and large beam aperture and are adopted by the linear accelerator to accelerate the particles[2]. The RF cavities are immersed in a liquid bath of 2 K or 4 K to maintain their superconductivity when the accelerator is running, and the liquid helium flows in the space between the jackets and the superconducting cavities to cool the RF cavities[3]. Currently, titanium is used to make helium vessel because it has a thermal expansion coefficient close to that of niobium. However, in order to lower manufacturing cost, reduce processing difficulty and increase mechanical stability of the RF cavity, a lot of efforts have been devoted to the making of helium vessel with stainless steel instead of niobium[4]. The transition joint between niobium and 316L stainless steel, which is the Achilles' heel of the stainless steel vessel technique, is not only required to show a high level of hermeticity at the room temperature as well as at 2 K for its operation in ultrahigh vacuum environment, but should also withstand the degassing heat treatment at 873 K or 1073 K together with SRF (superconducting radiofrequency) cavities[5], as well as the periodic thermal cycling between room temperature and cryogenic temperature (4 K or 2 K)[6]. The transition joint must be strong enough to resist stress caused by thermal expansion and remain strong after a number of thermal cycles. Because of the large difference in the welding properties of two metals, the research of Nb-316L stainless

Received date: December 25, 2018
Foundation item: National Natural Science Foundation of China (11622217); Key Research Project of Frontier Science from Chinese Academy of Sciences (QYZDY-SSW-JSC019); The National Key Project of Scientific Instrument and Equipment Development (11327802)
Corresponding author: Zhang Xingyi, Ph. D., Professor, Department of Mechanics and Engineering Sciences, College of Civil Engineering and Mechanics, Lanzhou University, Lanzhou 730000, P. R. China, Tel: 0086-931-8912480, E-mail: zhangxingyi@lzu.edu.cn

steel transition joints is quite challenging.

In general, dissimilar joints to bond two metal materials with distinct physical and mechanical features can be produced by either fusion or solid state welding[7]. However, in the fusion welding process, niobium has a strong tendency to diffuse into 316L SS and forms intermetallic compounds at the interface between[8]. Those intermetallic compounds in the welding interface cause brittleness and decrease the ductility[9]. A method of solid state welding, the explosive welding, can avoid such compounds, and produce composite plates which can be processed into transition joints of different specifi-cations, thereby significantly reducing the processing cost[10]. Explosive welding will take the advantage of controllable huge energy and shock waves generated by dynamite explosive, which causes high-speed collision of different metals, generating high temperature and high pressure at the collision contact, causing strong plastic deformation of the metal near the interface, and achieving the bonding of different metal materials[11]. Some researchers believe that a molten layer or a hard and brittle intermetallic layer can be formed at the bonding interface during the explosive welding process if inappropriate parameters such as excessive charge of explosive are adopted[12,13]. Such kinds of defects strongly degrade the mechanical properties and manufacturing perfor-mance of the composite plate[14].

The whole explosive welding process can be treated as adiabatic because of its short interaction time. Therefore, the microstructures of the interface are degenerated and distorted mostly by the immense force induced during the explosive welding process[15]. At the same time, the difference in the thermal expansion coefficient between the cladding and the base materials can also cause residual stress[16]. Taran et al[10] studied the residual stress states in explosive welded niobium-316L stainless steel bilayer pipe by means of neutron diffraction. The results showed that the stainless steel section of the joint is in tension state, while the niobium section is in compression states. Such stress conditions prevent the joint from being successfully utilized at liquid helium temperature, and necessitate the heat treatment of explosive welded Nb-SS adapter to release residual stress.

So far, there has not been any report on the explosive welding method being employed in the fabrication of Nb-316L SS composite plate. In our work, the influences of different post treatment conditions on the microstructure of the interface and on the mechanical properties of composite plate were evaluated. The morphology and elemental distribution near the bonding interface was investigated by scanning electron microscope (SEM) and energy dispersive X-ray spectrometer (EDS), respectively. Moreover, mechanical properties of the composite plate were characterized by tensile tests, shear tests and bending tests. Finally, the leak rates of two types of transition joints made with different Nb-SS adapters were tested with a vacuum detector. As a result, a set of appropriate parameters for post-treat processing has been determined and the leak-tightness of two types of Nb-316L stainless steel transition joints have been confirmed. In the future, we will try to fabricate the transition joint on the SRF cavities.

1 Experiment

A niobium-316L stainless steel composite plate was pre-pared by explosive welding between an SRF grade (RRR>250) niobium plate and a 316L stainless steel plate in Northwest Institute for Nonferrous Metal Research, China. The thickness of the base (316L stainless steel) and the flyer (niobium) plates were 14 and 4.5 mm, respectively, whereas their width and length were both 410 mm×360 mm. The chemical composition of niobium and 316L stainless steel is given in Table 1 and 2, respectively. The parallel arrangement was used for explosive welding setup as schematically shown in Fig.1. The stand-off distance between the 316L stainless steel layer and the niobium layer was 3 mm.

Table 1 Chemical composition of the niobium (wt%)

Ta	C	Fe	N	W	Mo	Ni	Ti	H	Nb
0.0100	0.0011	0.0015	0.0020	0.0006	0.0004	0.0001	0.0003	0.0004	Bal.

Table 2 Chemical composition of the 316L stainless steel (wt%)

Si	Mn	P	S	Ni	Mo	Cr	C	N	Fe
0.5000	1.3700	0.0270	0.0010	10.1100	2.0400	16.6500	0.0180	0.0080	Bal.

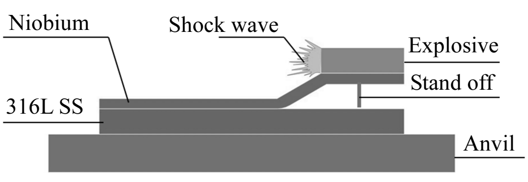

Fig.1 Schematic diagram of explosive welding

Planar samples were cut from the composite plate to show the micrstructure variation along the detonation direction, and dimensions were 18.5 mm×10 mm×3 mm. Samples were mechanically polished with sand paper (600# to 5000#, in 5 steps), then followed by a standard chemical-mechanical polishing (using 0.3 μm alumina slurry) to achieve a mirror-like surface finishing. The annealing temperature and period were selected at 1073 K for 1 h on the basis of the earlier works[5]. The morphology and micro-composite measurement was done on a scanning electron microscope (SEM, JSM-5 873LV) equipped with EDS module.

GB standards GB/T-228.1-2010, GB/T1329-2006, and GB/T 24584-2009 were adopted for preparing composite plate samples under different circumstances for the mechanical properties test. Shear and bending tests were conducted under the guideline of GB/T 6396-2008. All mechanical tests were carried out on a MTS-SANS CMT5000 universal testing machine.

A transition joint was fabricated with a piece of niobium cup, a piece of 316L stainless steel tubing (both with I.D. 54 mm, and O.D. 60 mm), and a 316L stainless CF63 flange. A piece of Nb/316L stainless steel composite ring served as the transition between niobium and stainless steel tubing. Fig.2 shows the drawing of such a transition joint. Two types of joints with different thickness composite rings (5 and 10 mm) were tested. The *d* denotes the thickness of the composite ring. The robust test was done with 60 min ultrasonic cleaning, liquid nitrogen thermal cycle for 10 times, and liquid helium thermal cycle twice. An INFICON UL1000 leak detector was employed to investigate whether the joints would survive after the robust test.

2 Results and Discussion

2.1 Morphology

The SEM images for a typical fresh bonding interface of Nb/316L stainless steel explosive welding composite plates are shown in Fig.3. The microstructure of joint interface demonstrates that cladding of 316L stainless steel to niobium was successfully achieved by the explosive welding technique. From the SEM inspection there are not any visible defects observed near the interface, including pinholes, melting voids or intermetallic compounds. Usually, in the explosive welding, two types of bonding interfaces can be seen on the cross section view of the explosive welding joints, wavy and straight[17-19]. Our Nb/316L stainless steel composite plate exhibits standard wavy morphology at the bonding interface. Previous research has interpreted the wavy interface and the mechanism of its formation during explosive welding[20]. Also,

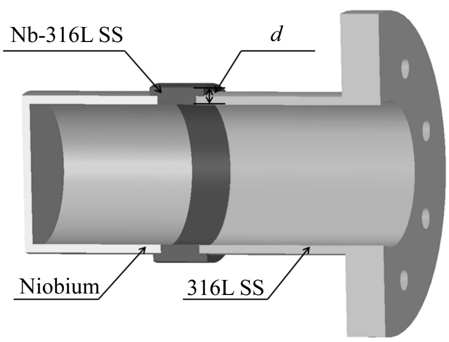

Fig.2 Drawing of a transition joint

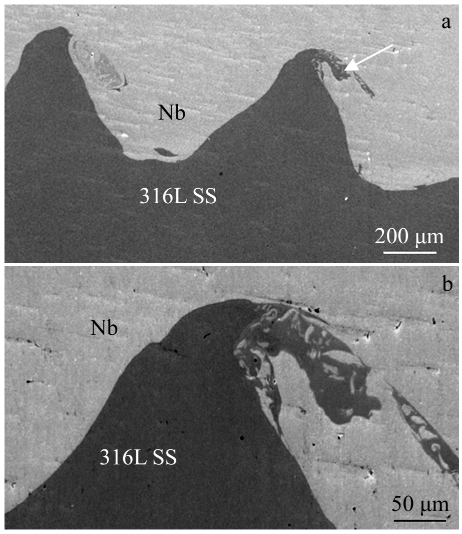

Fig.3 SEM morphology near the Nb-SS interface (a) and enlargement for the whirlpool strucutre (b)

some researchers have reported that the wavy structure is more desirable in the explosive welding process due to its larger contacting area and higher bonding strength[12, 20].

The Nb-SS interface (arrow in Fig.3a) is enlarged and shown in Fig.3b. It can be clearly seen from the SEM image that stainless steel particulates are wrapped and enclosed by niobium jet. Similar structures, in which base material is captured and wrapped by flyer, were reported in other explosive bonding studies[21]. The formation of such whirlpool relies heavily on the impact speed of niobium jet, which causes the pulverizing of stainless steel and captures it. Compared with the previous results, the amount of dynamite we employed in the bonding process was smaller. Therefore a niobium jet with a lower impact speed finally leads to a much smaller whirlpool structure.

Fig.4a is an SEM image taken on a Nb-SS composite sample after annealing at 1073 K for 1 h. There is not any visible inter-diffusion between the niobium and the stainless steel region after the annealing. An EDS line scan across the interface (Fig.4b) shows a clear Nb-SS boundary, which further supports the absence of such inter-diffusion, and suggests the annealing at 1073 K would impose little influence on the composite material's bonding properties.

2.2 Mechanical tests results

2.2.1 Tensile test

In order to study the mechanical properties of the sample after various treatments, a tensile test was performed. The strain-stress relationships for different samples are shown in Fig.5a and 5b. Summarized mechanical properties can be found in Fig.5c. The sample processed only by explosive welding without heat treatment has an ultimate tensile strength, a yield strength, and an elongation of 776 MPa, 616 MPa, and

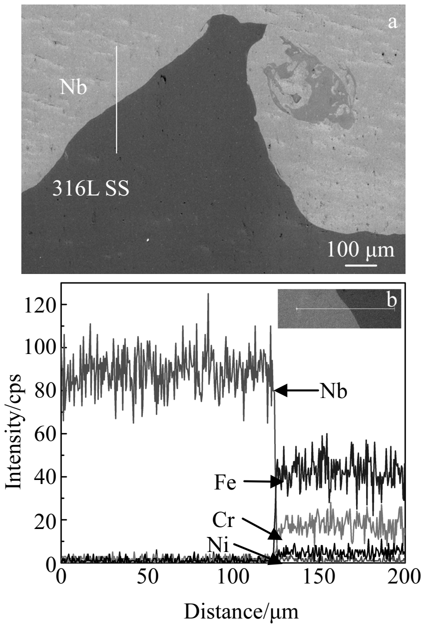

Fig.4 SEM morphology for a sample annealed at 1073 K for 1 h (a) and EDS line scan results along the white line in Fig.4a (b)

13%, respectively. No phenomenon of macroscopic delamination on the bonding interface was observed. The ultimate tensile strength of the sample heat treated at 1073 K for 1 h is 609 MPa, 21.5% lower than that of the untreated sample, but its elongation is 4.5% lower than the counterpart. The evolution of composite plate's mechanical properties is a result from the stress release during the annealing. Such results improve the feasibility of manufacturing SRF cavities' helium vessel from stainless steel and Nb-SS joints. Additional tensile tests were conducted at liquid nitrogen (LN2, 77 K) and liquid helium (LHe, 4.2 K) temperature. The results are presented in Fig.5d. From the cryogenic tensile tests, we observed a sudden drop of stress force as displacement increases. It suggests there might be fracture in the niobium part of the composite plate which causes the sliding of cryogenic extensometer, and results in the measured stress far beyond the reasonable range (depicted in Fig.5a and 5b). The predicted fractures were observed on the tensile test samples when the samples were warmed up to room temperature after the cryogenic test. Fig.6a and 6b are the pictures of such kind of fractures. All fractures happened in the niobium region because at the same temperature, niobium has a much smaller tensile strength than 316L stainless steel. Fig.6 also reveals that composite plate breaks in layers when extended along the bonding surface. At LN2 temperature, the plate's ultimate tensile strength, yield strength, and elongation are 750 MPa, 687 MPa, and 4.74%, respectively. Those values shift to 797 MPa, 750 MPa, and 2.36% at LHe temperature. Comparing the three sets of numbers, it can clearly be seen that the composite plate exhibits much tougher properties (higher

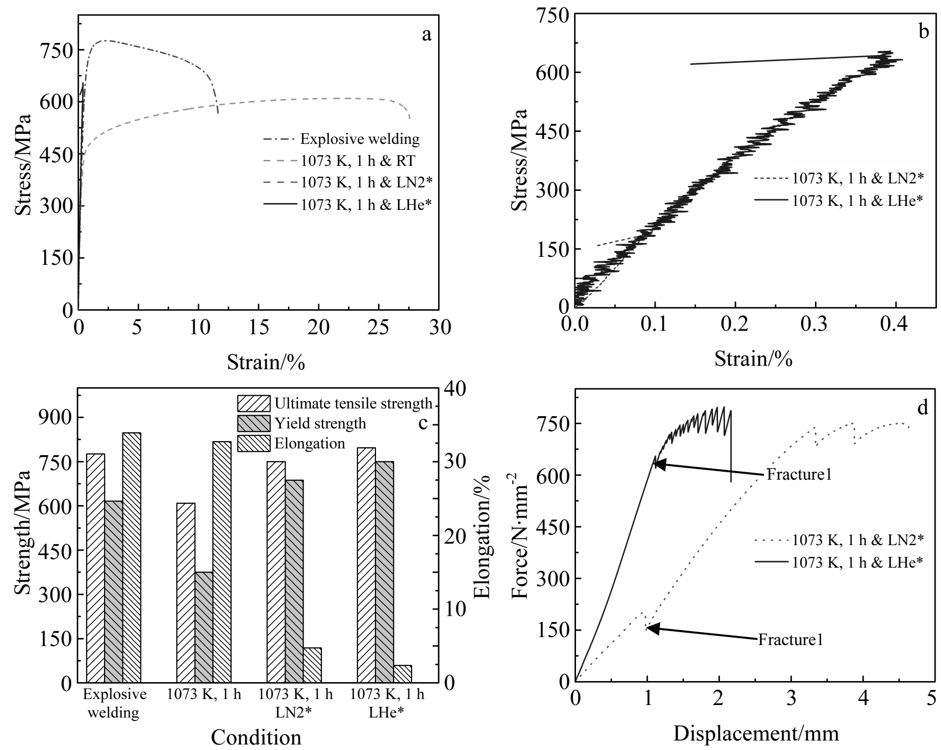

Fig.5 Stress-strain curves for tensile test (a), enlargement for stress-strain curves for tensile test (b), tensile propreties (c), and force-displacement curves for tensile test (d)

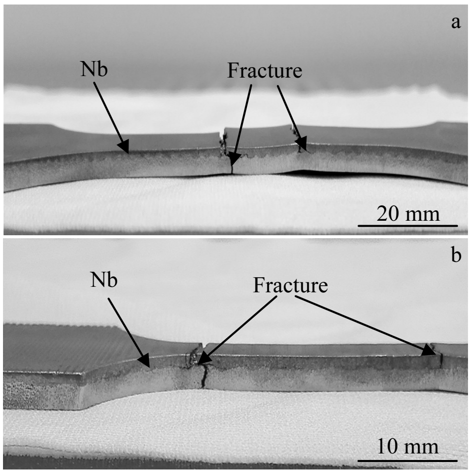

Fig.6 Delamation observed after cryogenic tensile tests: (a) after LN2 test and (b) after LHe test

strength and smaller elongation) at cryogenic temperature than room temperature, while the difference between LN2 and LHe sets is much smaller. In the future research of SRF cavity material, we have no need to conduct the mechanical testing under liquid helium but replace it with experiments under liquid nitrogen.

Beside cryogenic mechanical performances, mechanical properties after thermal cycles are also critical to the application of Nb-SS composite materials in fabricating SRF cavities' helium vessel. Standard tensile tests were carried out at room temperature for samples just after annealing or submerging in LN2, or LHe for 24 h. The results are summarized in Fig.7. The ultimate tensile strength and yield strength of the composite samples after thermal cycle are reduced compared with those of the uncycled sample, but within a small extent. The large difference between the thermal expansion coefficients of niobium and 316L stainless steel, may cause delamination and deteriorate the mechanical properties of the composite material after thermal cycles.

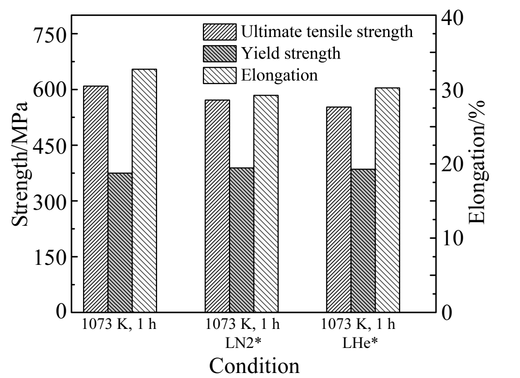

Fig.7 Room temperature tensile tests for annealed (a), annealed+ LN2 cycled (b), and annealed+LHe cycled (c) samples

2.2.2 Shear test

To verify the bonding strength, shear tests were performed on an as-received sample, an annealed sample, and an annealed sample at LN2 temperature. Fig.8a shows a typical sample appearance after a shear test. The fracture always happens at the Nb-SS interface. The wavy fracture surface is consistent with the Nb-SS interface seen in Fig.3 and 4. The shear tests results are plotted in Fig.8b, which illustrates that shear strength increases after annealing and dramatically decreases after LN2 thermal cycle. Those phenomena can also be explained by the releasing of stress and the large difference in thermal expansion coefficients.

2.2.3 Bending test

On the purpose to understand the composite plate's ability to resist delamination caused by manufacturing, such as deep drawing or stamping, bending tests were conducted followed the standard protocol, GB/T 6396-2008. Both as received and annealed samples were tested. It can be seen from Fig.9 that there is not any visible separation, tear, fracture, or rupture observed. This indicates the composite plate can meet the engineering requirement.

2.3 Leak check for the transition joint

The leak-tightness of every connection on the transition joint (see Fig.2) was tested with a leak detector to check the feasibility to adopt Nb-SS composite plate in SRF cavities' helium vessels. Two transition joints with Nb-SS composite rings, 5 and 10 mm thick were tested. The connection between niobium cups and composite rings were made through electron beam welding, while the connections between stainless

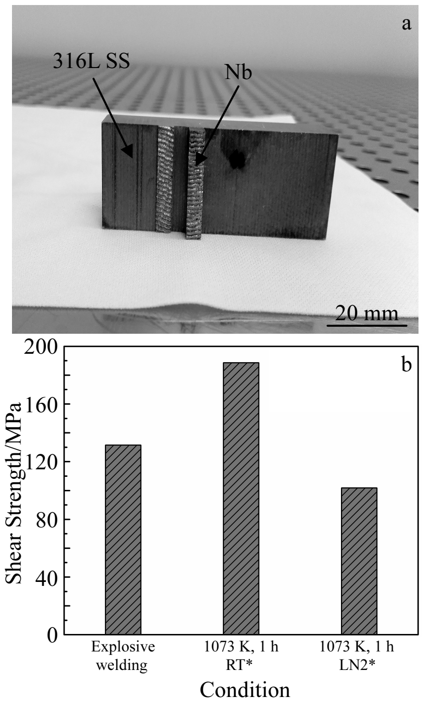

Fig.8 Typical fracture outlook of shear test (a) and test results (b)

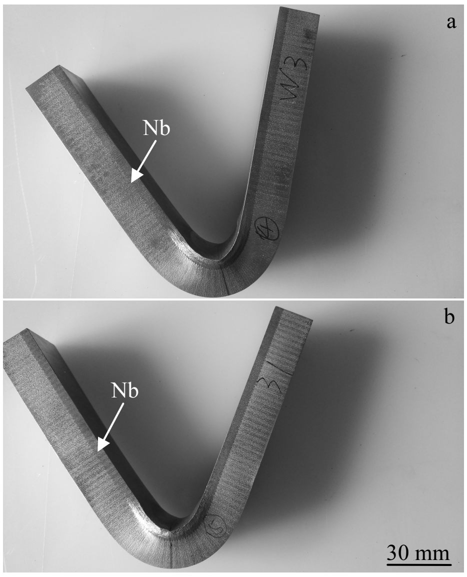

Fig.9 Bending test of as-received explosive welded plate (a) and plate after annealing (b)

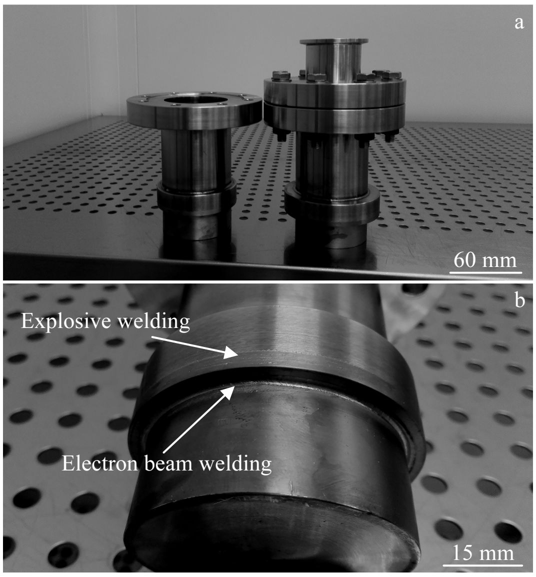

Fig.10 Bending test of as-received explosive welded plate (a) and plate after annealing (b)

parts (ring-tubing and tubing-flange) were made by argon arc welding. Fig.10 shows the appearance of the transition joints. The seams for both and explosive welding can be seen on the joints. From the previous results, we understand that annealing can release the stress accumulated in the electron beam and explosive welding processes and is advantagous for mechanical fabrication. Therefore, both joints were annealed after electron beam welding and before the final argon arc welding process. The annealing temperature is 1073 K, for 1 h.

Fig.11 Leak check for the joint

The leak check at LN2 temperature was as follows: putting the joints in a LN2 Dewar, then taking them out and putting them into a helium bag for leak test. The leak check at room temperature and 77 K both shows the joints' leak rates are smaller than 1.1×10^{-8} Pa·L/s (see Fig.11).

3 Conclusions

1) SRF grade niobium and 316L stainless steel were successfully bonded through explosive welding. The interface of composite plates has a typical wavy morphology, and is free of pin-holes, melting zone and brittle intermetallic layer. After annealing, there is not any diffusion phenomenon observed.

2) The composite material is tougher under cryogenic environment. The mechanical properties do not differ much between LN2 test and LHe test, which provides a more economical way to characterize the composite samples. Both tensile test and shear test indicate the samples survive LN2 and LHe thermal cycle and are still suitable for the manufacturing of helium pressure containers. Bending test manifests the material is good for common manufacturing technique employed in general pressure containers.

3) Leak check on the transition joint shows the leak rate lower than 1.1×10^{-8} Pa·L/s, which meets the requirement of helium vessel fabrication. All results suggest that Nb-316L stainless steel joint made by explosive welding is a feasible route towards the adoption of stainless steel helium vessel in the fabrication of SRF cavity and other kinds of helium container.

References

1 Xiao Guoqing, Xu Hushan, Wang Sicheng. *Nuclear Physics Review*[J], 2017, 34(3): 275 (in Chinese)

2 Reece C E. *Physical Review Accelerators and Beams*[J], 2016, 19(12): 124 801

3 Pierini P, Bertucci M, Bosotti A *et al*. *Physical Review Accelerators and Beams*[J], 2017, 20(4): 042 006

4 Kumar A, Ganesh P, Kaul R *et al*. *Journal of Materials Engineering and Performance*[J], 2015, 24(2): 952

5 Barkov F, Romanenko A, Grassellino A. *Physical Review*

Accelerators and Beams[J], 2012, 15(12): 122 001
6 Dhakal P, Chetri S, Balachandran S *et al*. *Physical Review Accelerators and Beams*[J], 2018, 21(3): 032 001
7 Durgutlu A, Gülenç B, Findik F. *Materials & Design*[J], 2005, 26(6): 497
8 Kumar A, Ganesh P, Kaul R *et al*. *Journal of Manufacturing Science Engineering*[J], 2017, 139(1): 015 001
9 Zhu B, Liang W, Li X R. *Materials Science and Engineering A*[J], 2011, 528(21): 6584
10 Taran Y, Balagurov A M, Sabirov B *et al*. *Materials Science Forum*[J], 2013, 768-769: 697
11 Yang Y, Zhang X M, Li Z H *et al*. *Acta Materialia*[J], 1996, 44(2): 561
12 Mousavi A A A, Al-Hassani S T S. *Journal of the Mechanics and Physics of Solids*[J], 2005, 53(11): 2501
13 Mousavi S A A A , Sartangi P F. *Materials & Design*[J], 2009, 30(3): 459
14 Durgutlu A, Okuyucu H, Gulenc B. *Materials & Design*[J], 2008, 29(7): 1480
15 Honarpisheh M, Asemabadi M, Sedighi M. *Materials & Design*[J], 2012, 37: 122
16 Sedighi M, Honarpisheh M. *Materials & Design*[J], 2012, 37: 577
17 Lysak V I, Kuzmin S V. *Journal of Materials Processing Technology*[J], 2012, 212(1): 150
18 Kaçar R, Acarer M. *Materials Science and Engineering A*[J], 2003, 363(1-2): 290
19 Acarer M, Demir B. *Materials Letters*[J], 2008, 62(25): 4158
20 Kaya Y, Kahraman N. *Materials & Design*[J], 2013, 52: 367
21 Zhou Q, Feng J R, Chen P W. *Materials*[J], 2017, 10(9): 984

爆炸焊接制备超导射频腔用铌-316L 不锈钢过渡接头

王若旭[1,2,3]，何　源[3]，谭　腾[3]，郭学鹏[4]，宋　健[4]，任军帅[4]，张生虎[3]，张兴义[1,2]

(1. 兰州大学 土木工程与力学学院，甘肃 兰州 730000)

(2. 兰州大学 西部灾害与环境力学教育部重点实验室，甘肃 兰州 730000)

(3. 中国科学院近代物理研究所，甘肃 兰州 730000)

(4. 西北有色金属研究院， 陕西 西安 710016)

摘　要：利用爆炸焊接方式进行了铌和 316L 不锈钢的连接。为了观察复合材料的性能，对爆炸焊接和热处理后的复合材料进行了结合面微观结构和力学性能研究。微观结构研究表明结合面没有脆性金属间化合物形成且复合材料热处理后没有发现结合面有元素扩散。还对复合材料进行了室温和低温环境下的拉伸测试、剪切测试和弯曲测试。拉伸测试结果表明液氦温度下复合材料的强度高于室温，同时还观察到在液氦环境下复合材料有分层现象出现。最后进行了 Nb-316L SS 过渡接头的设计、加工和真空检漏，结果表明真空漏率满足工程要求，从而验证了 Nb-316LSS 复合材料用于 SRF 超导腔体氦夹克的可行性。

关键词：爆炸焊接；铌；不锈钢；过渡接头；液氦

作者简介：王若旭，男，1984 年生，博士生，兰州大学土木工程与力学学院力学系，甘肃 兰州 730000，电话：0931-8912480，E-mail: wangruoxu@impcas.ac.cn