Cold Welding — Experimental Investigation of the Surface Preparation Methods

Similar and dissimilar metal combinations with different surface preparations were investigated for the best shear strength at the interface

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ABSTRACT. This paper presents a systematic experimental investigation for cold welding of five different metal combinations — Al-Al, Cu-Cu, steel-steel, Al-Cu and Al-steel — applying seven different surface preparation methods, including anodizing of Al, semibright electrolytic Ni plating, electroless Ni plating, heat-treated electroless Ni plating, electrolytic hard Cr plating, scratch brushing and degreasing with acetone. After roll welding with varying reductions, the weld strength was tested by a shear test system developed in the present work. The weld strength curves for alternative methods of surface preparation were compared for each metal combination. It was found that different surface preparation methods resulted in different weld strengths. The semibright Ni plating and electroless Ni plating are optimum for Al-Al, electroless Ni plating for Cu-Cu, heat-treated electroless Ni plating for steel-steel, and scratch brushing for Al-Cu and Al-steel.

Introduction

Cold welding is a solid-state welding process using pressure and plastic deformation of the base metals being joined to establish welds below the recrystallization temperature of the metals (Ref. 1). Cold roll welding is tonnagewise one of the most important industrial cold welding processes applied in the production of compound metal plate. It is of vital importance to investigate the technological aspects of this process in order to improve the quality of the products and to enable the production of complex metal combinations.

Among many parameters, preparation of the metal surfaces is one of the most important ones governing weld formation. In the practice of cold welding, scratch brushing has been widely applied and recognized as an efficient surface preparation method. Later investigations revealed that the function of scratch brushing is not only to clean, but also locally to form a brittle cover layer on the metal surfaces by work hardening of the surface layer (Refs. 2–6). Based on these observations and the understanding of the basic welding mechanisms, it was earlier proposed to artificially establish a brittle cover layer (anodizing of Al or Ni plating) on the interface surfaces of the metals (aluminum or copper) to be joined (Refs. 7–12). These preliminary investigations indicated a promising prospect for extending the application of this surface preparation method, thereby leading to more comprehensive investigations on other metal combinations, applying also other surface preparation methods.

This paper presents a systematic experimental investigation of cold roll welding of similar and dissimilar metal combinations, applying various surface preparation methods to more comprehensively investigate the behavior of different plating layers in cold roll welding of various metal combinations. To obtain shear strength measurements of the roll-welded specimens with low scatter, a shear test system was designed and specified in detail in the present work. The shear strength curves corresponding to alternative methods of surface preparation were compared, and the optimal surface preparation methods were found for each metal combination.

Experimental Procedure

The cold roll welding experiments were carried out on a two-high laboratory rolling mill with a loading capacity of 50 tons. The roll diameter was 132 mm (5.2 in.), and the rolling speed was 26 rpm corresponding to a peripheral speed of 180 mm/s (425 in./min). During the welding process, the rolling load was recorded.

Experimental Materials

In the experiments, the following four metals were applied: annealed aluminum (Al 99.5%), semihard aluminum (Al 99.5%), annealed copper (electrolytic) and low-carbon steel (C < 0.1%). The workpieces with initial dimensions
of 170 x 25 x 3 mm (6.7 x 1.0 x 0.12 in.) were cut out from large cold-rolled plates with a thickness of 3 mm (0.12 in.). The annealed aluminum was applied for roll welding of aluminum to aluminum, whereas the semihard aluminum was applied for roll welding of aluminum to copper and aluminum to steel. The stress-strain curve of each material was estimated by Watts' and Ford's plane strain upsetting test (Ref. 13), orienting the longitudinal direction of the tools perpendicular to the rolling direction to simulate the conditions in the roll welding process. The following stress-strain curves were obtained:

\[
\sigma_{\text{Al, annealed}} = 134 e^{0.274} \\
\sigma_{\text{Al, semihard}} = 151 (0.260 + e^{0.133}) \\
\sigma_{\text{Cu, annealed}} = 403 e^{0.260} \\
\sigma_{\text{Fe, annealed}} = 720 e^{0.240}
\]

where \( e = \ln(\frac{h_0}{h_1}) \) is the equivalent strain in simple upsetting with \( h_0 \) and \( h_1 \) as the initial and final height of the workpiece.

Methods of Surface Preparation

All workpieces were surface prepared prior to cold pressure welding. The following seven surface preparation methods were applied (Ref. 14):

- Degreasing, (D)
- Scratch brushing, (B)
- Semibright (matt) Ni plating, (M)
- Electroless (chemical) Ni plating, (C)
- Heat treated electroless Ni plating, (T)
- Hard Cr plating, (H)
- Anodizing of aluminum, (A)

All plating layers were applied to a thickness of 5 \( \mu \)m. Before welding, all metal surfaces, except the scratch-brushed surface, were degreased with acetone and dried in an oven at 150°C for 5 min.

Cold Roll Welding Experiments

The two metal strips to be joined were positioned with the two prepared surfaces against each other. In order to prevent sideslip between the two strips, they were fastened by prewelding the front ends in a hydraulic press just before rolling. A guide was mounted at the entrance of the rolling mill to correctly position the strips passing through the roll gap and to prevent sideslip of the two strips during rolling. No lubricant was applied in the cold rolling process. For each metal combination with each specified surface preparation method, a series of experiments (with 15-20 samples) was carried out with varying reduction from 25% to about 75%.

Testing of Weld Strength

Considering the small thickness of the welded specimens, the shear test method earlier applied by Vaidyanath, et al. (Ref. 15), is applied in the present work. Figure 1 shows an outline of the testpiece. After drilling the two fixture holes, the edges of the testpiece were milled. Finally, to perform a shear test, two grooves with a width of 3 mm (0.118 in.) were milled one on each side of the testpiece with a separation of \( a \). The dimensions of the testing area and the groove depth were determined according to the individual thicknesses of the two welded metals, in order to ensure that a fracture occurs at the weld interface by shear rather than in one of the base metals by tension. The width \( a \) of the testing area was determined as:

\[ a = 1.2 h_{1w} \]

where \( h_{1w} \) is the final thickness of the weaker metal element. The relationship between the groove depth \( d \) and the corresponding final thickness \( h_1 \) of the
After roll welding, the weld strength was tested for each welded sample by the shear test system described above. The strength curves of each metal combination are compared for alternative methods of surface preparation. The experimental results for all welding combinations investigated in the current work are presented below.

**Roll Welding of Al-Al**

Figure 2 shows an example of the shear strength curves as a function of the total reduction in the case of cold roll welding Al-Al with two-sided semibright Ni plating. In the diagram, the scattered markers are the measured experimental data, whereas the solid line is the fit curve obtained by a third order polynomial regression. It is seen that the scattering of the measured data is low, implying that the testing system developed in the present work is applicable. To clearly show the relationship of weld strength in different conditions, only the fit curves are presented in the figures below.

Figure 3 shows the shear strength curves of roll welding Al-Al with one-sided and two-sided anodizing. It is found that a one-sided plating layer is better than a two-sided. This is generally found for all different plating layers. It is probably due to the very brittle nature of the surface oxide layer on Al ensuring that the fracture of the oxide layer will easily occur together with the one-sided plating layer on the opposite side. Two-sided plating layers are not favorable, since the enlarged thickness of the interface layers and the liable mismatch of the two fractured plating layers during deformation will not facilitate joining in case of Al-Al.

Figure 4 shows a comparison of the
shear strength curves obtained with one-sided surface preparations. It is seen that the semibright and electroless Ni plating results in the smallest threshold reduction, anodizing a little larger, and hard Cr plating the greatest. It is also noticed that the slopes of the strength curves obtained with anodizing and hard Cr plating are steeper than those obtained with semibright and electroless Ni plating.

Figure 5 shows a comparison of the shear strength curves obtained with two-sided surface preparations. It is noticed that the semibright and electroless Ni plating result in smaller threshold reduction, while scratch brushing and anodizing give medium reduction, and hard Cr plating and degreasing result in the largest. It is found again that the slopes of the strength curves obtained with scratch brushing, anodizing and hard Cr plating are steeper than those obtained with semibright and electroless Ni plating and degreasing.

The reasons for the difference in the slopes of the strength curves will be further investigated and explained by fractographies in a future paper.

**Roll Welding of Cu-Cu**

Shear strengths were tested for each of the eight series of Cu-Cu. Figure 6 shows a comparison of all the shear strength curves obtained. It is found that two-sided electroless Ni plating results in the smallest threshold reduction. One-sided electroless Ni plating, semibright Ni plating and hard Cr plating result in medium threshold reduction. Scratch brushing results in the largest threshold reduction, whereas degreasing only was not successful in this range of experiments. At higher reductions, the hard Cr plating results in the highest weld strength, the electroless Ni plating medium and the semibright Ni plating the poorest. This too will be discussed in detail in a future paper.

When the strength curves obtained with the same plating layers in the form of one-sided and two-sided are compared, it is found that the two-sided generally yields a higher strength than one-sided for all the three plating layers applied. The reason is probably that the surface oxides of copper are rather ductile and thereby not likely to break up and expose the virgin base metal (Ref. 16). When a brittle cover layer is plated on the surface, the fracture of the cover layer will promote the exposure of the underlying virgin metal. In cold welding of Cu, the application of brittle cover layers as a surface preparation was found to be beneficial.

**Roll Welding of Steel-Steel**

Shear strengths were tested for each of the ten series of steel-steel. Figure 7 shows a comparison of all the shear strength curves that were obtained in the experimental range of investigation. It is found that the two-sided heat-treated electroless Ni plating results in the highest weld strength, the two-sided electroless Ni plating medium and the semibright Ni plating the poorest. This too will be discussed in detail in a future paper.

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medium results and the scratch brushing gives poor results. All the remaining series investigated were unsuccessful, because fracture of the weld occurred immediately after rolling. This is because the pressure in roll welding of steel-steel is very high, resulting in a rather high ductility of the surface layers, thereby impeding the weld formation for many of the surface layers.

**Roll Welding of Al-Cu**

Figure 8 shows the strength curves obtained for cold roll welding of Al-Cu with electroless Ni-plating applied on different sides. It is found that the one-sided plating on the Cu side gives the best performance compared with the two-sided plating and the one-sided plating on Al. This has been generally noticed for all different plating layers. This may be explained by the different properties of the oxide films on Al and Cu. The oxide film on Al is, however, very hard and brittle (Ref. 16). When a brittle cover layer is plated on the surface of Cu, the fracture of the cover layer will promote the exposure of the base metal, thereby facilitating the weld formation. When the brittle cover layer is plated on the already brittle Al surface, the benefit of the plating layer will not be as significant as on the Cu surface.

Figure 9 shows the comparisons of the strength curves obtained with two-sided plating layers. It is seen that the weld strength decreases in the following order: scratch brushing, hard Cr plating, electroless Ni plating, semibright Ni plating, and degreasing.

An explanation for the success of scratch brushing may be that relative sliding occurs at the interface when roll welding two different metals due to the inhomogeneous deformation. This may facilitate breaking up of the surface in the areas covered only with a thin contaminant film, thereby promoting weld formation.

Explanation of the different performance of different plating layers is rather complicated, because they are not only dependent on the properties of the oxide films on the metal surfaces, but also on the characteristics of the cover layers. This will be discussed in a future investigation studying the micrographs of fractured weld interfaces and the properties of the cover layers.

**Roll Welding of Al-Steel**

Figure 10 shows the strength curves obtained for cold roll welding Al-steel with an electroless Ni-plating layer applied on one or both surfaces. It is seen that the weld strength obtained with two-sided plating and one-sided plating on the steel surface are almost identical, and better than that obtained with one-sided plating on the Al surface. The explanation to this phenomenon is that the surface film of steel is difficult to fracture. Plating the steel surface with a brittle cover layer will facilitate fracture of the surface layer thus improving the weld.

As shown in Fig. 11, the strength curves obtained for all 12 series of cold roll welding Al-steel are plotted in the same diagram. It is found that the method of scratch brushing gives the best strength, the two-sided plating and one-sided plating on the steel surface of electroless Ni and hard Cr give medium results, whereas the one-sided plating on the Al surface of hard Cr and electroless Ni, the one-sided semibright Ni plating on the steel surface, anodizing of Al and only degreasing both surfaces give poorer strength.

It should be mentioned here that the semibright Ni-plating layer was not suitable for cold roll welding of Al-steel. One-sided plating of the steel resulted in large threshold reduction and poor strength, and two-sided plating and one-sided plating of the Al produced no weld. This is explained by the increased ductility of the semibright Ni-plating layer under greater pressure causing delayed exposure of the virgin surface.

**Conclusions**

Systematic experiments were carried out to investigate the influence of different surface preparation methods on the weld formation in cold pressure welding. Five metal combinations were selected applying seven different surface preparation methods.

It was found that different surface plating layers resulted in different weld strength in the same metal combination due to their different properties. It was also found that the same plating layer would perform differently in different metal combinations and even in the same metal combination when plated on different sides due to the influence of hydrostatic pressure on the ductility of cover layers, and the properties of the surface oxide films in combinations of dissimilar metals.

For each metal combination, an optimum surface preparation method has been found. Semibright and electroless Ni plating were optimum for roll welding Al-AI; electroless Ni plating for Cu-Cu, heat-treated electroless Ni plating for steel-steel, and scratch brushing for Al-Cu and Al-steel.

**References**