Cold Welding — Fractographic Investigation of the Weld Formation

An investigation was conducted to discover why various surface preparations prior to cold welding have such a marked influence on weld strength

W. ZHANG AND N. BAY

ABSTRACT. Fractographic investigations of the weld formation in cold welding were carried out with a scanning electron microscope (SEM) applying a number of different methods of surface preparation before welding. It was found that the significant difference in behavior of the different surface layers may be explained by the difference in a few basic properties. Two parameters were introduced to represent these properties, namely the ductility and the fragment geometry of the surface layers after fracture. These parameters can quantitatively describe the influence of the surface dressing on the weld formation in cold welding.

Introduction

In cold welding, surface preparation of the metals before welding has vital influence on the resulting weld strength. It was shown in Ref. 1 that different surface preparation methods resulted in large differences in weld strength curves of the same metal combination. It was furthermore observed that the same kind of surface preparation performed differently with different metal combinations and even with the same metal combination when plated on different base metals. All these phenomena indicate that surface preparation of the base metals is essential in cold welding and influences the weld strength in a complex manner.

To obtain a better understanding of the mechanisms governing weld formation and the varying functions of the different surface preparation methods, a comprehensive fractographic investigation was carried out of the weld interface surfaces after fracture by means of a scanning electron microscope (SEM). By investigation of the micrographs, two parameters representing the properties of the surface layers are introduced, namely the ductility (G) and the dimension ratio (t/w) of the deformed thickness of the surface layer and the average width of the fragments of the surface layer. These quantitative parameters open a good chance for development of the theoretical models that will be presented in the next paper of the present series.

W. ZHANG and N. BAY are with Institute of Manufacturing Engineering, Technical University of Denmark, Lyngby, Denmark.

Observations by SEM

To clearly see the behavior of the surface layers, the roll welded strips were divided at the interface by peeling and the interface surface with plating layer was then observed by SEM. For each welding combination with one-sided plating, four specimens with different reductions were observed. It is impractical to present all the micrographs in this paper. For this the reader is referred to Ref. 2. Some examples of the SEM micrographs are presented below.

Weld Interface Surfaces in Cold Welding of Similar Metals

Figures 1–4 are micrographs of fractured weld interface surfaces of Al-Al with one-sided surface plating layers (observing the plated surface). All these micrographs were taken from the specimens at a reduction of about 60% and at the same magnification. It is clearly seen that the fragment sizes of different plating layers are significantly different. They are large in cases of semibright and electroless Ni plating, smaller in the case of anodizing and very small in the case of hard Cr plating. Because the initial thicknesses of all plating layers were 5 µm, the dimension ratio (t/w) between the deformed thickness of the plating layer and the average width of the fragments will be small and will thereby facilitate the weld formation in semibright and electroless Ni plating as compared with hard Cr plating. In the case of anodizing, weld formation will be of medium quality. This explains the difference in the threshold reductions shown in Fig. 4 in Ref. 1.

KEY WORDS

Cold Welding
Cold Roll Welding
Aluminum
Copper
Steel
Cover Layer
Ductility
Hydrostatic Pressure
Fragment Geometry
Weld Formation

In the case of cold roll welding steel-steel, semibright Ni plating is almost completely ductile as seen in Fig. 5, where no clear cracks are visible. Semibright Ni plating was not successful in cold welding steel-steel (see Fig. 7 in Ref. 1). Figure 6 shows electroless Ni plating to be ductile, too. However, if the electroless Ni plating layer is heat treated 3 h at 300°C (572°F) before roll welding, it becomes very brittle as shown in Fig. 7. It is further noticed that the fragment size of the heat-treated electroless Ni plating layer after fracture is larger than that of the hard Cr plating layer shown in Fig. 8, implying a better performance in the weld formation (see Fig. 7 in Ref. 1).

Weld Interface Surfaces in Cold Welding of Dissimilar Metals

Figures 9 and 10 show micrographs of weld interface surfaces of Al-steel with one-sided electroless Ni plating on the Al surface and the steel surface, respectively. It is noticed that the same plating layer performs differently when plated on different sides in the same metal combination. Because the pressure is similar for the same metal combination, the difference in the two cases should be caused

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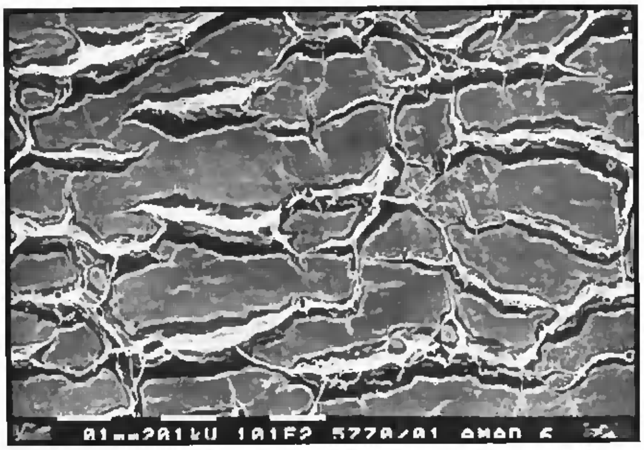

Fig. 1 — Weld interface surface after fracture, cold roll welding Al-Al with one-sided semibright Ni plating (AMAD), Y = 0.603.

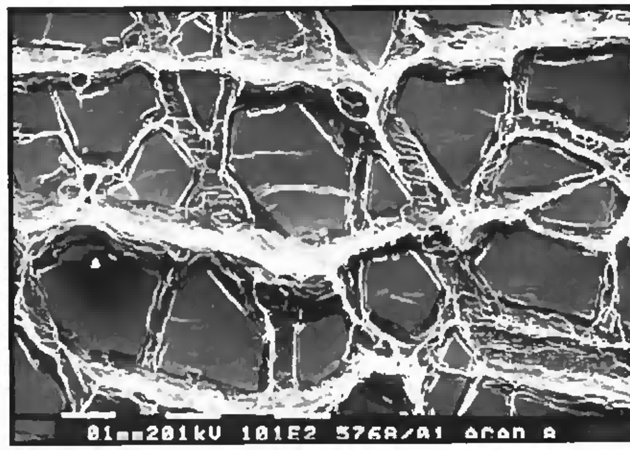

Fig. 2 — Weld interface surface after fracture, cold roll welding Al-Al with one-sided electroless Ni plating (ACAD), Y = 0.595.

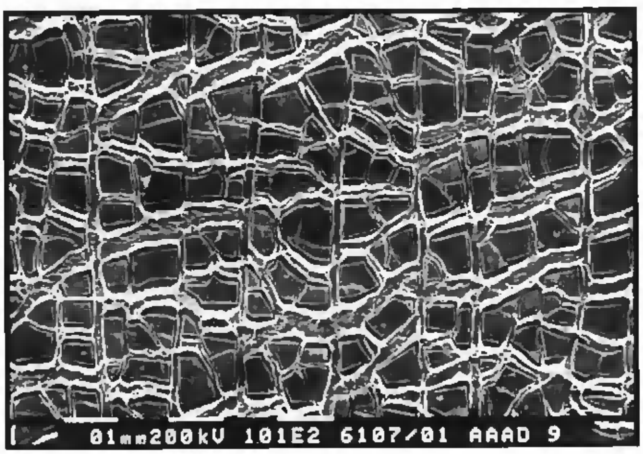

Fig. 3 — Weld interface surface after fracture, cold roll welding Al-Al with one-sided anodizing (AAAD), Y = 0.602.

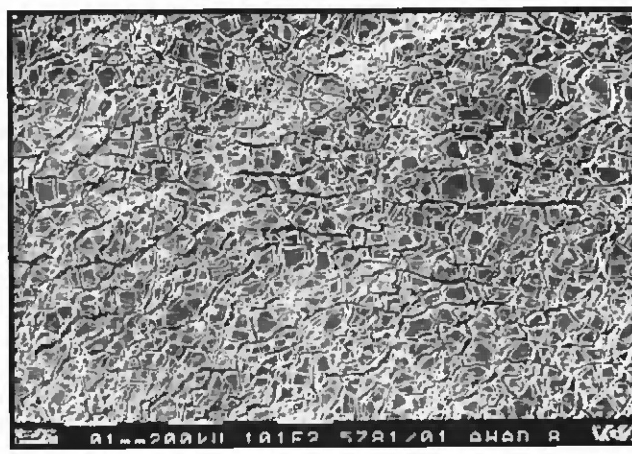

Fig. 4 — Weld interface surface after fracture, cold roll welding Al-Al with one-sided hard Cr plating (AHAD), Y = 0.597.

by the inhomogeneous deformation of the two metals. When the surface layer is plated on the Al surface, the plating layer would fracture sooner (at lower surface expansion) due to larger deformation of Al (compared to steel), and the elongation of the plating layer is impeded by the less deformed steel strip, thereby the plating layer shows less ductility. When the surface layer is plated on the steel surface, the fracture of the plating layer will be delayed (to a higher surface expansion), and the elongation of the cover layer will be enhanced by the more deformed Al strip, thus the cover layer shows more ductility.

Quantitative Representatives of the Properties of Cover Layers

The strategic surface layer provided on one or both of the base metals acts as a cover protecting the metal surface from direct contamination by oxidation, etc. It is therefore named the cover layer (Ref. 3).

As seen from the micrographs, the ductility (G) and the fragment geometry (t/w) are two important parameters governing the performance of different cover layers. To quantitatively represent the properties of cover layers, these parameters are measured using the micrographs and defined as follows.

Ductility (G) of Cover Layers

Due to a possible ductility in the cover layer there is a difference between the nominal surface expansion and the true surface exposure forming virgin metal surfaces at the weld interface. The nominal surface expansion of base metal, Y, is given by:

$$Y = \frac{A_1 - A_0}{A_1} = \frac{h_0 - h_1}{h_0} \qquad (1)$$

and the true surface exposure ψ expressing the fraction of virgin metal surface after cold welding is given by:

$$\psi = \frac{A_1 - A_c}{A_1} \qquad (2)$$

where A_0 is the initial surface area, A_1 is the final surface area after cold welding and A_c is the surface area covered by cover layer after cold welding. The ductility G of the cover layers is now defined as:

$$G = \frac{Y - \psi}{Y} = 1 - \frac{\psi}{Y} \qquad (3)$$

Equation 3 expresses the amount of reduction of exposed weld interface due to ductile spreading of the cover layer. G = 1 represents a completely ductile cover layer, whereas G = 0 represents a completely brittle cover layer.

The ductility of the plating layers is estimated by measuring the true surface exposure (Equation 2) on the micrographs with an image measuring system (Ref. 2), whereas the nominal surface expansion is obtained from the measured thickness after rolling (Equation 1). For each combination of metal and surface plating, mi-

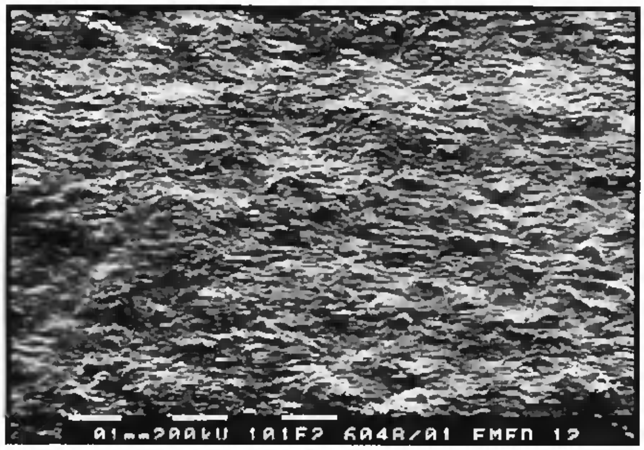

Fig. 5 — Weld interface surface after fracture, cold roll welding steel-steel with one-sided semibright Ni plating (FMFD), Y = 0.583.

Fig. 6 — Weld interface surface after fracture, cold roll welding steel-steel with one-sided electroless Ni plating (FCFD), Y = 0.612.

crographs of four specimens at different reductions were measured to get four pairs of data for the true surface exposure (ψ) and the nominal surface expansion (Y). An average value of G is then estimated for the combination by a linear regression of Y with respect to ψ, where the slope is 1-G as found in Equation 3.

Figure 11 shows the diagram of the ductility of different plating layers in cold roll welding of Al-Al. It is found that the ductility increases in the following order: hard Cr plating → anodizing → electroless Ni plating → semibright Ni plating.

In the case of cold roll welding of steel-steel (Fig. 12), the semibright Ni plating becomes almost completely ductile and electroless Ni plating is very ductile, but hard Cr plating is still rather brittle. The ductility of the heat-treated electroless Ni plating turned out to be very low, which resulted in a better weld formation as presented in Ref. 1. This implies that the procedure applied to embrittle the electroless Ni plating layer was successful.

Figures 13 and 14 show the diagrams of the ductility of different plating layers in cold roll welding of Al-steel with one-sided cover layers on the Al surface and the steel surface, respectively. A very consistent ductility ranking of cover layers is found in both cases in agreement with that of the Al-Al roll welding. It is noted that the ductility is larger when plating on the steel surface than on the Al surface. This is due to the earlier mentioned inhomogeneous deformation of the compound material.

In order to observe the ductility of cover layers in different metal combinations, *i.e.*, at different hydrostatic pressures, Figs. 15 and 16 show the ductility of semibright Ni plating and hard Cr plating in different welding combinations. The asterisk indicates which of the two metals has been plated. It is noticed that the ductility of the semibright Ni plating layer is very sensitive to hydrostatic pressure; its ductility increases as the pressure increases — Fig. 15. This may explain the different performance of this layer in different metal combinations. The ductility of hard Cr plating is almost unaffected by pressure — Fig. 16.

Table 1 — Ductility of Different Plating Layers in Different Welding Combinations

Combinations	Ductility of cover layers (G)				
	Semibright Ni	Electroless Ni	Anodizing	Treated Ni	Hard Cr
Al-Al	0.256	0.067	0.039	—	0.030
Al*-Cu	0.150	0.008	−0.057	—	0.024
Al-Cu*	0.242	0.159	—	—	0.043
Cu-Cu	0.363	0.156	—	—	0.048
Al*-Fe	0.643	0.135	0.070	—	0.045
Al-Fe*	0.688	0.318	—	—	0.066
Fe-Fe	0.930	0.716	—	0.056	0.039

The * marking indicates which of the two metals has been plated.

Table 1 shows a complete view of the ductility of different plating layers in different welding combinations.

Dimension Ratio (t/w) of the Fragments of the Cover Layers

The dimension ratio (t/w) of the fragments of the cover layer is obtained by directly measuring the average width (w) of the fragments of the cover layer with micrographs and estimating the deformed thickness (t) of the cover layer knowing the initial thickness (t_0) and the already estimated true surface exposure (ψ) and the nominal surface expansion (Y). According to volume constancy, in cases of plane strain problems the following relationship exists:

$$A_c t = A_0 t_0 \qquad (4)$$

Inserting Equations 1 and 2 into 4 leads to

$$t = \frac{1-Y}{1-\psi} t_0 \qquad (5)$$

The initial thickness of the plating layers was estimated by weighing, knowing the mass density of the plating materials and the dimensions of the specimens.

For each combination of metal and surface plating, micrographs of four specimens at different reductions were measured. An average value of t/w is then calculated for the combination. During deformation, the fragments will expand due to the ductility of the cover layer, and the thickness of the cover layer will at the same time be reduced according to the law of volume constancy, but the dimension ratio t/w of the fragments has turned out to be constant in plane strain deformation for a given combination of metals and surface plating.

To give a complete view of the dimension ratio (t/w) of the fragments of cover layers, Table 2 shows a map of the t/w value of different plating layers in different welding combinations. It is noticed that the t/w values of the fragments of anodizing and hard Cr plating are generally larger than those of semibright and

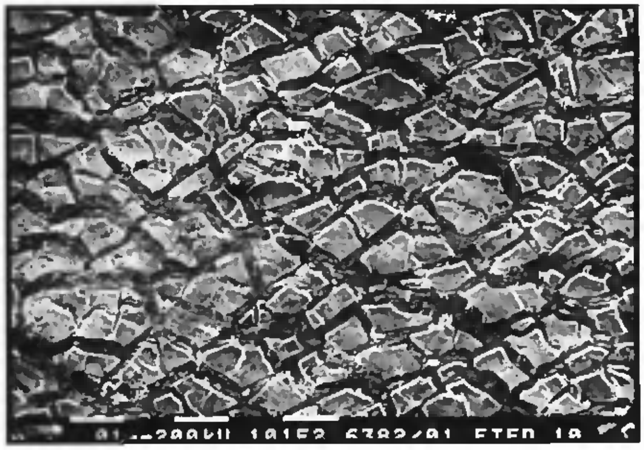

Fig. 7 — Weld interface surface after fracture, steel-steel with one-sided heat-treated electroless Ni plating (FTFD), Y = 0.610.

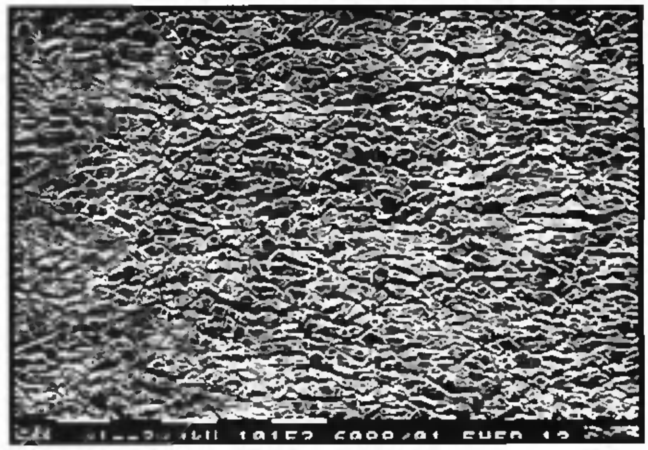

Fig. 8 — Weld interface surface after fracture, cold roll welding steel-steel with one-sided hard Cr plating (FHFD), Y = 0.607.

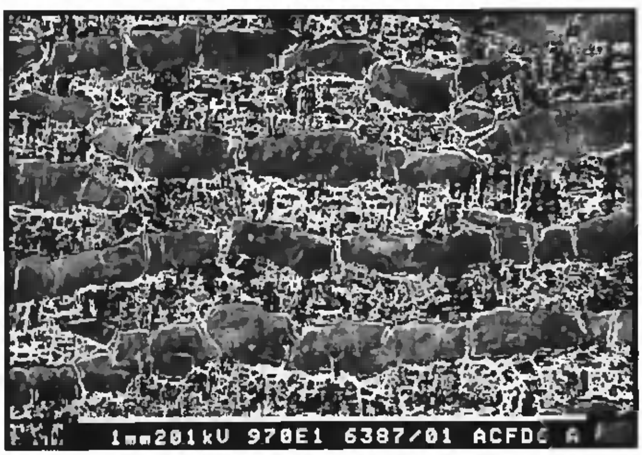

Fig. 9 — Weld interface surface after fracture, cold roll welding Al-steel with one-sided electroless Ni plating on Al surface (ACFD), Y = 0.598.

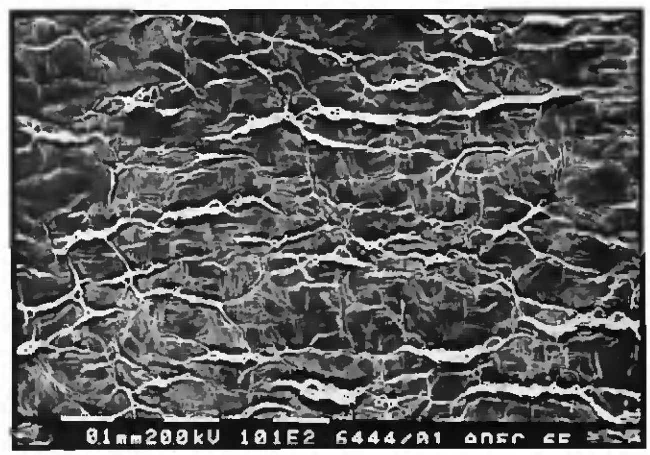

Fig. 10 — Weld interface surface after fracture, cold roll welding Al-steel with one-sided electroless Ni plating on steel surface (ADFC), Y = 0.603.

Table 2—Ratio (t/w) of the Fragments of Plating Layers in Different Welding Combinations

	t/w value of the fragments of cover layers				
Combinations	Semibright Ni	Electroless Ni	Anodizing	Treated Ni	Hard Cr
Al-Al	0.049	0.053	0.133	—	0.197
Al*-Cu	0.074	0.142	0.258	—	0.191
Al-Cu*	0.105	0.070	—	—	0.222
Cu-Cu	0.092	0.077	—	—	0.276
Al*-Fe	0.018	0.051	0.336	—	0.278
Al-Fe*	0.079	0.044	—	—	0.264
Fe-Fe	none	0.049	—	0.128	0.429

The * marking indicates which of the two metals has been plated.

electroless Ni plating.

It is further noticed that there is no significant influence of pressure, or metal combination, on the t/w value of semibright and electroless Ni plating, whereas the t/w value of anodizing and hard Cr plating increases as the pressure increases. This is probably due to the very brittle nature of the latter two plating layers (Table 1).

Discussions

The preparation of metal surfaces before cold welding has earlier proved to be of vital importance to the weld formation (Ref. 1). The present investigation indicates that this may be explained by the different behavior of different cover layers quantified by two properties, *i.e.*, the ductility and the geometry of the fragments. These properties are bound to have significant influence on the weld formation and their combined influence on the weld strength appears to occur in a complex way as noticed experimentally in Ref. 1.

Correlation of the Properties of Cover Layers with the Weld Formation

The ductility (G) of cover layers directly influences the exposure of the virgin base metal surface. At the same surface expansion of the base metal, higher ductility of the cover layer will result in less exposure of the virgin base metal surface. Therefore, the weld strength obtained will be lower.

The geometry (t/w) of the fragments of cover layers directly relates to the extrusion of base metal through cracks in the cover layer, because the extrusion may become an incomplete process not reaching steady-state conditions in the

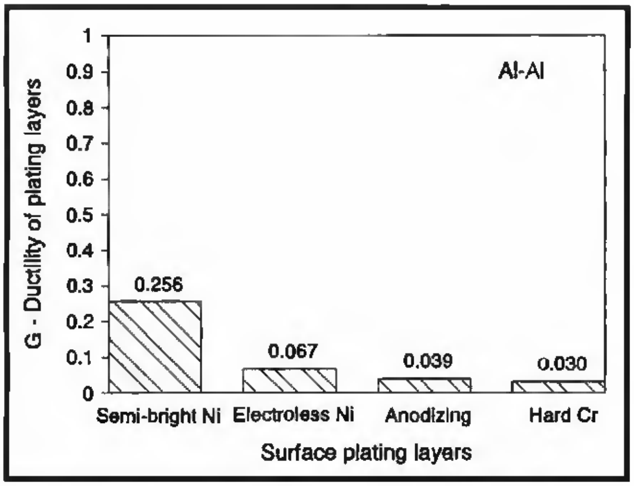

Fig. 11 — Ductility of different plating layers in cold roll welding Al-Al.

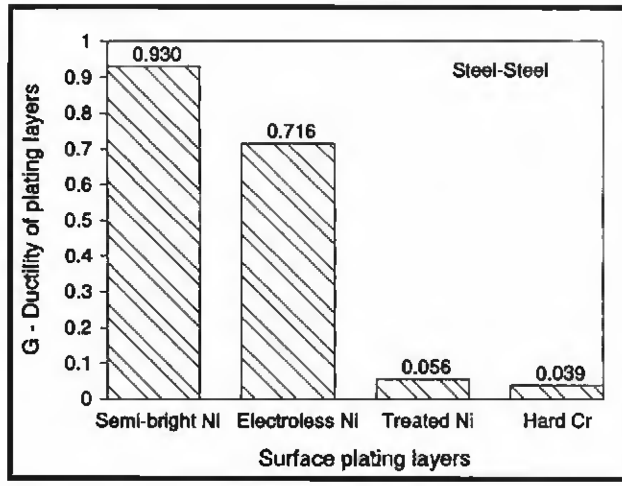

Fig. 12 — Ductility of different plating layers in cold roll welding steel-steel.

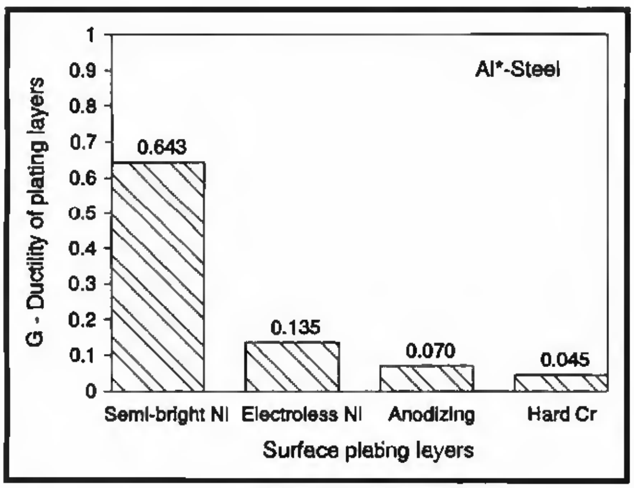

Fig. 13 — Ductility of different plating layers in cold roll welding Al-steel with cover layer on Al surface.

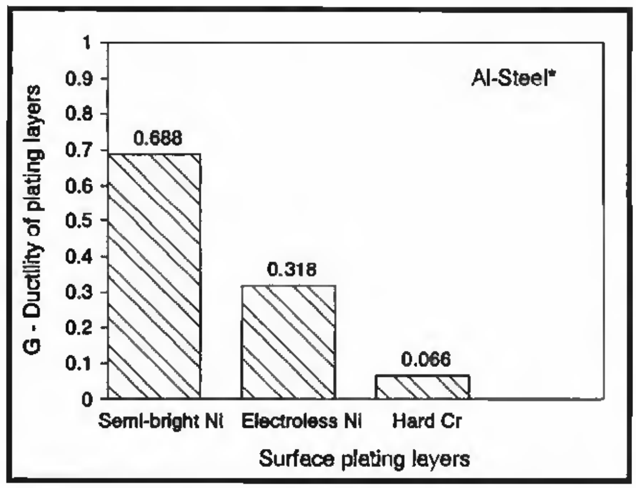

Fig. 14 — Ductility of different plating layers in cold roll welding Al-steel with cover layer on steel surface.

case of a small ratio (t/w) of the fragments. This is generally the case in cold welding of metals with thin surface layers. In such case, the pressure necessary for extrusion of the base metal through the cracks will depend on the relative extrusion length, *i.e.*, the dimension ratio (t/w), and thus influence the weld formation. The larger the dimension ratio (t/w) of the fragments is, the more difficult will be the weld formation due to the necessity of a relatively longer extrusion length.

The combined effect of these two parameters makes a complex influence on the weld strength curves. As presented in Ref. 1, the weld formation in the case of softer metal combinations generally initiates at a lower threshold reduction with semibright and electroless Ni plating than with hard Cr plating and anodizing of Al. This can be explained by the smaller dimension ratio (t/w) of the fragments, which will easily enable an onset of the weld formation due to a lower necessary pressure for the extrusion of base metal through the cracks. However, at higher reductions and/or harder base metal combinations, higher weld strength is normally obtained with hard Cr plating and anodizing of Al, as well as heat-treated electroless Ni plating in cold welding steel-steel. This is because the extrusion of the base metal through cracks at high reductions becomes easier and because lower ductility of the cover layer causes increasing exposure of the virgin base metal surface, both factors that facilitate weld formation.

Influence of Hydrostatic Pressure on the Ductility of Cover Layers

The ductility of the same cover layer can be different in different welding combinations. As was mentioned earlier, the hydrostatic pressure at the same deformation varies in different metal combinations. The ductility of the cover layers will be influenced by the hydrostatic pressure.

It has been noticed that semibright and electroless Ni plating layers were more sensitive to the influence of hydrostatic pressure than were anodizing of Al and hard Cr plating layers (Table 1). A rather successful semibright Ni plating layer in roll welding Al-Al will fail completely in roll welding steel-steel due to a rapid increase in the ductility of the cover layer (referring to Ref. 1). The failure of some cover layers in a few metal combinations, *e.g.*, steel-steel and Al-steel, is usually caused by the increased ductility of the cover layer, except for the hard Cr plating layer.

Performances of Plating Layers in Welding Combinations of Dissimilar Metals

As has been noticed, the same plating

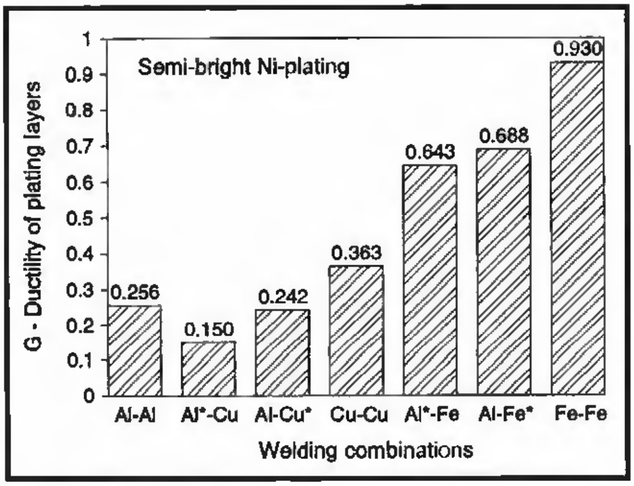

Fig. 15 — Ductility of semibright Ni plating layer in different welding combinations.

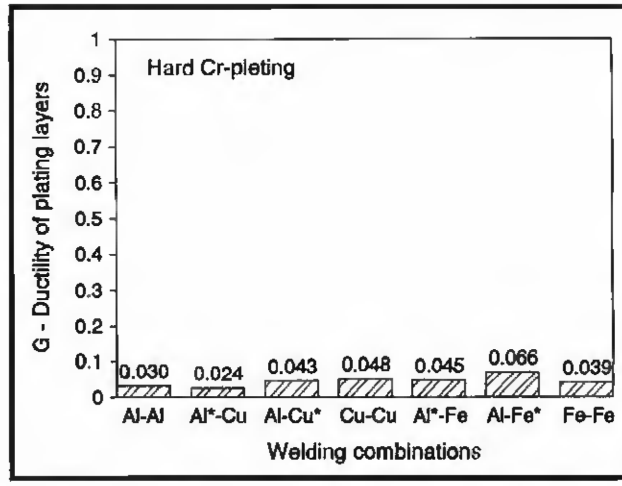

Fig. 16 — Ductility of hard Cr plating layer in different welding combinations.

layer will function differently in the same combination of dissimilar metals when it is plated on different metal surfaces. The explanation for this is rather complex. Among many parameters, the different properties of the surface oxide films and the inhomogeneous deformation due to different yield stresses of the base metals may be considered as the dominating ones influencing the weld formation.

The natural oxide layers of different metals are different. The oxide layer of Al is very hard and brittle and therefore easy to break up, whereas the oxide layer of Cu is rather ductile and thus difficult to break up, which means it impedes weld formation. When a brittle cover layer is plated on the Cu surface, and thus replaces the ductile Cu-oxide layer, the fracture of the cover layer will assist exposure of the base metal, thereby facilitating the weld formation. When a brittle cover layer is replacing the already brittle Al-oxide layer, the advantage of the plating layer will not be so pronounced as on the Cu surface.

In the case of roll welding Al-steel, the inhomogeneous deformation due to different yield stresses of the metals plays an important role. Larger surface expansion of the Al surface will facilitate the breaking up of the plating layer on the steel surface, therefore exposing the maximum area of virgin base metal surface.

In combinations of dissimilar metals, the extrusion of soft metal through cracks in the cover layer is always easier than the extrusion of hard metal. By covering, the harder metal exposure of and contact between virgin surfaces is facilitated because the extrusion of the uncoated, oxidized and contaminated softer metal through the cracks of the cover layer will help to break up the surface layer on the soft metal. This is especially true for Al with a hard and brittle oxide film. When the cover layer is plated on the soft metal, the exposed virgin surface of the soft metal will be extruded through the cracks, but will not always meet the clean surface of the hard metal, because the surface of hard metal is only partially exposed. Therefore, plating on the hard metal will result in a more successful weld formation than plating on the soft metal. When plating on both surfaces of dissimilar metals, the likely mismatch of the cracks formed in the cover layers on different surfaces will result in less successful weld formation.

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

Conclusions

Through the fractographic investigations of the weld formation in cold welding, two parameters have been defined to represent the properties of cover layers. These are the ductility (G) and the dimension ratio (t/w) of the fragments of cover layers. By observation of the micrographs and measurement of these parameters, the following main phenomena have been found:

- Different surface plating layers give different weld strengths in the same metal combination due to their different properties. Semibright and electroless Ni plating layers fracture in a smaller dimension ratio (t/w) of the fragments resulting in smaller threshold reduction to initiate welds. However, hard Cr plating, anodizing and scratch brushing result in higher weld strength at larger reductions due to the lower ductility of the cover layers.
- The same plating layer performs differently in different metal combinations, due to the influence of hydrostatic pressure on the ductility of cover layers. Semibright Ni plating, which is rather successful in roll welding Al-Al, gives very poor results or fails in roll welding Al-steel and steel-steel due to its increased ductility.
- In combinations of dissimilar metals, the weld strength is higher when plating on the metal with ductile oxide film and the metal with higher yield stress (harder metal). Plating on the Cu surface in roll welding Al-Cu and on the steel surface in roll welding Al-steel gives better weld strength than plating on the Al surface.

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