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Explosive Coating of Ag–Cu Filler Alloy on Metal Substrates and Its Effect on Subsequent Brazing Process

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An austenitic stainless steel plate was coated with a sheet of Ag–Cu filler alloy by using explosive energy to simplify the subsequent brazing operation. The coated specimen had a typically wavy interface, and there were no defects like void. The adhesion at the interface was retained even after heating at a temperature of more than eutectic point of the Ag–Cu binary system (1 052 K), although the molten Ag–Cu alloy did not show a good wettability on the stainless steel without coating. To investigate the effect of the coating on the interfacial microstructure and the bonding strength of finally obtainable joints, two coated specimens were overlapped and then heated at 1 173 K for 0.3 ks in a low vacuum. The obtained joint had a shear strength of about 200 MPa, and broke mainly within the Ag–Cu alloy after a shear test. The joint brazed with the Ag–Cu alloy was also fabricated under the same heating conditions. Its shear strength was about 90 MPa, and the fracture position was at the Ag–Cu alloy/stainless steel interface. This indicates that the substantial bond between the Ag–Cu alloy and the stainless steel, which is achieved by explosive energy, contributes to the subsequent brazing process. Additionally, a commercially pure Ti plate was used as a substrate. In this case, the advantages of the coating process could not be recognized in the finally obtained joint. It is found that the substantial bond provided by explosive energy is canceled by the formation of a reaction layer on the brazing operation.

KEY WORDS: austenitic stainless steel; titanium; Ag–Cu filler alloy; explosive coating; brazing.
in an evacuated silica tube to soften before shock coating. These bonding surfaces were finished with #1200 emery paper. These were degreased in acetone using an ultrasonic cleaner and dried with hot air.

The coating operation was carried out using experimental apparatus shown in Fig. 1. The Ag–Cu filler alloy was combined with Cu plates to play a role as a flyer plate and fixed parallel to the steel and Ti substrates. The distance between the Ag–Cu filler alloy and the substrate was 5 mm. The powdery explosive consisting mainly of ammonium nitrate was set on the flyer plate. Its detonation velocity is about 2400 m/s, and the explosive with a weight of 64.8 g was used. The flyer plate velocity on the coating was estimated to be approximately 320 m/s.

The substrate coated with the Ag–Cu filler alloy was cut into a rectangular block with dimensions of 10 mm × 10 mm × 5 mm. The surface of the Ag–Cu filler alloy was finished with #1200 emery paper. In some cases, the thickness of the Ag–Cu filler alloy on the substrate was adjusted from 0.3 to 0.15 mm by grinding. After degreasing, two pieces were overlapped by the intermediary of the Ag–Cu filler alloy. This couple was fixed in a jig consisting of two Mo rods and two stainless steel blocks. The assembly was heated in the range from 1023 to 1173 K for 0.3 and 3.6 ks in a vacuum of less than 3 mPa. After a holding step, this was allowed to cool in the furnace to room temperature. To demonstrate the effectiveness of the coating, the bonding treatment was also carried out in a low vacuum of approximately 1 Pa, which was provided only by an oil rotary vacuum pump.

For comparison, the Ag–Cu filler alloy with a thickness of 0.3 mm was inserted between two stainless steel blocks and between two Ti blocks, respectively, and then heat treated under the same conditions. This corresponds to conventional vacuum brazing.

Fig. 2 shows external views of the specimen heated at 1173 K for 3.6 ks in a vacuum. (a) Non-coated specimen. (b) Coated specimen.

3. Results and Discussion

3.1. Stainless Steel Coated with Ag–Cu Filler Alloy Sheet

Figure 2(a) shows an external view of stainless steel coated with Ag–Cu filler alloy sheet by using explosive energy. The thicknesses of the steel and the alloy sheet were 5 mm and 0.3 mm, respectively. An optical micrograph of its interface is shown in Fig. 2(b). The specimen had a typically wavy interface and there were no defects like void. An eutectic structure in the Ag–Cu alloy could not be seen in an optical microscopic scale because of its fineness. TEM observations were carried out at the interface between the steel and the alloy sheet. There was a fine grain region in the vicinity of the collision interface. It was difficult to index Debye ring patterns taken from this region, since austenitic stainless steel, Ag and Cu have a FCC structure and these lattice parameters are pretty close. There is also a possibility that a supersaturated solid solution of Ag and Cu is formed by melting and subsequently rapid solidification at the contact surface. It is presumed, however, that the formation of the fine grains in the vicinity of the collision interface occurred in the Ag–Cu alloy side with relatively lower melting point. Such a microstructure appears to be helpful for substantial bond at the interface, as reported on the explosively welded Cu–Be alloy/stainless steel joint.

Figure 3 shows external views of the specimen heated at 1173 K for 3.6 ks in a vacuum. In Fig. 3(a), the Ag–Cu alloy sheet with dimensions of 10 mm × 10 mm × 0.3 mm was fixed on the stainless steel by using a steel wire before the heat treatment. The alloy became agglomerated on the steel. This indicates that the wetting of the molten Ag–Cu alloy is essentially poor on the stainless steel. On the other hand, the bonding state was retained in the coated specimen even after heating, as shown in Fig. 3(b). The adhesion achieved by explosive energy is found to be unaffected by the melting of the Ag–Cu alloy. Therefore, we do not need attention to the wetting in the subsequent brazing operation.
3.2. Joining of Stainless Steel Coated with Ag–Cu Filler Alloy Sheet

To utilize the advantage of explosive coating, two stainless steels, which were coated with the Ag–Cu filler alloy sheet with a thickness of 0.3 mm, were overlapped and bonded at 1 023, 1 073 and 1 173 K for 3.6 ks in a vacuum. Figures 4(a) and 4(b) show optical micrographs of the interface in the joints fabricated at 1 023 K and 1 173 K, respectively. Figure 4(a) corresponds to solid state bonding, and the Ag–Cu alloy remained thickly at the interface. In the joints bonded at 1 073 and 1 173 K, a large amount of the molten Ag–Cu alloy overflowed out of the interface. Consequently, the thickness of the Ag–Cu region decreased from 0.6 mm in total to about 0.1 mm, as shown in Fig. 4(b). The excluded alloy formed spherical blocks in touch with the joint. No reaction layers could be seen between the filler alloy and the steel in all cases.

The bonding strength of these joints is shown in Fig. 5. The joint bonded at 1 023 K showed the lowest strength of less than 50 MPa. Figure 6(a) shows a SEM micrograph of its fracture surface. The fracture surface was relatively flat and smooth, and had a fine eutectic structure of the Ag–Cu alloy. The opposite surface also showed the same microstructure. Therefore, the fracture position is thought to be located in the contact surface of the Ag–Cu alloy sheet. It is noteworthy that there were many voids indicated by white arrows. This indicates that the shrinkage and disappearance of such defects was not promoted by deformation and diffusion at interface during the bonding process. On the other hand, the joints bonded at 1 073 and 1 173 K had a high bonding strength of about 200 MPa, as shown in Fig. 5. These joints broke within the Ag–Cu alloy after the shear test. A micrograph of its fracture surface is presented in Fig. 6(b). The aspect differed markedly from that in Fig. 6(a). This results from fusion welding between the alloy sheets. In Fig. 5, the bonding strength of the joint using the alloy sheet whose thickness was mechanically adjusted to 0.15 mm before bonding is also plotted. The total thickness of the alloy sheet was 0.3 mm before bonding. After bonding, the interfacial microstructure was similar to that in Fig. 4(b). It seems that the bonding strength and its dispersion are slightly affected by the initial thickness of the alloy sheet.

Since the bonding of the steel to the filler alloy is already completed by the coating process, the subsequent brazing operation is equivalent to fusion welding of the filler alloy. This has a possibility to be practicable under an extreme condition such as lower vacuum level and shorter holding time. To conduct this verification, the joint using the coated steels was fabricated at 1 173 K for 0.3 ks in a rough vacuum, which was provided only by an oil rotary vacuum pump. Its bonding strength is shown in Fig. 7. Before bonding, the alloy sheet on the steel was mechanically ground from 0.3 to 0.15 mm thick, and its total thickness in a couple was 0.3 mm. For comparison, “non-coated” joint brazed with the Ag–Cu alloy sheet with a thickness of 0.3 mm was also prepared under the same heating condition. The bonding strength of the coated joint was almost equal to that in Fig. 5, and approximately 2 times higher than that of the
non-coated joint. In this case, the fracture position was within the Ag–Cu alloy, while the non-coated joint broke at the Ag–Cu alloy/stainless steel interface. This indicates that the substantial bond between the Ag–Cu alloy and the stainless steel due to explosive coating is retained through solid–liquid state in the bonding treatment. As a result, the pre-bonding by explosive energy serves to make a high-strength joint under the simplified brazing condition. In other words, the combination of explosive coating and brazing is a beneficial bonding process for the Ag–Cu alloy/stainless steel system.

3.3. Joining of Ti Coated with Ag–Cu Filler Alloy Sheet

As shown in Fig. 4, no reaction layer could be observed at the Ag–Cu alloy/stainless steel interface. To investigate the influence of the reaction layer on the bonding process proposed in the present study, a commercially pure Ti was selected as a substrate with reference to the Ag–Ti and Cu–Ti binary phase diagrams.

The bonding of the Ti substrate to the Ag–Cu filler alloy sheet was well achieved by using explosive energy, as well as the combination of the Ag–Cu alloy and the stainless steel due to explosive coating is retained through solid–liquid state in the bonding treatment. As a result, the pre-bonding by explosive energy serves to make a high-strength joint under the simplified brazing condition. In other words, the combination of explosive coating and brazing is a beneficial bonding process for the Ag–Cu alloy/stainless steel system.

![Fig. 7. Shear strength of stainless steel/stainless steel joints bonded at 1173 K for 0.3 ks in a low vacuum. Ag–Cu filler alloy with a thickness of 0.3 mm was used in non-coated specimen. In coated specimen, two steels coated with the filler alloy of 0.15 mm thick were overlapped.](image)

The non-coated joint also broke at the Ag–Cu alloy/Ti interface by the shear test, and the aspect similar to Fig. 8(b) was frequently confirmed by SEM observations. These results show that the bonding strength of the Ti/Ti joint brazed with the Ag–Cu filler alloy is greatly influenced by the reaction layer formed at the interface.

The substantial bond between the Ag–Cu alloy and the substrate, which is provided by explosive energy, is canceled by the formation of the reaction layer at the interface. In conclusion, the combination of explosive coating and brazing leads to the greatest benefit in non-reactive system such as Ag–Cu alloy/stainless steel system.

4. Conclusions

Austenitic stainless steel and Ti plates were coated with a sheet of Ag–Cu filler alloy by using explosive energy to simplify the subsequent brazing operation. Its effectiveness was discussed on the basis of the interfacial microstructure and the bonding strength of finally obtainable joints. The main conclusions are summarized as follows.

(1) Although the stainless steel coated with the Ag–Cu alloy was heated at a temperature of more than eutectic point of the Ag–Cu binary system, their adhesion at the interface was retained. This indicates that the influence of wetting between both materials is negligible in the subsequent brazing operation.

(2) In the stainless steel, two coated specimens were overlapped and then heated at 1173 K for 0.3 ks in a rough vacuum. The obtained joint had a bonding strength of about 200 MPa. This was approximately 2 times higher than that of the non-coated joint, which was brazed with the Ag–Cu alloy under the same heating condition. The brazing operation via the coating process is equivalent to fusion welding of the alloy. Therefore, the pre-bonding by explosive energy is of help to the fabrication of a high-strength joint through the simplified brazing operation.

(3) In the Ti/Ti joint bonded by the intermediary of the Ag–Cu alloy, the pre-bonding by explosive energy did not
have an advantage on the shear test. This is attributed to the formation of a reaction layer at the interface. In other words, the combination of explosive coating and brazing leads to the greatest benefit in non-reactive system such as Ag–Cu alloy/stainless steel system.

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