An Investigation into the Production of Bi- and Tri-Layered Strip by Drawing Through Wedge-Shaped Dies

A.K. Taheri and S.A. Majlessi

This article describes the experimental work carried out to investigate the feasibility of producing multi-layered metallic strip by cold drawing. Two types of strip were prepared. The first was a bi-layered strip of aluminum/mild steel. The second type of strip was a tri-layered material made of aluminum/copper/aluminum layers. To examine the effects of process variables, the amount of deformation and the die angle were varied, and the drawing force and the strength of the interface bond were measured. The results of numerous experiments revealed that drawing stress increases almost linearly with an increase in relative reduction in area. Drawing stress also exhibits a minimum point when plotted versus die angle. It was observed that formation of an interfacial bond requires a minimum threshold value for reduction in area. Based on scanning electron microscopy observations, a mechanism for cold weld formation is explained.

1 Introduction

In recent years, much attention has been directed toward the manufacture of metallic parts from multilayered materials by various industries. This is due to the fact that metallic parts produced from single metals or alloys do not always provide all the mechanical and physical properties required under the operating conditions. The advantage of multilayer materials stems from the fact that one metallic layer can, for example, provide the desired strength, whereas other layers may provide good electrical or thermal conductivity, wear resistance, radioactive resistance, or corrosion protection. These materials are used in a number of different manufacturing industries. In the chemical industry, for example, bimetallic materials are used for production of containers and pressure vessels. In the nuclear industry, uranium rods are clad with aluminum, stainless steel, or zirconium alloys. Another popular application of bimetallics is in the heat measurement industry for production of thermostats.

A number of different processes are used to produce bi- and tri-layered materials. These operations include diffusion bonding, powder metallurgy, casting, hot rolling, extrusion, sintering, deposition, plasma spraying, and explosive welding. Using these processes, bi- and tri-layered strip of high quality can be produced; however, high production cost, sophisticated technology, and difficulties arising during manufacturing make these processes less attractive. One of these manufacturing difficulties is incompatibility between the two materials and in some cases formation of brittle intermetallic phases at the interface between the two layers.

In the present article, a relatively simple and economic drawing process for the manufacture of bi- and tri-layered strip is described. In this process, two or three layers of different materials are simultaneously drawn through a wedge-shaped die at room temperature. Due to deformation, cold welding occurs at the interface, and therefore, a bi- or tri-layered bonded strip is produced.

A.K. Taheri, Associate Professor, Metallurgical Engineering Department, Sharif University of Technology, Tehran, Iran; and **S.A. Majlessi**, Assistant Professor, Mechanical Engineering and Engineering Mechanics Department, Michigan Technological University, Houghton, Michigan.

2 Materials and Experimental Method

The following experiments were carried out using three types of materials, *i.e.*, commercially pure aluminum, mild steel, and copper. Aluminum 1100-0 was used in the as-received condition, whereas the 1020 mild steel and the commercially pure copper were annealed before experiments. The chemical composition of the copper is given in Table 1. These materials were obtained in the form of strip of 25.4 mm (1-in.) width. The nominal thicknesses of the strip were 1.37 mm (0.054 in.) for aluminum, 3 mm (0.118 in.) for mild steel, and 1 mm (0.039 in.) for copper. To better characterize these materials, their mechanical properties were determined by conducting plane-strain compression tests. The effective stress-effective strain relationship of each of these materials was then approximated with a power law equation of the form:

$$\bar{\sigma} = k\bar{\varepsilon}^n \quad [1]$$

with material parameters as shown in Table 2. Determination of the stress-strain relationship of these materials was also needed to model the drawing process. This task, which is based on an upper-bound approach, is under development.

Table 1 Composition of Copper

Cu	99.98%
Zn	5 ppm
Fe	3 ppm
Ni, As	2 ppm
S	5 ppm
O	200 ppm
Mn,Pb,Sb,Co,Cd,Se,Te	1 ppm
Sn, Bi	Nil

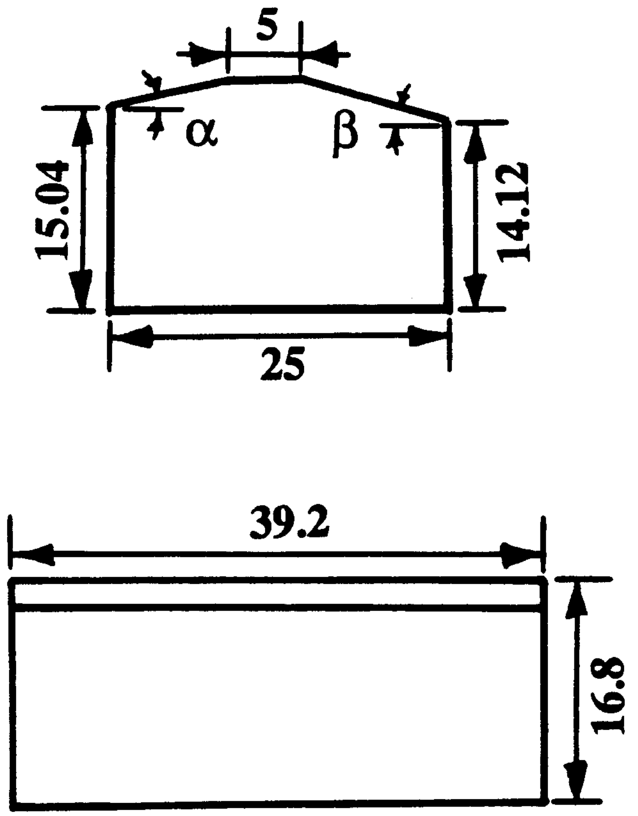

Fig. 1 Dimensions of one half of the drawing die in millimeters.

Two sets of experiments were conducted. In the first set, bilayered strip of aluminum/mild steel were drawn through a wedge-shaped die. In the second experiment, tri-layered strip with an arrangement of aluminum/copper/aluminum were produced. Figure 1 shows one half of a die along with its dimensions in millimeters. Figure 2 shows the three layers of materials entering the die and the drawing apparatus. An schematic presentation of the sectional view of the drawing apparatus is depicted in Fig. 3. To investigate the effects of the die angle on the quality and properties of the product, several different die angles, as listed in Table 3, were examined. Throughout the tests, a preparation process was carried out for each strip prior to drawing. This consisted of forming the tag on each strip by rolling one end of the strip, followed by degreasing the surfaces of the strip with carbon tetrachloride solution. Then the surfaces that would become the interface planes were cleaned using a steel brush to remove any oxide films.

Lubrication inside the die was provided by a mixture of mineral grease and graphite powder. The drawing stress was measured by a compression load cell located between the die and the drawing bench, as shown in Fig. 3. The output of the load cell was continuously recorded on an *X-Y* recorder. After the strip was drawn, the strength of the interface bond between the layers was determined using the standard ASTM peeling tests.[1] After peeling, the thicknesses of the individual layers were measured within a resolution of 0.01 mm and recorded for further evaluation.

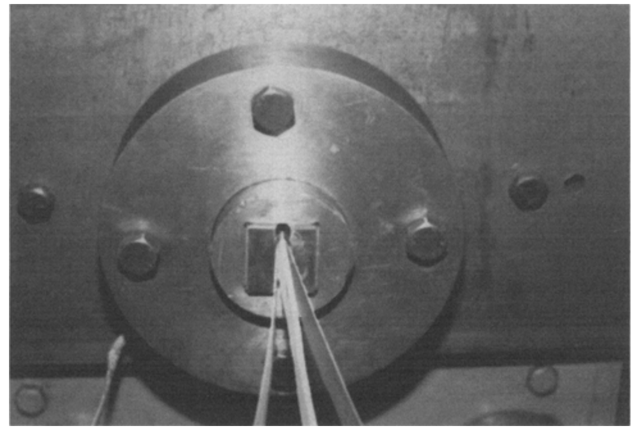

Fig. 2 Three strips of aluminum, copper, aluminum, and the drawing die.

Table 2 Material Constants

Material	K ksi	K kg/mm^2	*n*
Aluminum	29.86	21	0.3
Copper	59.16	41.6	0.2
Mild steel	88.18	62	0.26

Table 3 Half Die Angles

α	5	10	15	20	25
β	2.5	7.5	12.5	17.5	22.5

3 Experimental Results

3.1 *Effects of Relative Reduction in Area in Tri-Layered Strip*

Relative reduction in area (RA) is defined as the ratio of the decrease in the thickness of each layer to the initial thickness of that layer. The total relative reduction in area is then the ratio of decrease in the thickness of the whole cross section (all layers) to the sum of the initial thicknesses of the layers. Figure 4 depicts variations in the drawing stress as a function of the total relative cross-sectional reduction for a tri-layered strip of aluminum/copper/aluminum. As shown in this figure, drawing stress increases with an increase in the relative reduction in area. It was expected that in each test different layers of a multilayered strip would undergo different amounts of deformation, and therefore, the relative reduction in area would vary from layer to layer. Numerous experiments revealed that the above expectation was valid. Figures 5 and 6 show how the relative reduction in individual layers compare for drawing a strip of aluminum/copper/aluminum with die angles (2α) of 10 and 20°. Because the aluminum layers on each side of the copper have the same thickness, their relative reductions are the same, and therefore, only one value is shown in the figures.

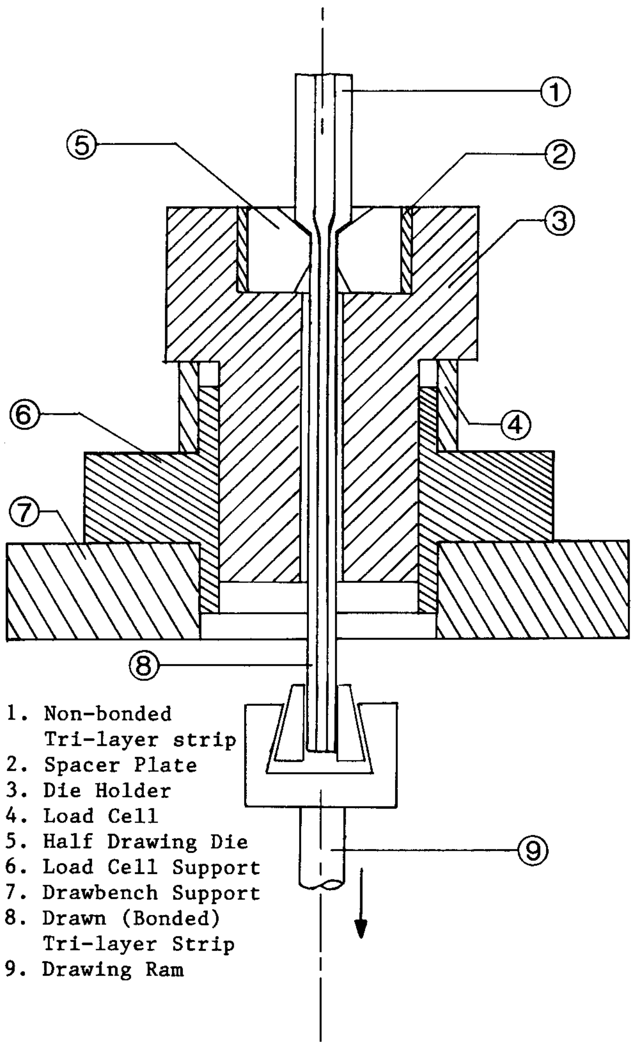

Fig. 3 Schematic presentation of a cross-sectional view of the drawing apparatus.

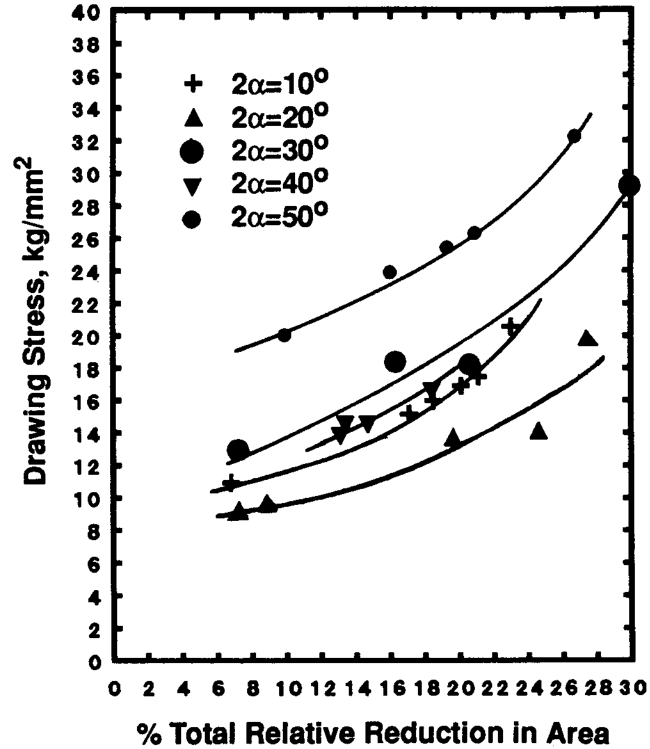

Fig. 4 Variations in drawing stress with percentage of total relative reduction in area for strip of aluminum/copper/aluminum.

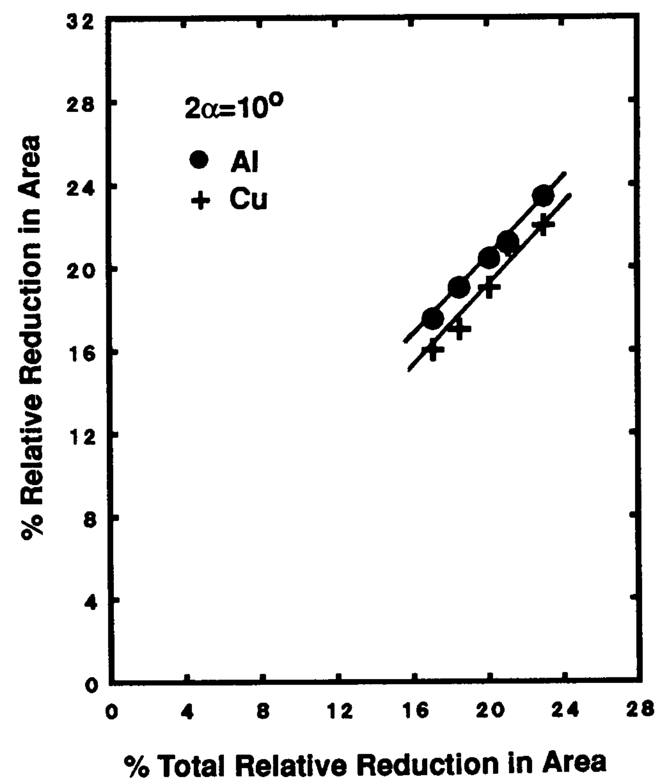

Fig. 5 Variations of relative reduction in area of individual layers with total relative reduction in area for strip of aluminum/copper/aluminum. Die angle = 10°.

It is expected that similar to conventional monolayered strip drawing, an optimum die angle that corresponds to the minimum drawing stress can be identified. Figure 7 shows variations of the drawing stress as a function of the total reduction for the same strip of aluminum/copper/aluminum. These variations are shown for die angles ranging from 10 to 50°. The values depicted in this plot are taken from the results of Fig. 4. For any reduction in area, there is an optimum angle for which drawing force is a minimum. This optimum die angle increases with an increase in reduction in area.

3.2 *Effects of Relative Reduction in Area in Bi-Layered Strip*

Figure 8 shows variations of the drawing stress in terms of the total relative reduction in area for a bi-layered strip of aluminum/mild steel. This strip was drawn using die angle of 40°. Similar to the case of tri-layered strip, an increase in reduction in area increases the drawing stress. Due to dissimilarities in the

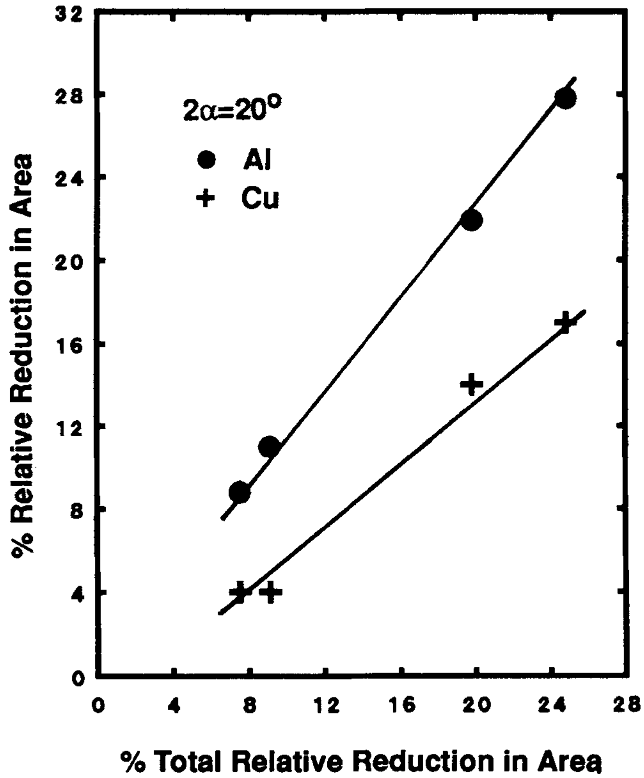

Fig. 6 Variations of relative reduction in area of individual layers with total relative reduction in area for strip of aluminum/copper/aluminum. Die angle = 20 °.

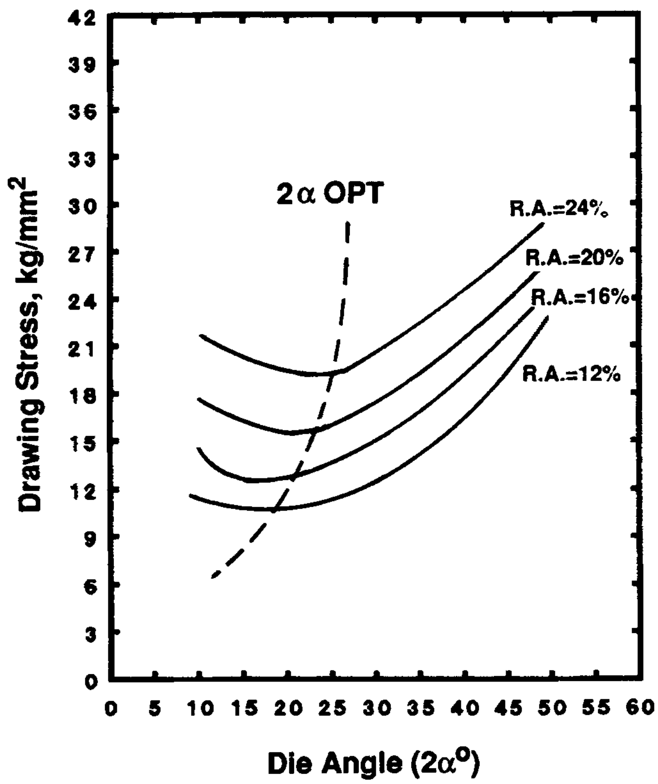

Fig. 7 Variations in drawing stress with die angle for strip of aluminum/copper/aluminum.

mechanical properties of the two materials, the drawing process causes different amounts of reduction in area for each layer. Figure 9 shows the relative reductions in area for aluminum and mild steel as a function of total reduction of the strip. Similar to the case of tri-layered strip, an increase in the total deformation causes a linear increase in the relative reduction in individual layers.

3.3 *Cold Weld Between Layers*

It has been observed that for tri-layered strips of aluminum/copper/aluminum a cold weld forms between layers, provided that the total reduction in area exceeds 20%. With regards to the effect of the die angle on formation of a cold weld, it was observed that increasing the die angle caused a cold weld to form at a lower reduction in area. In the case of bi-layered strip, a cold weld between layers was evident at reductions of 8% or more.

To determine the strength of the cold weld between layers, an attempt was made to measure shearing strength of the interface by using a standard ASTM tensile shear testing. This effort was not successful, because the fracture occurred in the aluminum layer and not at the interface; therefore, it was not possible to compare the bond strength of specimens. Next, an ASTM standard T-peel testing was considered, and it appeared to provide a reasonable measure of bond strength. In this test, two layers of the strip were pulled away from each other in opposite directions and almost in a perpendicular direction to the remaining unpeeled strip. The standard test specimens were 25.4 mm (1 in.) wide and 228.6 mm (9 in.) long (bonded length), with unbonded layers bend 90 ° apart before pulling. Although this test had been originally designed to measure the peel resistance of adhesives, it allowed tearing of all specimens from the interface, and therefore, a comparative measurement of the weld strength became possible. Strength of the bond was measured in terms of the energy required to peel the layers (break the cold weld) per unit area of the interface, according to the following equation:

$$U_P = \frac{F \cdot l}{w} \qquad [2]$$

where w denotes the width of strip; l is the crosshead movement of the machine corresponding to one unit length of interface debonding; and F is the average peeling load. This energy was measured during the steady-state breakage of the bond, where the pulling load reduced to a stable value after an initial overshoot. The experiments were conducted on an Instron machine, and peeled specimens were stored for subsequent electron microscopic examination of the interface. The test procedure is given in detail in Ref 1. Figure 10 depicts the variations of the cold weld strength for a bi-layered strip of aluminum/mild

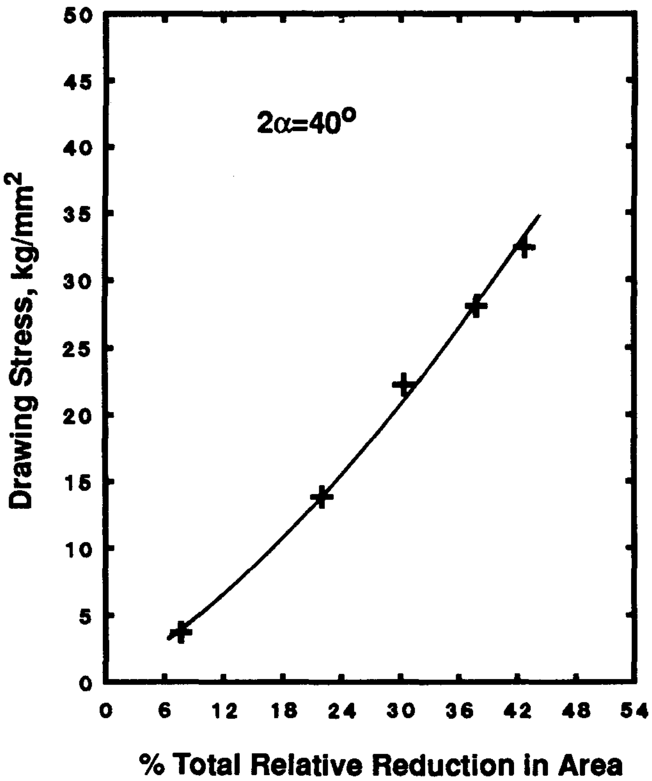

Fig. 8 Drawing stress versus percentage of total relative reduction in area for the bi-layered strip of aluminum/mild steel. Die angle = 40°.

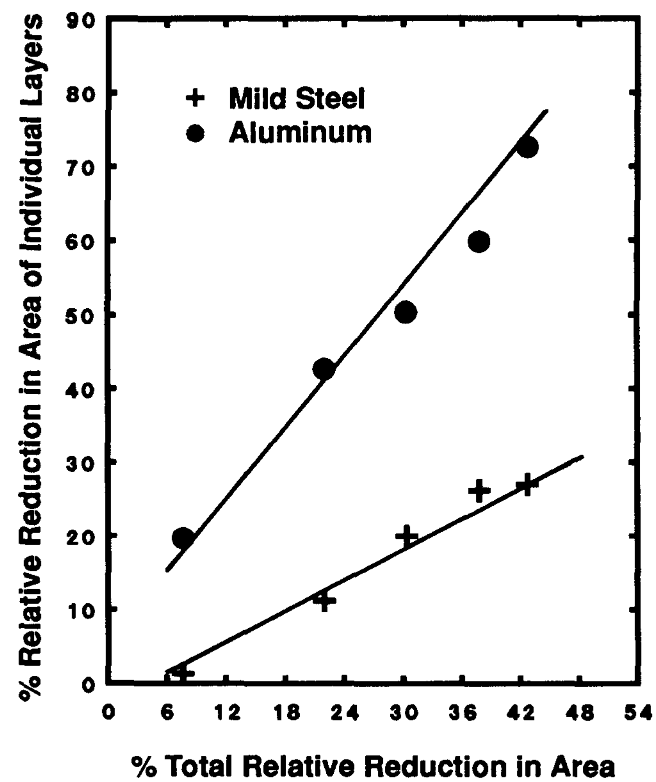

Fig. 9 Relative reduction in area of individual layers in a bi-layered strip of aluminum/mild steel. Die angle = 40°.

steel. These variations are shown as a function of the total relative reduction in area of strip.

3.4 *Surface Texture*

The surface texture of a number of strip was examined using a scanning electron microscope. Figure 11 shows the texture of an aluminum layer before it was drawn to make a bi-layered aluminum/mild steel strip. Figure 12 shows the same surface after it was drawn and subsequently peeled to expose the interface. The welded regions are seen clearly in this picture. Figure 13 shows the surface of a copper strip after the drawing and peeling processes. The cracks observed on the surface of this specimen are due to the drawing process. The cold weld strength of this particular specimen was found to be quite low, such that peeling could be done by exerting a small force by hand. This small (almost zero) peeling force eliminated the possibility that these cracks had formed during the peeling process. The weak cold weld of this specimen might be due to a small relative sliding between the layers, as discussed in the next section.

4 Discussions and Conclusions

The experimental results as discussed above reveal that manufacture of bi- and tri-layered strip by a drawing operation is feasible. Formation of the cold weld at the interface, however, requires a minimum amount of deformation (reduction in area). The requires deformation decreases as the die angle increases. As shown in Fig. 10 for the case of aluminum/mild steel strip, the cold weld does not form for reductions in area less than about 8%. An increase in deformation, however, causes a rapid increase in the cold weld strength of this combination.

Formation of the cold weld in the drawing process has been attributed to a number of different phenomena. However, most researchers relate formation of the cold weld to the breakage of the surface oxides, formation of cracks at the interface, and therefore exposure of the virgin metal inside the cracks.[2-8] The latter causes the virgin metal of the two strips to form a cold weld under pressure. Microscopic investigation of the surface texture verifies the above hypothesis. As shown in Fig. 13, the drawing process has caused a large number of cracks to appear on the interface surfaces of the material, which expose virgin metal. Brushing of the interface surfaces before deformation may also cause a layer of work-hardened material, which in turn helps the crack formation. New surfaces of oxide-free materials are formed on each side of the interface, which will come into contact with each other under pressure inside the die and thus form a cold weld. Accordingly, it is expected that any parameter that expedites the formation of interface surface cracks will aid the cold weld process. It has been reported, for example, that a relative sliding motion of the two materials during the forming process causes the surface oxides to break and

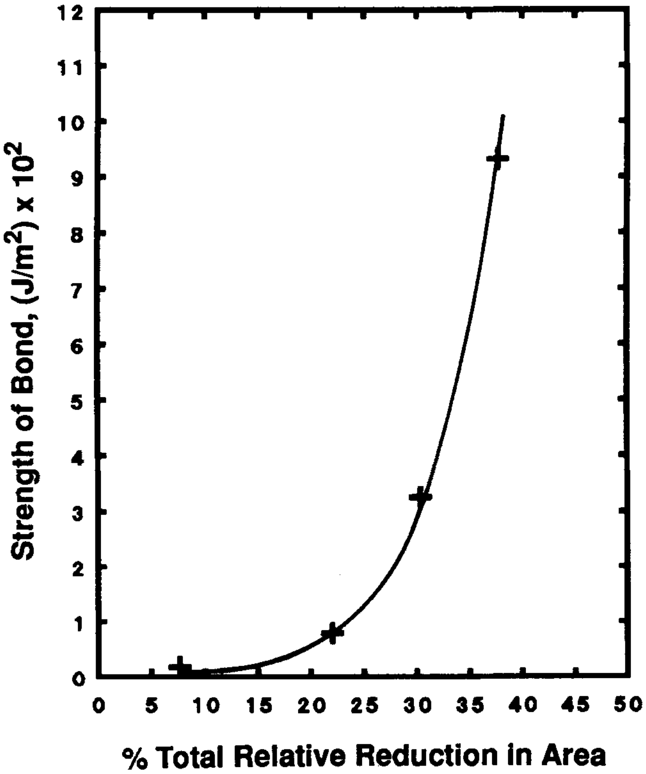

Fig. 10 Strength of the cold weld interface versus total relative reduction in area for bi-layered strip of aluminum/mild steel.

therefore helps cold weld formation.[9] Results of the present research also verify the same conclusions. As shown in Figs. 5, 6, and 9, the individual layers in a bi- and tri-layered strip undergo different amounts of deformation, and therefore, relative motion occurs between them. As the dissimilarity between the strengths of layers in the strip increases, the difference in thickness reductions of the layers also increases. This, in turn, causes a more relative sliding motion to occur between the layers and therefore promotes formation of the cold weld. Comparison of Figs. 5 and 6 reveals that an increase in die angle also causes the difference in deformation of layers to increase, and therefore, relative motion between layers increases. The increase in relative motion then causes a stronger interface cold weld.

It should be noted that breakage of oxide film and exposure of the virgin metal are not sufficient conditions for formation of an interface bond. A strong cold weld requires relatively high deformation to occur in both the softer and the harder metals.[10-13] As shown in Fig. 10, an increase in the total relative reduction in area causes a rapid increase in the strength of the weld. A strong bond is achieved with about 37% reduction. In reference to Fig. 9, this amount of total reduction in area causes considerable deformation in both the softer and harder layers.

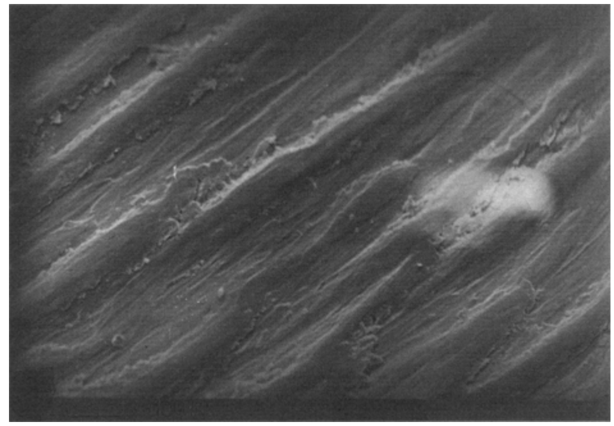

Fig. 11 Scanning electron micrograph of aluminum surface after it was brushed and before drawn to make a bi-layered strip of aluminum/mild steel. Magnification 200 ×.

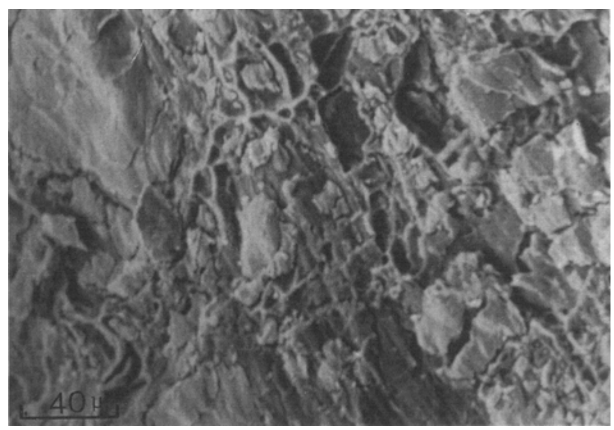

Fig. 12 Scanning electron micrograph of aluminum surface after it was drawn with mild steel to a reduction in area of 40.5% and subsequently peeled. Magnification 500 ×.

Acknowledgments

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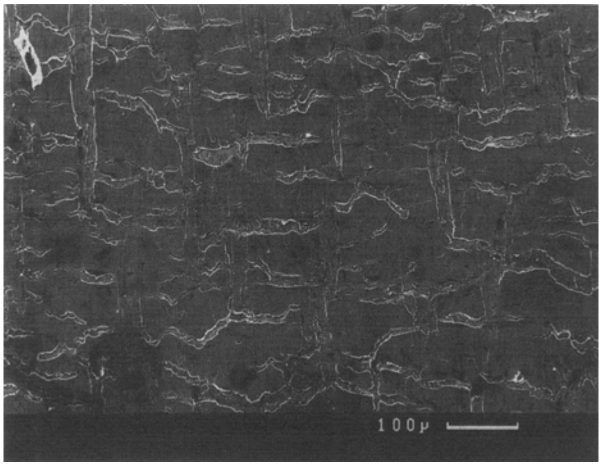

Fig. 13 Surface of copper after drawing with reduction in area of 38.6% and subsequent peeling, in a tri-layered strip of aluminum/copper/aluminum. Magnification 121 ×.

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