SIMULTANEOUS CASTING OF ALLOY COMPOSITES*

G. J. Binczewski and W. K. Kramer

Abstract

The cladding of direct chill ingots by the simultaneous introduction of two different alloy liquids into the mold has been accomplished on a production basis. The technique utilizes the effect of spontaneous spreading of a liquid on a solid according to the surface tension expression $F_s > F_{lv} + F_{sl}$. The method presents the opportunity for many manufacturing benefits and unique product effects.

Eliminating the edge cracking of highly alloyed ingots during rolling has been achieved by cladding the ingot edges with a "low strength" alloy. The detrimental tensile forces at the edge of the sheet are reduced in magnitude by the plastic flow of the low strength alloy. This mechanism precludes the fracture, manifested as the edge crack, which would ordinarily occur in the uncladded core alloy edge under the given fabricating conditions.

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*A motion picture illustrating the actual casting process was shown during the presentation of this paper at the Feb., 1972 AIME Annual meeting in San Francisco, Calif.

Introduction

The utilization of composite metals to achieve certain described characteristics and final product effects has long been recognized in the metals industry. Various combinations of totally different metals or different alloys within the same base metal group are utilized for a wide variety of purposes which may be impossible or extremely costly to achieve by any other means. Metallurgical integrity of the structure, especially in the transition zone between the materials, is normally the primary factor which ultimately determines the success or failure of a process or an application.

A plethora of techniques have been, and are being, used to achieve the necessary bonding. (For purposes of subsequent clarity, the bonding will be referred to as cladding for the balance of this paper.) An analysis of the most popular and well known methods shows that they can be quickly classified into a few categories which utilize the following principal criteria:

1) Heat
2) Pressure
3) Surface Coherency

By application of any one or a combination of the above variables, virtually all of the familiar processes are covered, i.e., pressure welding, rolling, hydrostatic bonding, fusion welding, soldering, dip coating, brazing, electroplating, vacuum deposition, surface abrasion, flame spraying, etc.

The simultaneous casting of clad ingots of different metals or different alloy composites has intrigued cast shop metallurgists for decades. Indeed the first patents for such a product were issued more than 80 years ago in the steel industry (1), and there have been many others since that time. While technical feasibility may have been demonstrated, the various projected procedures generally failed the equally demanding economic and quality criteria. The aluminum industry has had its share of approaches to this problem. But today, in aluminum as in other metal industries, virtually all of the commercially important clad composites are manufactured by a combination of the pressure-heat process. This involves the bonding of two solids subsequent to the casting operation. More specifically, a solid or one alloy, usually a fabricated plate of predetermined thickness and surface condition, is cladded to a cast ingot or bloom by hot rolling or forging techniques.

Several notable attempts have been made in the aluminum industry to achieve the cladding by utilizing a solid-liquid approach. These efforts while partially successful have not been able to match the economic and quality results obtained by the solid on solid. These procedures could be broadly classified into two categories:

1) Pouring a liquid alloy around the periphery of a previously cast and solidified core which may have been heated or unheated.

2) Pouring a liquid (which would comprise the core) into a previously fabricated container of the clad alloy which acted as a mold.

Most often, the mechanics of the familiar D.C. casting process were used to make these composites. Complete bonding of the composite interfaces was usually not achieved. The latter was not an absolute requirement since final bonding could be effected during the subsequent hot working phase of the composite casting. Unfortunately, these efforts, while technically successful, have not been able to match the economic and quality results by the solid on solid fabrication procedures.

An Approach to a Rolling Problem Solution

The approach to simultaneous cladding during the casting operation was motivated by the edge cracking problems which have historically been a problem in sheet rolling operations (2). Edge cracks cause cobbles in the hot mills and lead to strip breaks in the cold rolling and continuous tension leveling operations. All of these effects result in lower metal recoveries, lower equipment efficiencies, and most importantly, higher costs. The combined net result is lower productivity.

There have been many published investigations into the causes of edge cracking during strip rolling. Basically, three factors have emerged as the principal contributory variables: 1. Composition. Under equivalent rolling conditions, some alloys are inherently more prone to exhibit edge cracks. Edge cracking tendencies increase with increasing strength of the alloy and/or increasing magnesium contents. Also, the effect of some impurities, most notably sodium, can have dramatic effects on edge crack occurrence and severity. 2. Structure. Within some alloy systems the solidification rate can have a dramatic effect. 3. Mechanical Effects. During the D.C. casting process such things as minor cold folding, liquation banding, and seemingly minor bleed outs can cause severe edge cracks.

Historically, the approach to circumventing the edge crack problem has been to increase the amount of edge trim that is taken at the various mill operations. On some alloys as much as 20% of the original hot rolled width is subsequently trimmed away in order to assure freedom from edge cracks.

A Simple Rolling Analogy

The classical and basically simple examination of the state of stress which exists in the rolling operation suggested a method of approach to the solution of the edge crack problem. A casual analysis of the applied rolling forces prompts an expectation that the existing stresses would be compressive and the capacity for deformation of the rolled metal would be much greater than normally observed. In practice, however, cracks develop on the edges of rolled sheet much sooner than expected under given conditions and a careful perusal indicates that the reason for the cracks is the existence of tensile forces on the edge of the sheet.

In sheet rolling, it is the roll opening which basically determines the reduction of thickness. If we make the assumption of a constant uniform roll opening across the width of the roll, the metal is actually observed to elongate a greater amount down the center of the sheet than at the extreme edges. The functional forces which are exerted by the rolls on the metal cause it to flow both parallel and transverse to the rolling direction in proportion to the frictional forces exerted upon it by the rolls. The magnitude of the frictional force tending to keep the metal from extending in any direction is proportional to the nearest free surface. This is always a short distance in the rolling direction being never more than one half of the arc of contact between the roll and the metal. However, in the transverse direction the distance to the nearest free surface is generally much greater than this, up to one half the full width of the sheet. As a result, the extension in the transverse direction is virtually zero in the center of the sheet, and the change in length is equal to the change in thickness. But at the edge of the sheet a different set of conditions prevail and the incremental distance to the nearest free surface may be less in the transverse direction than in the longitudinal, and the extension is divided between transverse extension and elongation in the rolling direction. Since the three principal strains must be equal to zero, and since the thickness is determined by the spacing between the rolls, the sum of the longitudinal and transverse elongations must be equal to the change in thickness. Under these conditions the extension in the longitudinal direction must be less at the edge of the sheet than at the center (of the width). It, therefore, follows that the edge must be under tensile stress in the longitudinal direction. It is the existence of this tensile stress which initiates edge cracking.

The tensile stress at the edge of a sheet exists in both hot and cold rolling operations. It is the magnitude of this tensile stress in combination with the metallurgical characteristics of a particular alloy which determines both the initiation of an edge crack and the extent of its propagation. Of course, the conditions of rolling must also be considered and such factors as roll shape, speed, lubrication, and the superimposed tensions between stands and terminal equipment cannot be totally ignored. In fact, much can be done in the latter area to alleviate the effect of edge cracks. However, efforts directed at controlling the primary crack occurrence mechanism present the best opportunity for eliminating edge cracks.

A Proposed Solution

In aluminum rolling operations, the lower strength alloys such as 1145, 1100, 3003, and 7072 are observed to be essentially free of edge cracks. Combining the elements of the previous mechanism analysis with the above observations suggests that cladding a low strength alloy on the edges of a higher strength alloy which is prone to edge crack would prevent the cracking. Two effects are proposed:
1. The free surface at the exposed edge is moved further away from the parent core alloy which should decrease the magnitude of the tensile forces in the transition zone.
2. The higher purity alloy on the edge will accommodate the edge tensile forces generated during rolling by plastic flow rather than by fracture.

This proposal suggested that the edge cladding be achieved during the casting process rather than by roll bonding through edge rolling procedures. Since casting techniques to achieve this did not exist, a casting development program involving time and expense was indicated. However, to prove the merit of the proposal with respect to the end effect of eliminating cracks, a simulated casting approach was used.

Several ingots of the high strength alloy 5086 were clad on the edges with a low strength 1100 alloy. The ingots measured 18" x 40" x 120" and the clad alloy was deposited on the ingot core thicknesses from 0.75" to 1.0" by the large electrode heliarc welding technique (3) as illustrated in Figures 1 and 2. A typical welded clad edge ingot is shown in Figure 3.

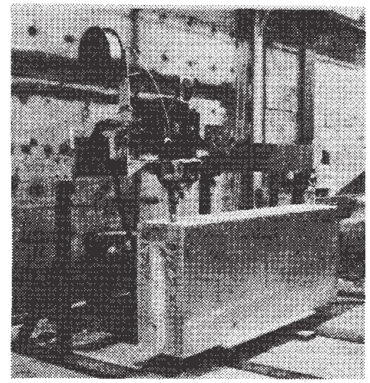


Fig. 1. Welding fixture with ingot in position for edge welding.

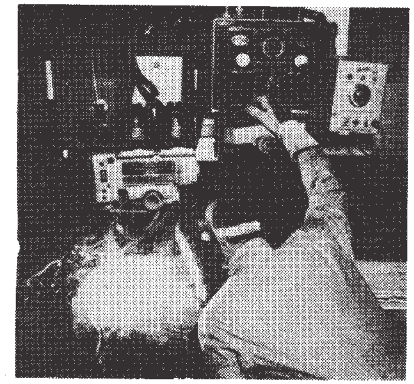


Fig. 2. Action illustration of welding operation.

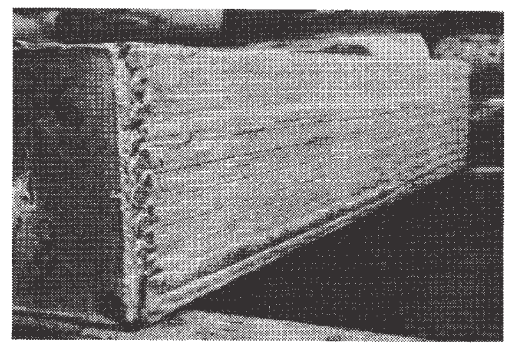


Fig. 3. Edge of weld cladded ingot prior to rolling.

To reduce the effects of potential variables to a minimum, only one edge was clad on several ingots to allow direct comparison of the clad versus the unclad edge. These ingots were hot rolled to a nominal 0.100" thickness with no edge trim. The clad edge showed no evidence of edge cracking and was characteristic of 1100 alloy while the unclad edge contained the severe edge cracks characteristic of the 5086 alloy. (In normal operations, the cracked edges are simultaneously slit away during the hot mill coiling operation to preclude strip breaks during cold rolling.)

Additional cold rolling of the experimental coils down to 0.010" thickness further verified the projected behavior that the clad edge was not prone to edge cracking. The favorable results indicated that the project to develop a casting procedure for applying the clad edge was justifiable.

Simultaneous Casting of a Clad Ingot

The authors initial attempts to cast a clad ingot by introducing both alloy liquids into the direct chill mold simultaneously were aimed at direct liquid-liquid contact with a suitable quiescent baffle arrangement. While successful results were achieved with this approach, the continuous control problems which it presented to a production oriented operation were too formidable for the process reliability desired. To circumvent this difficulty, the liquid-solid method was developed. This involved the simultaneous introduction of two liquids into the mold. A small embryo "ingot" of the clad alloy was generated and the liquid of the core alloy contacted it immediately to effect the necessary bond. A schematic cross section of the mold area appears in Figure 4.

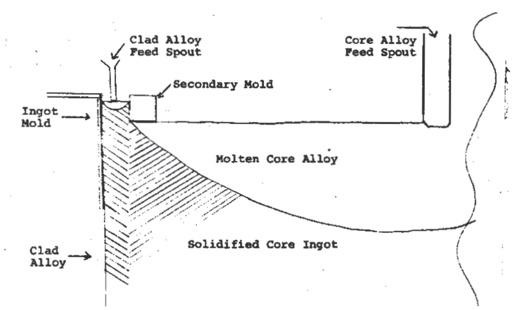


Fig. 4. A schematic of the casting process showing one half of the ingot section. The thickness of the ingot is perpendicular to the view and the width is transverse from left to right.

The initial phase of this work required the development of a procedure for the "low strength" alloy casting control. The lowering rate of the composite ingot would be limited by the casting characteristics of high strength core alloy. Since an ingot of 5086 alloy with an 18" x 40" cross sectional area was being cast with a 1.0 inch thick clad edge at a nominal lowering rate of 2.0 inches per minute, the clad edge volume amounted to a 1" x 18" x 2" or 36 in^3 which required a casting rate of 3.6 lbs/min spread over the disproportionate dimensions of 1" x 18" cross section. The technique necessary to accomplish this was successfully perfected and the end product was as illustrated in Figure 5.

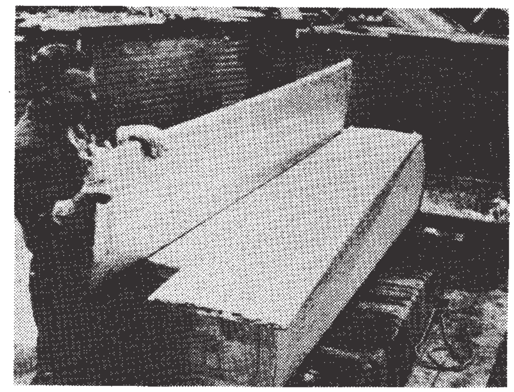


Fig. 5. As cast 1 in. x 18 in. x 120 in. "ingot" of the cladding alloy cast at a rate of 3.6 lbs/min.

Casting the Full Composite

Subsequent development work with the full composite revealed which casting process variables were most critical to the achievement of a bond between the two alloys. The temperature of both alloys at the time of contact between them was a very significant factor and experimentation indicated the temperature latitude which could be tolerated. Metal condition with regard to such factors as cleanliness and fluidity proved to be of secondary importance but could not be ignored.

An entire series of full production size ingots weighing 10,000 pounds each were successfully cast. The typical appearance of the full size clad-composite ingots is shown in Figures 6 and 7. Etched, cross sectional slices from several ingots are illustrated in Figure 8.

The subsequent fabrication sequence was: 1. Scalp the ingot faces. 2. Homogenize. 3. Hot roll in continuous sequence; a. Reversing mill to 6.0 inches thick, b. Reversing mill to 1.0 inches thick, c. Continuous mill to 0.100 inches thick. 4. Cold roll to 0.010 inches.

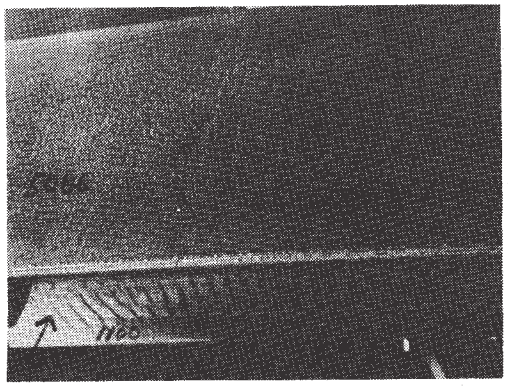


Fig. 6. As cast composite ingot showing clad edge (arrow). Face of ingot is 5086 core alloy.

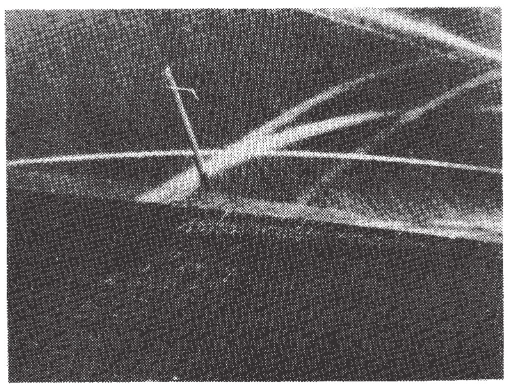


Fig. 7. Scalped ingot face. Pencil points to bonding line between the dark appearing core alloy and light appearing edge clad alloy.

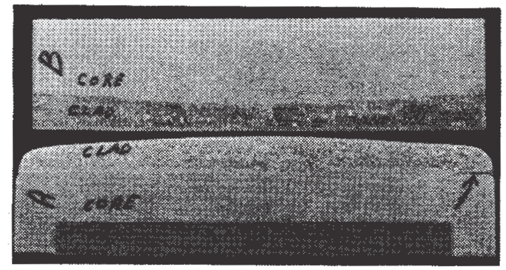


Fig. 8. Etched cross sectional slices from edge clad ingots showing some different designs used. Arrow points to a small area of a lack of bonding in specimen A.

Slitting of the clad edge was purposely omitted to appraise the total effect on the elimination of the edge cracks.

A series of coils rolled from ingots with only one edge clad are illustrated in Figures 9, A and B, at the hot mill thickness of 0.100 inches. Figure 9A illustrates the appearance of the unclad as-cast edge of the 5086 core alloy and shows the typical edge cracking experienced with this condition. Figure 9B is a closeup view of the identified coils of Figure 9A. The opposite, untrimmed clad edge of the same coils in Figure 9 are shown in Figure 10. The complete absence of edge cracks is apparent.

The coil identified as number 1 in Figures 9 and 10 presents a special case of an attempt to isolate the effects of potential variables in the casting and/or fabricating process. The cladding was applied to only one half of the length of one ingot edge which resulted in the remainder of this edge having the normal liquated appearance and effect of the 5086 alloy core. The opposite edge of the ingot was not clad and contained the normal liquated core alloy edge. A 1.0" thickness of this "normal" edge was machined away for the entire edge length to simulate the effect of edge scalping compared to edge cladding on edge crack occurrence. (Scalping of the as-cast ingot edges has long been known to improve the fabricated edge condition, but has not been commercially utilized because the cost of the operation was not generally commensurate with the results obtained.) Thus, in this single ingot, the variables of ingot composition, casting conditions, homogenization, hot rolling, and cold rolling were eliminated. An examination of both sides of coil number 1 in Figures 9 and 10 illustrates the comparative effect of edge cladding versus edge scalping versus the normal as-cast edge. In Figure 9 the inside wraps are the clad 1100 alloy edge portion, while the outside wraps are the normal, unclad, as-cast ingot edge of the 5086 alloy. No edge cracking at all is visible in the inner clad wraps while gross edge cracking is evident in unclad, as-cast outer wraps of the core alloy. In Figure 10, the scalped opposite edge of coil number 1 shows that relatively uniform small edge cracks to a depth of 0.125 inches occurred. While edge scalping obviously reduced the severity of the edge cracks when compared to the normal, as-cast, core alloy edge, a slitting operation would still be required prior to cold rolling since these cracks would cause strip breaks during cold rolling or tension levelling. The clad edges exhibited no edge cracking and could be cold rolled in final thickness without slitting.

Fig. 9.A. A series of untrimmed hot rolled coils at 0.100" thickness showing severe edge cracks on the unclad 5086 core alloy. The inner portion of coil number 1 is an untrimmed clad edge.

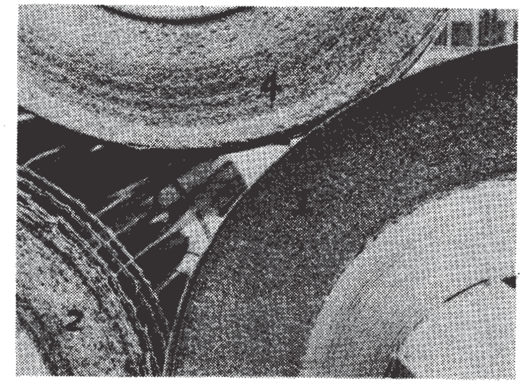


Fig. 9.B. A closeup view of coils 1, 2, and 4 of Figure 9A. Note the severity of the edge cracks in the 5086 core alloy and the complete absence of edge cracks in the 1100 alloy clad portion of coil 1.

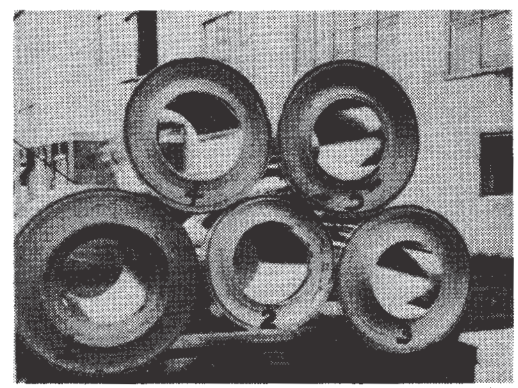
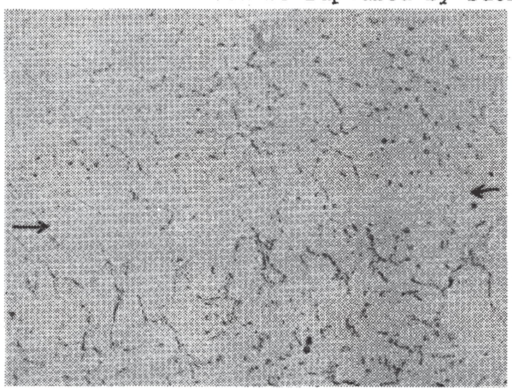


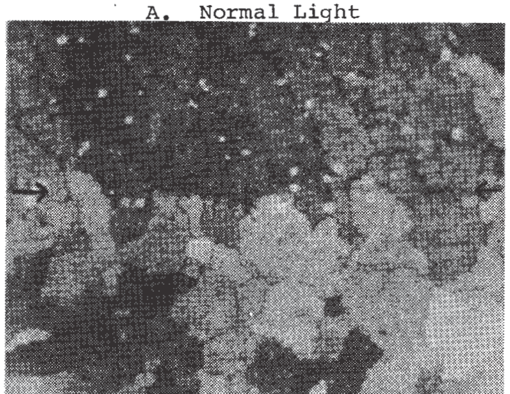
Fig. 10. Opposite side view of the same coils of Figure 9. Coil 2, 3, 4, and 5 are the untrimmed clad edges and exhibit no edge cracks. Coil 1 is the untrimmed scalped edge of the 5086 core alloy and shows small edge cracks but of considerably lesser severity than the opposite unscalped edge of Figure 9.

Evaluation of the Bonded Area

The bonding area between both alloys of the clad composite was sharp, distinct, and metallurgically continuous as illustrated in Figure 11, A and B. Extensive microstructural surveying of many interface areas showed that the desired effect was achieved. The integrity and continuity of the interface is further indicated in Figure 12 which shows the interfacial areas from as-cast ingot sections subjected to various types of mechanical deformation. In no case could the interface area be ruptured by such tests.



A. Normal Light



B. Polarized Light

Fig. 11. Microphoto of the as-cast interface between the 1100 clad alloy (top half of picture) and the 5086 core alloy (bottom half). Continuity is complete and no imperfections are visible. Unetched, X100.

Fig. 12. Mechanically deformed specimens of the as-cast clad core interface areas showing integrity of the bond. A was bent transversally until a crack occurred in the 5086 alloy. The crack stopped at the clad 1100 alloy and did not affect the bonded interface. B represents a 90° zero "T" bend at the bonding line. C are some machine chips from the A specimen etched to reveal the bonding line arrow and demonstrate the bond integrity. D is a 150° bend.

A more emphatic illustration of bond integrity is indicated in Figure 13. In the course of the development, this particular ingot resulted from a deliberate change in casting conditions after normal bonding had been achieved. Attempts were made to dislodge the bonded portion of the cladding by trying to raise and lower the 10,000 pound ingot with an overhead crane sling as indicated. Dynamic conditions similar to a person operating a yo-yo were used but were unsuccessful. The cladding strip finally fractured near the sling area.

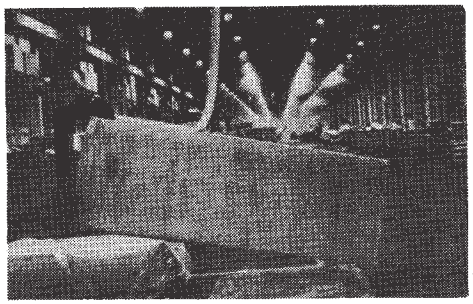


Fig. 13. Ingot suspended from an overhead crane by a partially edge clad liner. Attempts to dislodge the remainder of the cladding from the bonded area were unsuccessful.

Discussion

The authors attempts to achieve the simultaneous bonding during the casting operation were directed at an application of adhesion theory and establishing and controlling those variables associated with the wetting of a solid by a liquid according to the expression $F_s > F_{lv} + F_{sl}$. This states that spontaneous spreading of a liquid on a solid occurs when the surface tension of the solid is greater than the sum of the surface tension of the liquid in contact with its vapor and the interfacial tension between the solid and the liquid (4). While direct measurement of these conditions proved to be extremely difficult under the operating conditions employed, the temperature conditions were indicated to be the most important single variable. They could be influenced by various means such as molten metal temperature control, external cooling rate, and casting speed. The sharp microstructural demarcation between the two alloys and the complete absence of any evidence of a fusion (melting) type bond further affirmed the "wetting effect" result.

Several design changes were necessary before a totally reliable process was achieved on a production basis. The shape of the cladding layer was changed several times as indicated in Figure 8 which shows partially unbonded edge areas in Item A.

Whenever a non-bonded area was encountered, it became apparent during the rolling process. Essentially the unbonded interface areas were observed to perform similar to the characteristics of the separate alloys. The extreme clad edge of the rolled coil would appear normal and free of edge cracks, however, at the interface between the clad and the core alloy, "normal" cracks would be observed in the core alloy. This effect is illustrated in Figures 14 and 15 at intermediate and final thickness. The severity of these crack occurrences were directly relatable to the extent of the unbonded areas. Experienced rolling mill operators commented that strip breaks would have resulted if the cracking illustrated by Figures 14 and 15 had not been restrained by the clad alloy and had penetrated to the edge of the strip.

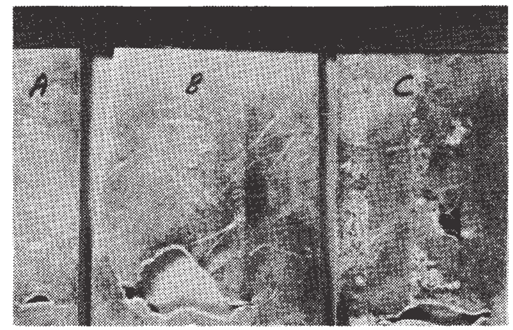


Fig. 14. Cracks in core alloy which result when non-bonded areas are rolled. The cracks stop at the clad alloy interface and do not extend to the edge of the sheet.

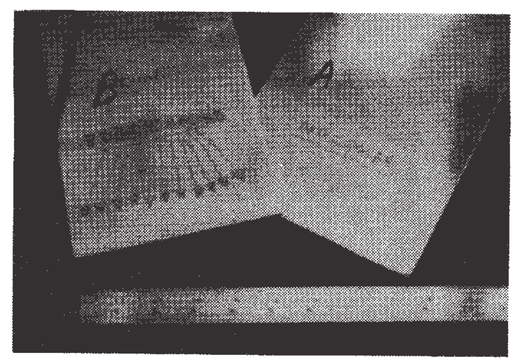


Fig. 15. Untrimmed clad edge strip cold rolled to 0.010 in. Note the cracks in the core alloy of B which resulted from an unbonded clad-core interface area. Specimen A shows the complete absence of any edge cracks and results when bonding is complete.

Conclusion

An extension of the simultaneous clad casting of ingot composites from the initial purpose of this development to eliminate edge cracks is self evident. Direct application to the normal cladding of ingot faces for the appearance, corrosion resistance, or economy effects can be directly accomplished and thereby eliminate many of the intermediate steps required in the conventional solid to solid bonding in general use. The method greatly extends the combination of alloys which can be used as composites. Also, present industry techniques have a limit on the relative thickness or percentage of cladding which can be applied while the casting development makes this limitless, from extremely thin to 50% or more. Extension of the process to other metals and dissimilar metal composites is straightforward.

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