Cold Pressure Welding of Aluminum and Copper by Butt Upsetting*

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Multiple stage butt welding is attempted. The advantage of this welding is that bonding can be accomplished with a small load and a small deformation by selecting a proper initial height and a proper height reduction in each stage. The effects of the virgin surface ratio and the normal pressure at the bonding surface on the bond strength are investigated. The advantage of the multiple welding is explained by those two parameters. The bond strength is significantly dependent on the virgin surface ratio. When the virgin surface ratio is high, the normal pressure is comparatively low, namely, nearly the same pressure as the tensile strength of the base metal.

Key Words : Cold Pressure Welding, Butt Welding, Bond Strength, Bond Efficiency, Virgin Surface, Oxide Layer, Bonding Surface, Bonding Pressure

1. Introduction

Cold pressure welding of metals has the following advantages. (1) There is no softening of a workhardened or heat treated metal since the process is carried out at room temperature. (2) This welding is suitable for electronic parts which may be broken by heating. (3) When dissimilar metals are welded, a brittle intercrystalline layer is not formed which is observed in the conventional heat welding at the interface of the metals.

Since the surface of the metal is generally covered with oxide layer, absorbed vapor layer and stained layer such as oil, welding cannot be achieved by just pressing two metals together. Cold pressure welding is accomplished with intimate contact of virgin metals which appear owing to the breakdown of the surface layers by plastic deformation of the base metals. This behaviour of the virgin metal is observed with a microscope [1-3] and analyzed by plastic theory to obtain the relationship between the bond strength and the surface expansion or the bonding pressure [4]. Plastic deformation such as upsetting [2,4-7], indentation [2,8,9], rolling [1,3,10-12] and extrusion [13] was attempted to expose the virgin surface. Recently a new method of cold pressure welding by divergent extrusion was proposed [14]. Other new methods [15-17] were reported in which sliding was applied between two surfaces to promote the breakdown of the surface layer. It was also reported that pre-treatment of the mating surfaces and the shape of tools are important factors for appearance of

the virgin surface and its close approach. However, in cold pressure welding, large deformation of the base metal is necessary and then high load must be applied. This is considered to be the biggest disadvantage.

This paper is concerned with multiple stage butt welding; butt upsetting is performed in several stages instead of one stage of the usual butt welding. The effects of the virgin surface ratio and the normal pressure at the bonding surface on the bond strength were investigated. An advantage of this welding, i.e., bonding can be accomplished with a small load and a small deformation, was discussed. Experiments were carried out in plane strain for combinations of aluminum-aluminum, copper-copper and aluminum-copper.

2. Experimental procedures

2.1 Multiple stage butt welding

Materials used were workhardened pure aluminum Al050 and tough pitch copper C1100. Specimens for the welding were made by machining to the shape of a rectangular parallelepiped of 16 mm thickness, 8 mm width and 40.5 to 54 mm height. The following pre-treatment of the mating surfaces of the specimen was made. Just before the bonding experiments, the mating surfaces were cleaned with acetone and scratched with a wire-brush.

Fig.1 shows schematic representations of a set-up for the multiple stage butt welding and the process of the experiment. Deformation in the normal direction to the paper surface is restricted and the plane strain is kept. One stage butt welding which is the same as the usual butt welding is performed as shown in Figs.1(a) and (b). Two pairs of dies ② and two specimens ① which are set at a distance of an initial height h_{1i} are advanced by two punches ③ up to a final height h_{1f} . The specimens flow out through the dies and the virgin metals emerge at the mating surfaces and then the bonding is achieved. The dies cannot move in the lateral

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direction due to a container ④. The angle of die θ is 15 deg and the punch speed is 2 mm/min. Two stage butt welding shown in Figs.1(a) to (d) is carried out as follows: After the first stage shown in Figs.1(a) and (b), the specimens are reset at a distance of h_{2i} and two blocks ⑤ are placed at the ends of the specimens as shown in Fig.2(c). The specimens are pressed again up to a height h_{2f} . Three stage butt welding is done in the same manner. Table 1 shows the initial height h_i (h_{1i} , h_{2i} and h_{3i} in respective stages) and the final height h_f (h_{1f} , h_{2f} and h_{3f} in respective stages). Symbols in Table 1 will be used in the following figures.

In the combination of aluminum and copper, if the initial height of both metals are the same, deformation (expansion) of aluminum will be larger because of a difference in the flow stress. Therefore, the initial height ratio of aluminum to copper was determined such that the mating surface expansions of two metals were almost equal.

Fig.1 Set-up for multiple stage butt welding and process of experiment.

2.2 Estimation of bond strength

The bonded specimen was machined to the shape as shown in Fig.2 and a tension test was performed. Circular notches were provided such that rupture would occur more easily at the bonding plane. The bond strength was defined as the rupture load divided by the initial area of the cross section.

Bond efficiency, namely, the ratio of the bond strength to the tensile strength of a monobloc specimen was derived. The monobloc specimen was deformed up to the same height as the bonded specimen by the set-up shown in Fig.1 and then was machined to the shape of the tensile specimen as shown in Fig.2.

Table 1 Initial heights h_{1i} , h_{2i} and h_{3i} , and final heights h_{1f} , h_{2f} and h_{3f} in each stage (mm).

	Sym-bols	1st stage		2nd stage		3rd stage	
		h_{1i}	h_{1f}	h_{2i}	h_{2f}	h_{3i}	h_{3f}
One stage welding	△	15	≥5	—	—	—	—
	▲	20	≥5	—	—	—	—
	▲	25	≥5	—	—	—	—
Two stage welding	○	15	5	15	≥5	—	—
	●	20	5	20	≥5	—	—
Three stage welding	□	15	5	15	5	15	≥5
	▢	15	7.5	15	7.5	15	≥7.5
	▣	15	10	15	10	15	≥10

Fig.2 Tensile test specimen.

Fig.3 Set-ups for (a) measurement of virgin surface ratio and (b) measurement of normal pressure at bonding surface.

2.3 Measurement of virgin surface ratio

Fig.3(a) shows a schematic representation of a set-up to measure the virgin surface ratio. Shapes and dimensions of specimen ① and dies ② are the same as those in the welding experiment shown in Fig.1. Material of the specimen was pure aluminum Al050 and the mating surface was covered with an alumite layer about 10 μm thick. The alumite treatment was conducted in 10 % oxalic acid at 20 °C by applying 60 volt A.C. for 10 min. The initial heights were half the values shown in Table 1 and the punch speed was 1 mm/min. P.T.F.E. sheet was used as a lubricant between the specimen and the punch. It was changed for a new sheet after each incremental deformation of 1 mm.

After deforming up to the prescribed height, the area covered with fragments of the alumite layer was measured by observing with a microscope from the normal direction to the alumite surface. The mean value of the area ratio of the virgin surface was derived at the center region of 8 mm length which was the same as the width of the tensile specimen.

2.4 Measurement of normal pressure

Fig.3(b) shows a schematic representation of a set-up to measure the normal

Fig.4 Relationship between virgin surface ratio α and total height reduction Δh_t .

Fig.5 Examples of relationship between normal pressure p and height reduction Δh .

pressure at the bonding surface. A pin ⑤ to measure the mean value of the normal pressure is located at the center of the punch ③. Strain gauges ④ are affixed on the surface of the pin. P.T.F.E. sheet was used as a lubricant and was changed for a new sheet after each incremental deformation of 1 mm.

3. Experimental results and discussion

3.1 Virgin surface ratio and normal pressure

Fig.4 shows the relationship between the virgin surface ratio α and the total height reduction Δh_t . Δh_t in the multiple stage butt welding is the sum of the height reduction in each stage. The symbols in the figure are shown in Table 1. It is found that α becomes large with increasing initial height h_i and that the number of stages does not affect α if h_i is the same.

Hard and brittle surface layer like alumite cannot be formed on copper. However, since the deformation of the copper specimen was quite similar to that of the aluminum one, Fig.4 is substituted for the relationship between α and Δh_t for the copper specimen.

Fig.5 shows examples of the relationship between the normal pressure p at the bonding surface and the height reduction Δh in each stage for the aluminum specimen at $h_i=15$ mm. p increases slightly as the stage advances.

By using Figs.4 and 5, the relationships between bond strength and the virgin surface ratio or the normal pressure are obtained which will be shown in the following.

3.2 Results of bonding

3.2.1 Bonding of aluminum and aluminum

Fig.6 shows the relationship between the bond efficiency η and the total height reduction Δh_t . The tensile strength of the monobloc specimen varied little with the height reduction since the material

Fig.6 Relationship between bond efficiency η and total height reduction Δh_t in Al-Al combination.

had been workhardened very much. Therefore, the tensile strength was determined as a constant value of 123 MPa (12.5 kgf/mm²). The bond efficiency η was supposed to be 0 % when the bonded specimen separated during machining to the shape for the tension test. Rupture took place at a plane other than the bonding surface in some specimens. In this case η was defined as 100 %.

In one stage butt welding, the bond efficiency η is about 60 % at the total height reduction Δh_t of 17.5 mm for the initial height h_{i1} of 25 mm (symbol $\blacktriangle$). However, in the three and two stage butt weldings (symbols $\boxplus$ and $\bullet$), η reaches about 100 % and 82 %, respectively, at almost the same value of Δh_t . This fact means that the multiple stage butt welding accomplishes sound bonding at a small height reduction and thus decreases wastage of the metal going out as flashes. The above result will be related with the virgin surface ratio α shown in Fig.4, namely, α becomes larger in the multiple stage butt welding even when Δh_t is the same.

Fig.7 Relationship between bond efficiency η and virgin surface ratio α in Al-Al combination.

Fig.8 Relationship between bond efficiency η and maximum bonding load F_f at the last stage in Al-Al combination.

When the height reduction is too small in each stage of the multiple stage butt welding, the bond efficiency is small (symbol $\boxplus$). This is explained as follows. Since the bond strength is small at a small height reduction, the bonding plane will separate during the operation of sliding the specimen in the container to prepare for the second or third stage upsetting. Then the virgin surface which has emerged at the prior stage is no more virgin.

Fig.7 shows the relationship between the bond efficiency η and the virgin surface ratio α obtained from Figs.5 and 6. All of the experimental points lie on a line irrespective of the initial height or the number of stages, and increase with increasing α . This result shows that the virgin surface ratio is a determining factor for the bond strength in cold pressure welding. Bonding begins at $\alpha=20$ % and the bond strength reaches the tensile strength of the monobloc specimen at $\alpha=65$ %.

Fig.8 shows the relationship between the bond efficiency η and the maximum load F_f at the last stage. F_1 and F_2 are the maximum loads at the first and second stages in the multiple stage butt welding, respectively. In the one stage butt welding (symbol $\blacktriangle$), η is about 55 % when $F_f=50$ kN. On the other hand, to obtain a similar value of η in the two stage butt welding (symbol $\circ$), F_f and F_1 should be about 34 kN and 37 kN, respectively. These bonding loads are considerably lower than that in the one stage butt welding. Furthermore, in comparison of the bonding loads between the two stage (symbol $\circ$) and the three stage (symbol $\boxplus$) butt weldings to achieve $\eta=100$ %, we get $F_1=37$ kN and $F_f=63$ kN for the former and $F_1=25$ kN, $F_2=40$ kN and $F_f=25$ kN for the latter. These results mean that the multiple stage butt welding accomplishes sound bonding with a small load when a proper initial height and a proper height reduction are selected in each stage. The decrease in

Fig.9 Relationship between bond efficiency η and maximum normal pressure p_f at the last stage in Al-Al combination.

the bonding load is attributed to the flashes which are produced during the prior stage, i.e., flashes need not be deformed as known in Fig.1. This is a big advantage of the multiple stage butt welding.

Fig.9 shows the relationship between the bond efficiency η and the maximum normal pressure p_f at the last stage. p_1 and p_2 are the maximum pressures at the first and second stages in the multiple stage butt welding, respectively. Fig.9 is similar to Fig.8 which shows the relationship between η and F_f . η is about 100 % when $p_f=105$ MPa ($p_1=152$ MPa, $p_2=191$ MPa) in the three stage butt welding (symbol $\square$). This value of p_f is smaller than the tensile strength of the monobloc metal of 123 MPa. This matter will be explained as follows. Since the oxide layer scarcely remains near the center of the bonding surface at the third stage, the mechanism of bonding which is generally accepted, that is, the virgin metals are extruded between the fragments of the oxide layer and the metals bond together, cannot be applied. Only a pres-

Fig.10 Relationship between bond efficiency η and virgin surface ratio α in Cu-Cu combination.

Fig.11 Relationship between bond efficiency η and maximum normal pressure p_f at the last stage in Cu-Cu combination.

sure to bring the virgin surfaces close to each other is necessary. Therefore, bonding will be accomplished with a comparatively small normal pressure.

3.2.2 Bonding of copper and copper

The advantage of the multiple stage butt welding emerged in the combination of copper and copper too, namely, sound bonding was accomplished at a small height reduction with a small load when a proper initial height and a proper height reduction were selected in each stage.

Fig.10 shows the relationship between the bond efficiency η and the virgin surface ratio α . The tensile strength of the copper specimen was a constant value of 387 MPa (39.5 kgf/mm²), since the specimen had been workhardened very much. The experimental points lie on a line irrespective of the initial height or the number of stages, similarly to Fig.7. This result verifies that the virgin surface ratio is the determining factor for the bond strength. Bonding begins at $\alpha=30$ % and η reaches 100 % at $\alpha=70$ %.

Fig.11 shows the relationship between the bond efficiency η and the maximum normal pressure p_f at the last stage. p_f is between 330 MPa and 600 MPa. In the three stage butt welding (symbol $\square$), η of 100 % is obtained when p_f is about 330 MPa which is smaller than the tensile strength of the monobloc copper. This behaviour is quite similar to that of aluminum.

3.2.3 Bonding of aluminum and copper

In order to make the mating surfaces of two metals expand almost equally, the initial height ratio of aluminum to copper was determined as follows. When the initial heights h_i (total height of the aluminum and copper specimens) were 15 mm, 20 mm and 25 mm, the ratios were 1/4, 1/4.75 and 1/5.25, respectively. These ratios were used at all stages of the multiple stage butt welding.

Fig.12 shows the relationship between the bond efficiency η and the virgin surface ratio α , where η is defined as the bond strength divided by the tensile

Fig.12 Relationship between bond efficiency η and virgin surface ratio α in Al-Cu combination.

strength of the aluminum specimen and α is derived from the height reduction of the copper specimen. It is found that the experimental points lie on a line and thus the virgin surface ratio is the determining factor for the bond strength even in the combination of dissimilar metals. Bonding begins at $\alpha=60\%$ and the bond strength reaches the tensile strength of the aluminum monobloc specimen at $\alpha=90\%$. It seems that bonding of dissimilar metals is a little difficult compared with bonding of similar metals.

Fig.13 shows the relationship between the bond efficiency η and the maximum normal pressure p_f at the last stage. In the three stage butt welding (symbol $\square$), $\eta=100\%$ at $p_f=200$ MPa. This value is about 1.6 times the tensile strength of the aluminum monobloc specimen and is about half the tensile strength of the copper monobloc specimen.

4. Conclusions

The multiple stage butt welding was attempted. The bonding load, the bond efficiency, the virgin surface ratio and the normal pressure at the bonding surface were examined. The following conclusions were drawn.

(1) The multiple stage butt welding accomplishes sound bonding at a small height reduction with a small load when a proper initial height and a proper reduction are selected in each stage.

(2) The bond efficiency η is significantly dependent upon the virgin surface ratio α irrespective of the initial height and the number of stages. Bonding begins at $\alpha=20\%$, 30% and 60% and the bond strength reaches the tensile strength of the monobloc specimen at $\alpha=65\%$, 70% and 90% , in the combinations of aluminum-aluminum, copper-copper and aluminum-copper, respectively.

(3) The normal pressure at the bonding surface is comparatively low at the last stage of the multiple butt welding. Sound bonding is achieved with nearly the

same pressure as the tensile strength of the monobloc specimen in bonding of similar metals. The pressure is between the tensile strengths of two metals in bonding of dissimilar metals.

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Fig.13 Relationship between bond efficiency η and maximum normal pressure p_f at the last stage in Al-Cu combination.