Research on the Microstructure and Mechanical Properties of WC-TiC-Co/steel Joints

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Abstract. Wear-resistant layer of cemented carbide on steel can improve its wear properties in particular areas, such as oil drilling. Herein, the WC-TiC-Co/steel joint, the WC-TiC-Co wear-resistant layer covers the steel surface, is fabricated by infiltration brazed, using Cu-Zn filler alloy and WC particles as solder. The microstructure and mechanical properties of as-obtained joint are investigated. The Longitudinal interface has good bonding and the existence of transverse gaps are surveyed on interface between WC-TiC-Co and solder. The element Mapping test shows the distribution of Co element in WC-TiC-Co block is uneven. And the present of element interdiffusion forms the diffusion layer in the joining zone between base materials and solder. The hardness and phase tests indicate that Co3Fe7, W2C phase were produced during brazing, but there are few impacted on the hardness by Co3Fe7, W2C phase.

1. Introduction
Tungsten cobalt titanium cemented carbide (WC-TiC-Co), composed of the hard phase of WC, TiC particles and the cohesive phase of Co, has attracted increasing attention and obtained widespread application in oil drilling, mining tools, geological exploration and other fields, owing to its excellent wear-resistance, high hardness and strength, corrosive resistance, good wettability and so on [1-2]. Nevertheless, the application of the WC-TiC-Co was limited because of its brittleness and high cost, with development of machine manufacturing technology [3].

Infiltration brazed, one kind of Brazing, is the technology that join cemented carbide block and filler to form a wear-resistant layer on the surface of the workpiece improving the wear and corrosion resistance of workpiece. This process mainly depends on the infiltration and diffusion of the filler. In addition, cemented carbide block does not melt, and basically maintains the original size shape and performance. there are not new compounds produced during brazing. More importantly, the base material still retains the original excellent properties [4-7]. Brazing has been widely used in the joining of cemented carbide and steel owing to its low cost, simplicity [7, 8]. Up to now, this manufacture is relatively mature, achieving disposable large-area join molding and ensuring that cemented carbide blocks can be installed accurately to designed position.

Herein, the WC-TiC-Co/steel joint, the joining of WC-TiC-Co and steel, is fabricated by infiltration brazed using Cu-Zn-Ni-Mn alloy (Cu-Zn alloy) and WC particle as solder. Therefore, the purpose of this report focus on researching the reason of gaps formation, discussing the microstructure and mechanical properties of as-obtained WC-TiC-Co/steel joint, exploring the microstructural evolution mechanism of the joint and putting forward a process optimization scheme. Hence, and X-ray radiographic inspection, scanning electronic microscopy (SEM) with an energy disperse spectroscopy (EDS), X-ray diffraction (XRD), and hardness tester were employed in this report.
2. Experimental
The fabrication of WC-TiC-Co/steel joint, use the WC-TiC-Co, Cu-Zn alloy, WC particles and steel by infiltration brazed. And the brazing temperatures range of the solder are 900-1000°C [1]. Inside, WC particle is utilized as a wear-resistant particle to improve the wear-resistant of interlayer.

The internal defects and bond force of the obtained joints were analyzed by the X-ray radiographic inspection. X-ray diffraction (SmartLab, Japan) using CuKα radiation were used to measured the existing phases of WC-TiC-Co and interlayer after brazing. For morphological inspection, the cross-sectional sample obtained by slicing treatment were polished using diamond papers (#120 up to #2500) and diamond paste (2.5). Then, the morphological and element distribution were test by SEM with an EDS (JSM-6510, Japan). In order to analy the mechanical properties of WC-TiC-Co, interlayer and steel, the hardness profiles were measured contain Rockwell hardness and Vickers-hardness.

3. Results and discussion

3.1. Macro analysis
As we can see from Figure 1, it is clear that no obvious cracking is observed. Long columnar WC-TiC-Co, with the size of 20 mm × 5 mm × 2 mm, is distributed longitudinally and is surround by solder. Moreover, the longitudinal distance between WC-TiC-Co is probably 3 mm and is almost twice the transverse width of solder (about 1.5 mm).

The X-ray radiographic inspection was carried out to further observe the bond ability and defects (welding defect, gaps, et) of the joints. As shown in Figure 2, it is apparent that the longitudinal interfaces of the WC-TiC-Co/Interlayer is continuous and unbroken, verifying that WC-TiC-Co gets well bonded with Cu-Zn filler alloy on the longitudinal direction. Small and transverse gaps are present on interface between WC-TiC-Co and solder, and are close to the edge of WC-TiC-Co. This result is further verified by SEM.

3.2. Phase analysis
Concerning the phase analyzed of the WC-TiC-Co and interlayer, the X-ray diffraction of phases were employed in Figure 3. Figure 3a illustrates that the Cemented carbide blocks has three phases, such as WC, TiC, and Co3Fe7. Figure 3a displays that the new phase Co3Fe7 is appear due to the Fe diffuses into cemented carbide during hold temperature and solidification process. The atomic radius of Fe and Co (Rw=2.02, RFe=1.72) is smaller than the atomic radius of W and Fe (RCo=1.76). Moreover, Fe and Co belong both transition elements. Therefore, the solid solubility between Fe and Co is greater. In other words, the Co3Fe7 is relatively easy to formed.

From Figure 3b, there are four phases on the interlayer, composing of WC, W2C, W2[C, O], Cu0.64Zn0.36. The formation of phase depends on the composition of raw materials and high temperature liquefaction treatment technology. The W2C phase is unstable and is formed by decarburization of the WC during brazing. At the same time, the W2[C, O] appear and is due to the oxide reaction of exposed WC and W2C with O atoms.
3.3. Microstructure characterization

Details about the microstructure and the element distribution of the joints were given by SEM images with EDS.

Figure 4a-b illustrates the Cu-Zn filler alloy gets bonded with the base material. In addition, there are the present of gaps on the transverse interface, in accordance with the analysis of the X-ray radiographic inspection image. The gap width is approximately 4.246 μm, confirming further that the transverse interface between WC-TiC-Co and solder is not tight.
From Figure 1, the transverse width of solder is about half the longitudinal width, verifying the formation of transverse gaps is associated with the width of interlayer. Hence, the bonding strength of interface is related to the width and length distance of the interlayer between cemented carbide. The interlayer is wide enough, means that the content of filler is adequate, it is not only good for the release of residual stress in interlayer, but also is instrumental in the fusion and interdiffusion of the WC-TiC-Co and solder. On the other hand, these phenomena are in contact with the interface wetting. The well bonding of cemented carbide block with solder requires sufficient interface wetting, fine brazing temperature and hold time. If not, the diffusion of the interface between materials are not sufficient, which gives rise to weak interface bonding and even unconjugated gap [7].

According to the SEM image and element mapping analyzed results of the joints (Figure 4-6), this alloy consists of the WC-TiC-Co, steel, Cu-Zn filler alloy and WC particles. And WC-TiC-Co block and steel are connected by the filler alloy. In Figure 5, it is clear that WC-TiC-Co contain Cu, Zn element, and Co element spread into filler alloy, not WC particle. More interestingly, there is a transition zone between steel and solder, including Fe, Mn, Cr, Cu, Zn, Ni element. Inside, Fe, Cr belong steel, Cu and Zn element come from solder element. The above phenomenon shows that the element interfacial diffusion is present among the WC-TiC-Co, solder and steel. The element diffusion process of between based materials and solder was described by Figure 7. When the brazing temperature reach the melting point of the Cu-Zn filler alloy, the melted filler alloy contact directly with steel with a pure surface, which is conductive to improving the wettability between materials and filler alloy. With the increase further of temperature, various element will diffuse and reaction driven by the present of concentration gradient and thermodynamics. At present, there is not only element diffusion in materials, but also diffusion between base materials and filler alloy. It will promote the element composition of filler alloy itself to be more even. Simultaneously, the diffusion layer with a certain thickness between base material (steel or WC-TiC-Co) and filler alloy are also formed [3].

So as to further understand the chemical composite of WC-TiC-Co given by EDS, the result is shown in Figure 8, there are Mn, Ni, Fe, Cu, Ti element in addition to W, C, Co. Moreover, the content of the Co element is below, and is uneven in each WC-TiC-Co block. The Co element has been diffusion of the WC-TiC-Co into the solder during the heating and melting process of the solder, leading to the content of Co reduction. The appearance is in accordance with Figure 5. Furthermore, from the microstructure characteristic of WC-TiC-Co in Figure 4c and d, the size of WC particles in different cemented carbide blocks is obviously different and is uniformity. Comparing with Figure 4c, the WC particles is finer in Figure 4d. Interestingly, the large particles are also existed in Figure 4d. These above-mentioned clearly illustrate that the absence of consistency and stability of composition and particle size between cemented carbide batches. It is difficult to take into account all the carbide blocks in certain manufacturing process, resulting inevitably in the differences of different cemented carbide blocks and their boundary properties.
Figure 5. The element mapping of the solder and WC-TiC-Co.
Figure 6. The element mapping of the solder and steel.
3.4. Hardness evaluation of WC-TiC-Co/steel composite joints

To evaluate the mechanical properties of WC-TiC-Co/steel composite joints in more detail, the hardness profile was conducted. At Table 1, the average Rockwell hardness of WC-TiC-Co is basically close to the conventional WC-TiC-Co material (85-90 HRA). The disaccord of Co element gives rise to the slight reduction of the Rockwell hardness of WC-TiC-Co at certain position. Furthermore, the Vickers-hardness value of solder (WC) and steel is similar to the conventional WC particle and steel, confirming that the present of the W_2C and W_2[C, O] phase has less effect on the hardness of the WC blocks.
However, the average Microhardness of solder (Cu-Zn) is obviously inconformity and this is related to the unevenly of element in micro area. From the analysis of mapping, the present of element interfacial diffusion between base material and filler alloy is observed, and this may lead to inhomogeneous composition in the micro area of the filled alloy.

Table 1. The hardness of WC-TiC-Co, solder (Cu-Zn), solder (WC) and steel.

| Sample          | Hardness average |
|-----------------|------------------|
| WC-TiC-Co       | 85.9HRA          |
| Solder (Cu-Zn)  | 121HV0.2         |
| Solder (WC)     | 2101HV0.5        |
| Steel           | 301HV0.2         |

4. Conclusion

- After brazing, the transverse interface between WC-TiC-Co and solder is not tight, and is related to the transverse width of interlayer.
- During brazing, the formation of $\text{Co}_3\text{Fe}_7$, $\text{W}_2\text{C}$, $\text{W}_2[\text{C}, \text{O}]$ phase has less influence on the hardness of WC-TiC-Co and interlayer, respectively.
- The diffusion layer depends on element interdiffusion and reaction in the joining zone between base materials and solder.

5. Recommend

Based on the above analysis and discussion, the optimization measures are as following:

- Properly increase the distance between cemented carbide blocks, especially the transverse direction. Cu-Zn based alloy has adhesive effect during brazing and it plays a significant role in improving the well bonding between WC-TiC-Co and steel. Expanding its width, means increasing the content of Cu-Zn alloy, ensure sufficient metal diffusion on interlayer and residual stress release.
- To be ensure as far as possible the composition uniformity and stability of cemented carbide blocks. As we all known, the weighty factor which affect the quality of joint are the performance of the base material and heat treatment process. The properties of cemented carbide block rely on the uniformity of chemical composition and size of WC, TiC particle. Therefore, it is the key step to guarantee the quality of joint.
- Optimization of process parameters, such heating speed, hold temperature, preservation time and so on. Moderate heat treatment parameters are helpful for the elimination of stress, gas emission, interface wetting and diffusion, fine grain size of the base metal during brazing.

Acknowledgments

This work was supported by China United Test & Certification Co., Ltd and Guobiao (Beijing) Testing & Certification Co., Ltd.

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