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Ultrasonic seam welding technologies of copper plate and tube for collecting solar energy①

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Abstract: The ultrasonic welding is applied more and more extensively due to its advantages such as environmental protection, cleaning and energy saving. By researching the mechanism on ultrasonic seam welding of copper plates and tubes for collecting solar energy, it is put forward that the ultrasonic metal welding process can be divided into two stages, and two factors make functions jointly to join the welded metal specimens. In order to successfully join the welding, three basic conditions must be satisfied, that is, there should be high frequency friction vibration in the contact interface; pressure must be imposed on the plate specimen during friction vibration; the time of friction vibration and pressure imposed should be proper. Furthermore, how to select the hardness of copper plate and tube and ultrasonic seam welding parameters is analyzed by experiments.

Key words: ultrasonic seam welding; friction vibration; atoms permeating
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1 INTRODUCTION

Ultrasonic welding technologies have been used in various industries because of its distinctive advantages such as safety, environmental protection and energy saving, for example, the welding of the end of a thread in electronic circuit and the tip of a integrated circuit, the welding of ceramics/metals and metals/metals, the welding of thermoplastics and aluminum plastics composites and so on. It is still a new field that ultrasonic welding technologies are used in the welding of copper plates and tubes for collecting solar energy, and it is still in trying and investigating stage in our country. Integrate copper board for heat collecting was developed in a few developed countries such as United States owing to the application of ultrasonic welding technologies. The board holds good performances of heat conducting, long service life and low reject rate.

At present, the study on ultrasonic welding technologies is mainly focused on welding process and quality of welding. For example, the effects of temperature rise, frequency and vibration mode of welding tip on qualities of welding were studied heavily[1] in the electronics industry; as ceramics is brittle and sensitive to residual stress, the processes and residual thermal stresses were investigated in detail[2-4] in the welding of ceramics/metals; in metals/metals welding industry, the study was focused on processes and vibration mode of welding tip[8, 9]; for the welding of plastics and aluminum plastics composites, its process, mechanism, energy conversion and mechanical properties of welding seam have been all studied systematically[5-7].

From the above mentioned, the mechanisms of ultrasonic welding have been studied not much and unanimous recognition on mechanisms has also not been reached currently. This paper studies the processes and mechanisms while joining copper plates and tubes for collecting solar energy by ultrasonic welding, and how to select the hardness of welded materials and ultrasonic seam welding parameters is analyzed theoretically and studied by experiments.

2 EXPERIMENTAL

Fig. 1 shows the configuration of ultrasonic seam welding system for copper plates and tubes.

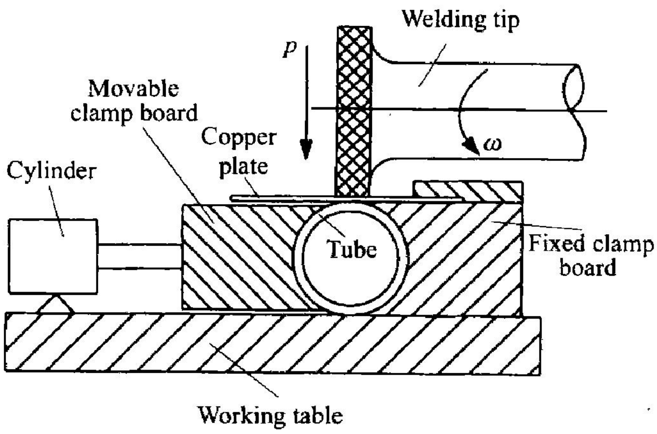

Fig. 1 Sketch of ultrasonic seam welding equipment for copper plates and tubes

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The copper plate is 0. 2 mm thick, the wall of the copper tube is 1 mm thick, and its outer diameter is 12 mm. The copper plate and tube must be welded together (as Fig. 1 shows) . And so as to satisfy the demand for continuous welding, the welding tip consists of a 15 - 20 kHz vibration with rotating and linear motion. There's a fixed clamp board on the table, moreover, a movable clamp board is joined with the cylinder fixed on the working table. During work, copper tube specimen is gripped by the two clamp boards and welding tip presses on the copper plate specimen with pressure p .

3 PROCESS OF ULTRASONIC METAL WELDING

The process of ultrasonic metal welding includes two stages: one is removing the oxidization film on metal surfaces and forming direct contact between two metal surfaces, the other is atoms permeating each other in direct contact zone.

3. 1 Removing oxidation film on metal surface and forming direct contact between two metal surfaces

A thin sheet of adsorption film and oxidization film will appear only if metal is exposed to air[10], as showed in Fig. 2.

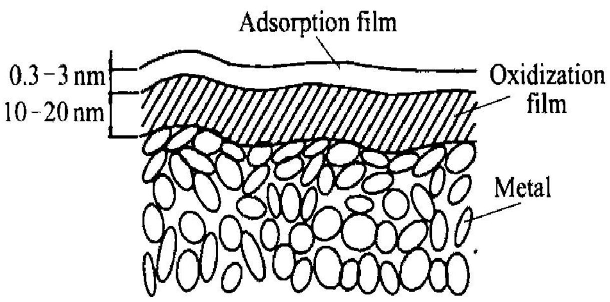

Fig. 2 Sketch of adsorption film and oxidization film on metal surface

The adsorption film is not stable and can dissolve easily with temperature increasing, while the oxidization film is relatively stable, however, it is brittle and can be crushed up easily. It is just the sheet of adsorption and oxidization film that makes the distance of atoms be too large to produce interaction each other in the two metal contact surfaces. During the course of ultrasonic welding, tangential friction vibration occurs in the contact interface of copper plate and tube specimens due to the high frequency and minute amplitude vibration of welding tip and its pressure action on the copper plate specimen. In common conditions, the metal contact is asperity contact as shown in Fig. 3. Therefore the adsorption and oxidization films in asperity contact zone are first crushed up and the contact changes to direct metal contact. Subsequently, plastic deformation will produce with the extrusion going on and the heights of asperity decrease. Thus new asperity contact zones form. The above processes are performed again and again. As a result, the direct metal contact areas increase continuously.

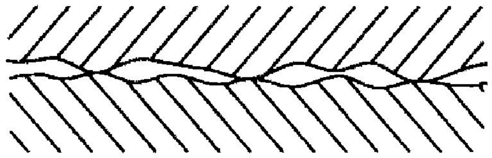

Fig. 3 Sketch of asperity contact on metal surface in common conditions

3. 2 Atoms of two metal specimens permeating each other

The direct metal contact is very close because there's high pressure in asperity contact zone, and also because the motion of atoms are stimulated, which makes them be at an unstable state. It's useful for atoms permeating in the contact interface. In addition, in the course of friction vibration, it only takes a very short time to complete the extrusion and plastic deformation and mass of friction heat produced can't be conducted in time and accumulate in the surface layer of asperity contact zone. Consequently the metal of surface layer in asperity contact zone becomes pliable or even melted. Thus, the atoms permeating is promoted. Finally the two weldments are joined together. So the nature of ultrasonic metal welding processes is atoms permeating in the contact interface of two welded metal specimens.

4 MECHANISM OF ULTRASONIC METAL WELDING

4. 1 Microstructure analysis of welding seam

Fig. 4 shows microstructure of the copper plate and tube's welding seam after being ultrasonic welded. While Fig. 5 shows the microstructure of the part, which hasn't been welded, but is close to the welding seam of the copper plate and tube.

After comparing Fig. 4 with Fig. 5, it's found that serious plastic deformation occurs in the welding interface. The deformation of plate specimen is even more obvious, and its grains are crushed into fibre in shape. However, deformation of tube specimen is relatively lighter. It only occurs in the thin sheet of interface and its grains are also crushed, but not into fibre. The copper plate and tube specimens are joined closely. The clear melted structure, metallurgical and chemical change cannot be observed in the welding zone. So it is metal bonds formed by atoms permeating that join the two metal specimens together in the course of ultrasonic welding.

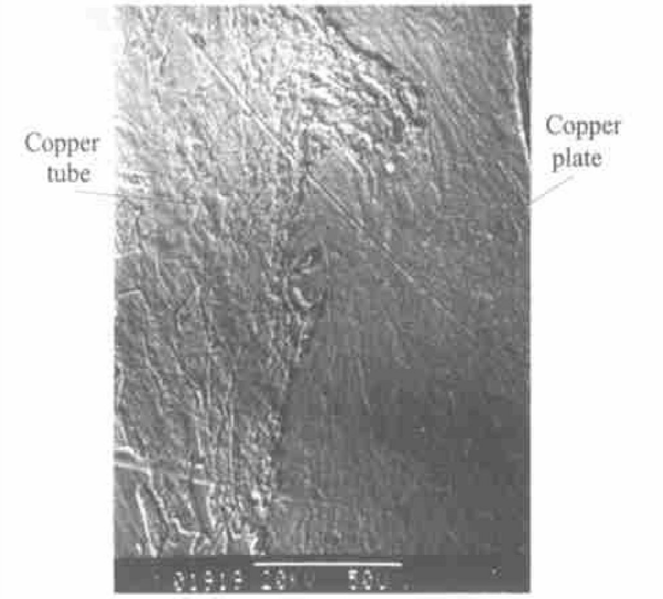

Fig. 4 Microstructure of welding seam

Fig. 5 Microstructure of copper close to seam

4.2 Formation mechanism of seam by ultrasonic welding

Unanimous recognition of welding seam formation mechanisms has not been reached currently and there are several views on this. By analyzing the welding process and microstructure of welding seam, this paper concludes that welding seam formation mechanisms should be investigated in the following two aspects.

4.2.1 Atoms bonding and permeating in interface

In the process of ultrasonic welding, fresh contact interface is formed continuously under the function of tangential friction vibration. On the fresh surface, the atomic coordination number is different to the coordination number within crystal, and the atoms are in high-energy state due to the decreased bonding numbers. While the distance of atoms between the two fresh contact interfaces can be measured as 0.1 nm, the atoms will bond each other and the surface energy be lowered. Furthermore, during welding process, mass of friction heat accumulates in the surface layer of asperity contact zone, consequently the metal of surface layer in asperity contact zone becomes pliable or even melted. Thus the atoms on the two surfaces permeate each other and the two welded metal specimens are joined together.

4.2.2 Interface interlock in the sheet of plastic deformation

As shown in Fig. 4, the interface is sawtooth in shape due to plastic deformation and the two welded surfaces are interlocked. The interlocked interface is useful for enhancing joining strength.

According to the above analysis, it can be concluded that it is the interface bonding and permeating of atoms in the surfaces and interlocked interface that make two welded metal specimens join together.

5 BASIC CONDITIONS OF ULTRASONIC WELDING

Based on the above analysis, the ultrasonic welding processes consist of fresh, close and direct metal contact under the functions of tangential friction vibration and pressure, and then the stimulated atoms in the fresh contact zone permeation each other. Therefore to make ultrasonic welding processes perform smoothly, three prerequisites must be satisfied. They are:

1) There should be high frequency friction vibration in the contact interface in order to form fresh and direct metal contact.

2) Pressure must be imposed on the plate specimen during friction vibration in order to make the fresh and direct metal contacts closely.

3) The time of friction vibration and pressure imposing should be proper so that the processes of atoms permeating are completed fully.

6 EFFECTS OF HARDNESS OF COPPER PLATE AND TUBE ON TENSILE STRENGTH OF WELDING

The relevant references don't present effects of hardness of welded specimens on welding processes and qualities. In this experiment, the results prove that the hardness of copper plate and tube has heavy influence on welding qualities.

When the wall of the copper tube is 1 mm thick, the high hardness value of copper tube should be selected in order to avoid that copper tubes are pressed flat or sunkenly. So the hardness of copper tube is selected as HV 100 - 110 in this experiment.

The hardness of plate specimens should be less than that of tube, because plastic deformation of plates is much more serious than that of tubes. Otherwise crackles occur easily in the verge of welding seam due to strain hardening. It is discovered by experiments that copper plate in seam zone is broken into pieces easily during welding process if the hardness value of copper plate is beyond HV 100. So the Vickers hardness of copper plate is seldom beyond HV 100. But the hardness of plates and tubes cannot differ too much. If the tube hardness is much larger or the plate hardness is much lower, it is very difficult to make the contact asperity of tube in the asperity contact zone deform during friction vibration, thus the areas of direct metal contact decrease and atoms permeating is hindered; as a result, the tensile strength of welding will be impaired. So the hardness value of copper plate must be selected properly. Fig. 6 shows the effects of hardness value of copper plate on tensile strength of welding. From Fig. 6, it is appropriate for the Vickers hardness of copper plates to be 80 - 90.

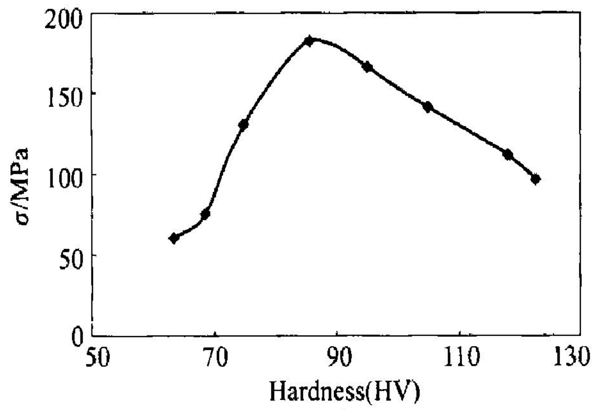

Fig. 6 Relationship of tensile strength σ and Vickers hardness of copper plates

7 EFFECTS OF WELDING PARAMETERS ON TENSILE STRENGTH

The welding parameters exert a tremendous influence on tensile strength. The main parameters of ultrasonic seam welding include vibration frequency f, amplitude A, static pressure p and welding velocity v.

7.1 Ultrasonic vibration frequency f and amplitude A

Increasing frequency can decrease amplitude on condition that ultrasonic power keeps unchanged. Decreasing amplitude can lessen fatigue damage that alternating stress brings to thin copper sheet. But the energy loss of high frequency vibration will grow with frequency increasing in acoustics system. So the selecting of frequency and amplitude must be proper. When ultrasonic welding is applied to copper plate and tube for collecting solar energy, the ultrasonic frequency should be high and its amplitude should be small because the thickness of copper plate is only 0.2 mm. On the other hand, low frequency and large amplitude can be taken because the yielding strength of copper is low and its plasticity is very good. Considering the two factors comprehensively, the vibration frequency is selected as 20 kHz and amplitude is 16 - 20 μm. In a word, the selecting of frequency and amplitude should depends on the thickness and mechanical properties of welded metal specimens.

7.2 Selecting of static pressure p

The tensile strength will not be high if static pressure is too small. The reason is that too small pressure will lighten the plastic deformation in asperity contact zone and reduce the area of direct metal contact. All of these are not beneficial to atoms permeating. On the other hand, too high static pressure will impair tensile strength because it makes deformation of seam zone too serious even crackles occur in the verge of welding seam. In this experiment, the static pressure of welding tip comes from air pressure, and it is $(4 - 6) \times 10^5$ Pa. Fig. 7 shows the relationship of tensile strength and static pressure. There is an optimum value of pressure by Fig. 7. The optimum value of pressure is decided on experiment.

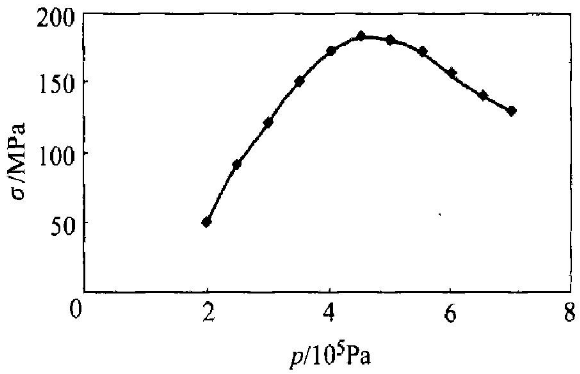

Fig. 7 Relationship of tensile strength σ and static pressure p

7.3 Selecting of welding velocity

From the point of view of productivity, the faster the welding velocity is, the higher the efficiency will be. But too high velocity will impair tensile strength because the process of welding cannot be completed fully. So does the too low velocity, because it will cause fatigue damage in the verge of welding seam. In this experiment the velocity from 2 to 12 m/min is suitable.

8 CONCLUSIONS

1) The ultrasonic seam welding process on copper plate and tube is a mechanical process. The process can be divided into two stages and three prerequisites must be met in order to make the process perform smoothly.

2) The two welded metal specimens are joined together through the function of mechanical interlock in the sheet of plastic deformation and atoms permeating jointly.

3) The hardness of metal specimen has significant influence on tensile strength of welding. The hardness of copper tube and plate is suitable to be HV 100 - 110 and HV 80 - 90 separately in this experiment.

4) It is critical to select welding parameters properly. As for ultrasonic seam welding of copper plate and tube for collecting solar energy, the parameters are selected as follows: static pressure $(4 - 6) \times 10^5$ Pa, frequency 20 kHz, amplitude 16 - 20 μm, welding velocity 2 - 12 m/min.

REFERENCES

[1] Jiromaru T, Hiroyuki Y, Kazuyoshi K, et al. Welding characteristics and temperature rise of high frequency and complex vibration ultrasonic wire bonding [J]. Ultrasonics, 1998, 36(1 - 5): 59 - 65.

[2] Matsuoka S. Ultrasonic welding of ceramics/metals using inserts [J]. Journal of Materials Processing Technology, 1998, 75(1 - 3): 259 - 265.

[3] Hagen K, Uwe S, Erwin R, et al. Residual thermal stresses in the case of the ultrasonic roll seam welding of glass/metal compounds —Part I: mathematical determination of the distribution of residual stresses[J]. Schweissen und Schneiden/Welding and Cutting, 1999, 51(7): 135 - 138.

[4] Hagen K, Uwe S, Erwin R, et al. Residual thermal stresses in the case of the ultrasonic roll seam welding of glass/metal compounds —Part II: measures for their reduction[J]. Schweissen und Schneiden/Welding and Cutting, 1999, 51(8): 162 - 165.

[5] Jiromaru T, Takako U, Katsuhisa Y, et al. Welding characteristics of ultrasonic plastic welding using two-vibration-system of 90 kHz and 27 or 20 kHz and complex vibration systems [J]. Ultrasonics, 1998, 36(1 - 5): 67 - 74.

[6] Kunihiko T, Hirokazu T, Toshiaki T, et al. Molecular movement during welding for engineering plastics using Langevin transducer equipped with half-have-length step horn [J]. Ultrasonics, 1998, 36(1 - 5): 75 - 78.

[7] Netzc C, Michaeli W. Correlation of welding parameters, energy conversion and mechanical weld seam properties for ultrasonic welding [A]. Annual Technical Conference-NTEC, Conference Proceedings, Vol. 37[C]. Soc of Plastics Engineers, 1991. 2490 - 2493.

[8] Jiromaru T, Tetsugi U. Welding characteristics of ultrasonic seam welding system using a complex vibration circular disk welding tip [J]. Japanese Journal of Applied Physics, Part 1: Regular Papers and Short Notes and Review Papers, 2000, 39(5): 2990 - 2994.

[9] Tsujino J, Ueoka T, Kashino T, et al. Transverse and torsional complex vibration systems for ultrasonic seam welding of metal plates [J]. Ultrasonics, 2000, 38: 67 - 71.

[10] ZHOU Ze-hua. Theory of Metal Cutting [M]. Beijing: Mechanical Industry Press, 1992. 109 - 111. (in Chinese)

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