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A STUDY OF ROLL-BONDING MS90 ALLOY TO STEEL UTILIZING CHROMIZED INTERLAYER*

B. TOLAMINEJAD** AND H. ARABI

Center of Excellence for Advanced Materials and Processing (CEAMP)
Dept. of Metallurgy and Materials Engineering, Iran University of Science and Technology(IUST), Narmak, Tehran, I. R. of Iran, Email: btolaminejad@iust.ac.ir

Abstract– This article describes a study of the application of a roll bonding technique to MS90(CuZn10) alloy strips and steel sheets using a chromized interlayer. It was found that the overall bond between these two metals resulted from two different types of bonds: a block bond, linking the MS90 alloy strips and chromium topcoat layer, and a blank bond, linking the MS90 alloy strips and bare steel surface in the area where the chromium coating has been fragmented. This study investigated the effects of plating time on the thickness of the coating layers and of the area fraction of the blank bond on the bond strength. The overall bond strength depends mainly on the strength and the area fraction of the blank bond. A linear relationship model exists between the overall bond strength and the area fraction of the blank bond. The bond strength of the blank bond was eight times greater than that of the block bond. The area fraction of the blank bond increased with increasing the coating thickness up to 55 μm, but thereafter decreased due to the rotation of the chromium blocks.

Keywords– MS90, roll bonding, steel, chromized layer, bonding mechanism

1. INTRODUCTION

Cold roll bonding processes take place at room temperature[1-3],and evidence of no solidified and cast structure at the interface has indicated no liquid or metal phase is formed, and therefore, a direct bond emerges in the solid state [4, 5].The external pressure, mechanical work and plastic deformation applied on the interface zone supply the activation energy for cold roll bonding [1,3]. Roll bonding is the establishment of an atom-to-atom bond between two pieces to be joined through intimate contact between contamination free areas [6-8].During the last three decades, the production of sandwich strips by the rolling process, a more efficient and economical approach compared to other types of processes, has become an increasingly important subject of study among researchers [9-12]. Bimetallic sheets and strips of steel and copper alloys are among the most successful types of laminated composites in use because of the comprehensive properties derived from the component materials. However, production of bimetal of copper alloy strips and steel sheets using existing solid-phase cold rolling techniques pose problems of low primary bonding strength, extraordinarily high reduction (about 70%) to ensure good bonding and high work hardening, which, when combined, serve to limit their further application [13]. Annealing heat treatment offers a promising solution, but the occurrence of the fragile oxide layer on the surface of steel sheets prevents the development of a strong bond if the operation is carried out in an environment without a protective gas cover. Electro plating is widely used to enhance the oxidation resistance of steel sheets at

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**Corresponding author

elevated temperatures. Of course, it should be mentioned that the effect of different coatings on the strength of the produced composite is variable.

In this study the chromium topcoat layer also has an oxide layer on it's surface. However, this oxide layer was very thin and tightly adherent, unlike that on the steel. Thus, the problems associated with a fragile oxide layer when attempting annealing can be solved, to a great extent, through the use of the chromium topcoat as an interlayer. The main purpose of this paper was to investigate the mechanism of interface bonding and to determine the factors that influence the bonding strength of bimetallics formed by rolling MS90 alloy strips and chromized steel sheets.

2. EXPERIMENTAL

a) Fabrication of MS90 alloy strip and hard chromized steel sheets

The base alloy, Cu–10.2% Zn–0.07% Fe–0.05% Pb, was charged into a crucible kept in a resistance-heated vertical muffle furnace. When the melt reached 1100°C, the furnace was switched off, the crucible taken out of the furnace, and the agitated melt poured into a steel mold. The cylinder ingot obtained was then extruded into strips of 45 mm width and a thickness of 0.4 mm at 800°C. The steel sheets of composition (in wt.%) Fe–0.54 C–0.35 Mn–0.0220 P–0.0014 S were cut into strips having dimensions of 75×50×3mm prior to chromizing in order to produce a satisfactory sound metallurgical bond [14]. The sheets were then degreased, rust removed and fluxed. After being rinsed with deionized water, the specimen was immersed in a chromium plating bath containing Pb-2.5%Sb anode, 300 g/l of chromic trioxide, 3 g/l of sulfuric acid at 53°C and 28 A/dm^2 for different times (10–60min). So various coating layer thicknesses were obtained by hard chromizing the steel in a bath of hard chromium. After chromizing, the specimens were cut into rectangles of about 25 mm^2 in area, carefully mounted, ground and polished to protect the edges. The specimens were etched with 3% nital and a solution of 25 g $FeCl_3$, 20 ml HCl, 100 ml H_2O to reveal the coating layer to be measured. The thicknesses of the coating layers were measured using a Nikon light microscope.

b) The roll bonding of MS90 alloy strips and chromized steel sheets

The main steps taken for welding MS90 alloy to steel by the cold rolling process were as follows:

1. The surfaces of both MS90 alloy and steel were cleaned to remove surface contamination.
2. The MS90 and steel strips in a pack were aligned.
3. Then the pack was cold rolled (Fig. 1) to produce a metallic continuity between strips at the interface.

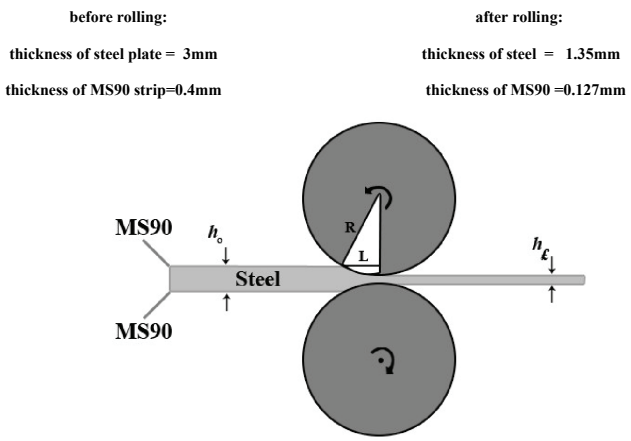

Fig. 1. Cold roll welding of MS90/Steel pack

For roll welding MS90 to steel, a roll pressure between 1000 to 3400 MPa and a threshold reduction of between 40 to 80 percent has been reported [3, 15]. This threshold reduction greatly depends on the surface treatment and the magnitudes of rolling parameters such as the diameter, rigidity and surface roughness of the roll, preliminary thickness of each layer before rolling and the geometry of the deformation zone. A small part of the surface at one end of the chromized steel sheet facing the MS90 alloy strip was then smeared with graphite. This was done to prevent bonding between the strip and the sheet at this particular interface during subsequent rolling. Finally, one of the steel sheets was placed in-between two MS90 alloy strips, and were immediately rolled together with an overall reduction of 56% to make a triplex plate. The triplex plate was then annealed at 700°C for 1hr. The quantity of the bond strength of the clad metal sheets were measured using the peeling test according to ASTM-D903-93. The results of peeling a triplex strip along the bond line are only dependent on the real metallurgical properties of the bond. In the peeling test the breaking off force is measured as follows, Fig. 2:

$$\text{Average peel strength} = \frac{Average\,Load}{Bond\,Width} \tag{1}$$

The peeling test was performed using an Instron tensile testing machine with a 1 KN load cell. The mean peeling force was measured by a clamping configuration illustrated in Fig. 3. A crosshead speed of 5 mm/min was used in the tests. The repeatability of the tests and the sensitivity of the load cell were 0.5 N and 0.1 N, respectively.

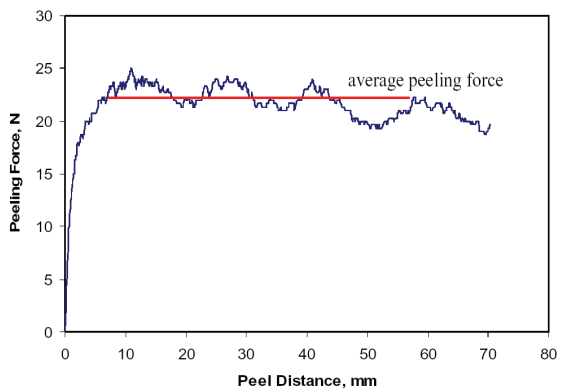

Fig. 2. The peeling force versus peeling distance and the method of calculation of average peeling force

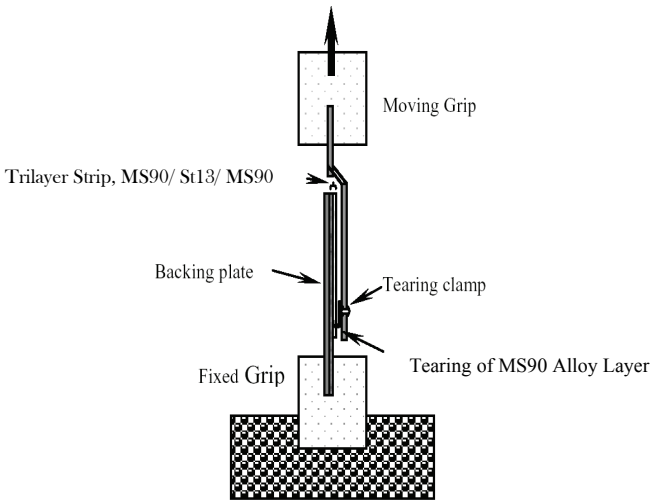

Fig. 3. Configuration of peeling test used in this investigation

3. RESULTS AND DISCUSSION

a) Morphology of the hard chromium layer

Following the chromizing at 53°C for the various times, the chromized layers were examined in the cross section. The thickness of the coating layers was measured and found to increase with increasing dipping time (Fig. 4). The data follow a parabolic relationship between thickness and dipping time, similar to those obtained for aluminizing by other researchers [16, 17]. The dependence of the bond strength on coating thickness is discussed in section 3b.

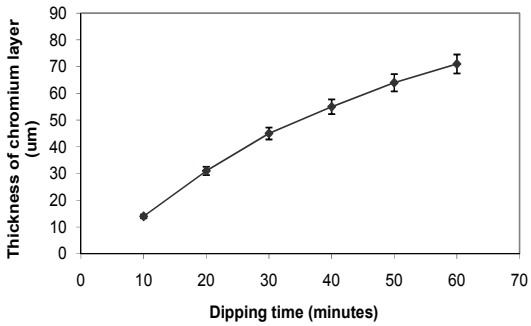

Fig. 4. The variation in the thickness of the coating layer with dipping time

b) Bonding strength

The variation of bond strength (peeling force) with dipping time for MS90/steel specimens is shown in Fig. 5. It shows that the bond strength increases with dipping time up to 40 min and decreases at longer times. It was observed that the dipping time had no effect on the occurrence, intermetallic and composition, but only on its thickness (Fig. 4) in these experimental situations. Thus, it was thought that the relationship between bond strength and coating thickness might be more direct than that between bond strength and dipping time. Therefore, the variation in bond strength with the coating thickness is plotted in Fig. 6. It is apparent that the bond strengths of the MS90/steel specimens increase with the hard chromium thickness up to 55 μm, but thereafter decrease.

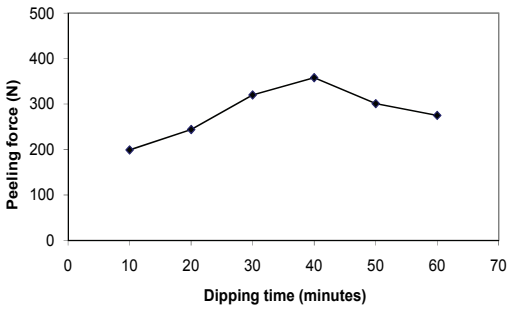

Fig. 5. The variation of peeling force with dipping time

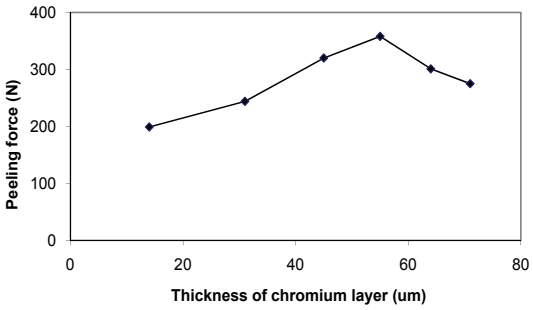

Fig. 6. The variation of peeling force with thickness of the coating layer

c) Bonding mechanism

Figure 7a shows a longitudinal section of a bonded specimen of an MS90 alloy/chromized steel sheet. It is clear that, in the rolling direction, the coating layer breaks into blocks, and blanks form between them. Figure 7b and the low magnification (Fig. 7c) are SEM micrographs of the fractured interface on the steel

side. The wider blanks in the direction of rolling are parallel to each other across the surface of the steel substrate. There are also narrower blanks perpendicular to the direction of rolling.

The formation of these blanks is due to the fact that, during the roll bonding, the steel substrate elongated in the direction of rolling, but the coating layer broke into small blocks, being unable to elongate along with the steel substrate because of its brittleness. The same practice also occurred for those blanks perpendicular to the rolling direction. In these experimental situations, the length of the longitudinal blanks was much greater than that of the transverse blanks, as shown in Fig. 7b. Therefore, in the rolling process, both the MS90 alloy strips and the chromium topcoat layer adjacent to the steel layer elongated in the direction of rolling and were simultaneously extruded into blanks to fill them. Thus, two different bonding processes took place. The MS90 alloy was bonded to the chromium blocks layer (block area).Meanwhile, the MS90 layer was bonded to the steel substrate in the blank area. The positions of the interfaces mentioned above are sketched in Fig. 8. Obviously, the overall bond strength depends on that of these two different bonds, i.e. the bond strength of the blank bond and the block bond. So far, some macroscopic theoretical models have been developed for roll bonding [6, 8, 18, 19]. For instance, Vaidyanath et al. have proposed the following equation for predicting bonding quality [6]:

$$S_w = S_m R_f (2 - R_f) \tag{2}$$

Where S_w is the strength of the bonds, S_m is the strength of the base metal, and R_f is the final reduction at the end of rolling pass. In this model, with attention to microscopic details, the total bond strength can be represented by the strengths of the two different kinds of bond in the following equation:

$$S = S_b F_b + S_c F_c \tag{3}$$

where S is the total bond strength, Sb is the bond strength of the blank bond, Sc is the bond strength of the block bond, Fb is the area fraction of the blank bond and Fc is the area fraction of the block bond. The area fractions are given by Eqs. (4) and (5)

$$F_b = A_b / A \tag{4}$$

$$F_c = A_c / A \tag{5}$$

where A is the overall bonded area, and Ab and Ac are the blank bond area and the block bond area, respectively. In order to determine Fb and Fc, an assumption is made that the contribution of the area of the transverse blanks to the total area is negligible because they are considerably narrower than the longitudinal blanks, whereas the widths of the longitudinal blanks and bonds are approximately the same. Considering the longitudinal blanks to be parallel to each other across the surface of the steel substrate, the following equations are used (Eqs. (6–8)):

$$F_b = l_b / l \tag{6}$$

$$F_c = l_c / l \tag{7}$$

$$F_b + F_c = 1 \tag{8}$$

where l is the total length of the bonded interface, lb is the length of the blank area and lc is the length of the block area on the top of the chromium interlayers, all three lengths being in the rolling direction. In order to measure l, lb and lc, the following equations are used (Eqs. (9–11)):

$$l = l_b + l_c \tag{9}$$

$$l_b = \sum_{i=1}^{n} l_{bi} \tag{10}$$

$$l_c = \sum_{i=1}^{n} l_{ci} \tag{11}$$

where i is the individual chromium block or blank between the chromium blocks as shown in Fig. 8, and n is total number of the blocks or blanks included in the length of l. The values of lbi and lci are measured on specimens by using the light microscope at a magnification of 400× on the end. In this experimental situation, considering the feasibility and precision of the experimental data of lb and lc, n is selected as 30.

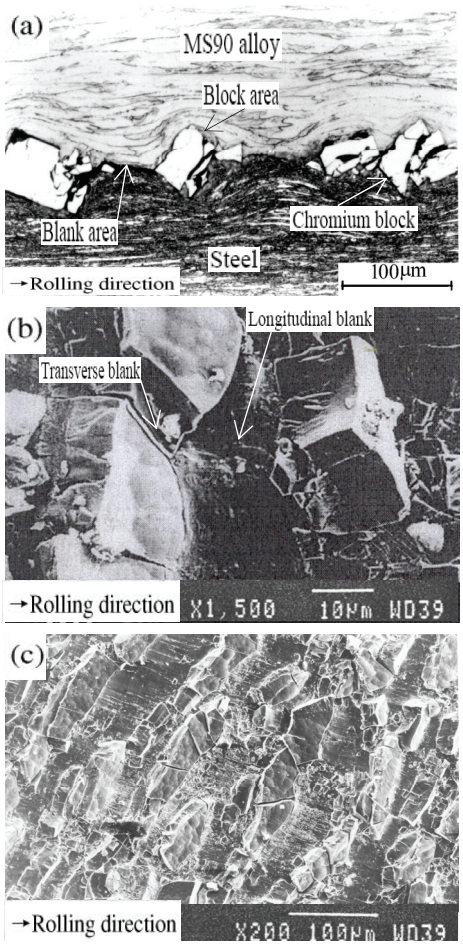

Fig. 7. Microstructure of the bonded interface: a) light micrograph of longitudinal section of MS90 alloy/chromized steel sheet at 53°C for 40 min; b) SEM micrograph of fractured interface on steel side; and c) SEM micrograph showing parallel blanks across fractured interface on the steel side

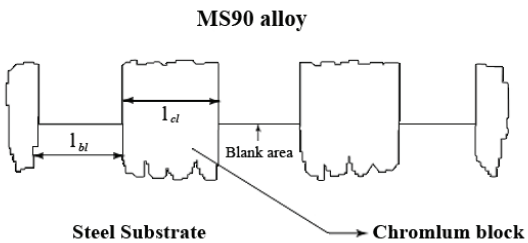

Fig. 8. Schematic diagram showing the position of the MS90/chromium topcoat layer

interface and chromium topcoat layer/steel interface after rolling

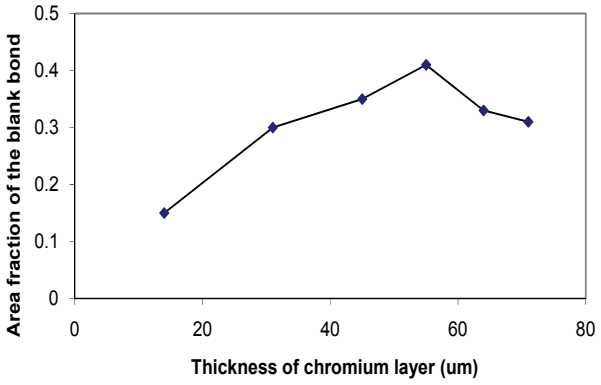

Fig. 9. The variation in area fraction of blank bond with the thickness of the coating layer

Figure 9 shows that the area fraction of the blank bond increases with the interlayer thickness up to 55 µm, but decreases at higher thickness values. The total bond strength can also be represented by the following equation (derived from Eqs. (3) and (8)):

$$S = (S_b - S_c)\, F_b + S_c \tag{12}$$

On the base of the above formula, there should be a linear relationship between S and Fb, with S increasing as Fb increases. The actual variation in bond strength with the area fraction of the blank bond for the MS90/hard chromized steel sheets is shown in Fig. 10. In line with Eq. (12), the data points fit a linear relation. The values of Sb and Sc can be obtained from the ordinates in Fig. 10. When the bonded area consists entirely of a block bond, the value of Fb is 0, and S becomes equal to Sc. Similarly, when the bonded area consists entirely of a blank bond, Fb will be 1, and F becomes equal to Sb. Consequently, from Fig. 10, Sb and Sc are found equal to 767.84 and 92.45 N, respectively.

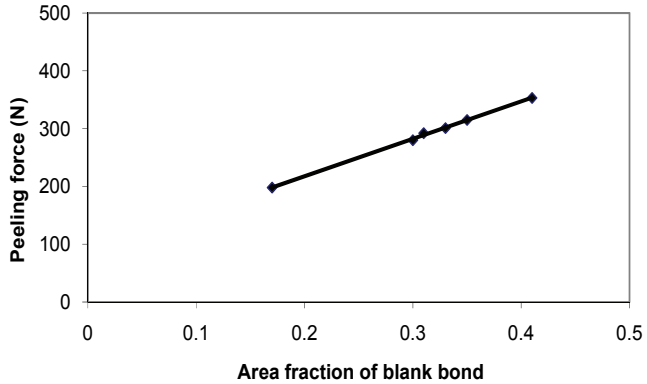

Fig. 10. The linear relationship between peeling force and area fraction of blank bond

Thus, the bonding strength of the blank bond is eight times greater than that of the block bond, and the total bond strength is principally dependent on the bond strength and the area fraction of the blank bond. The area fraction of the blank bond increases with the thickness of the chromium interlayer up to 55 µm but decreases beyond that value. This might result from two interactive factors. On one hand, when the thickness of the chromium layer increases and the steel substrate undergoes an increasing deformation during roll bonding, the fractured area of the chromium layer increases. This is due to the fact that the shear moduli at the substrate and chromium layer are very different [9, 20], and the hard chromium on the

surface of the substrate cannot have continuous flow with the substrate, thus it becomes severely fragmented.

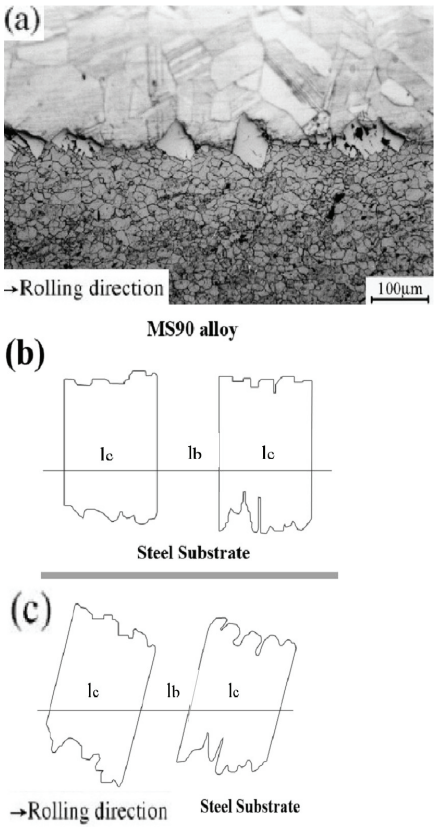

Fig. 11. a) Micrograph showing the rotation of the coating blocks (sample annealed for 1 hr at 700°C), b, c) Schematic diagram of the decrease in the area fraction of blank bond caused by rotation

At the same time, the blocks within the fragmented chromium layer begin to rotate from an initial position almost perpendicular to the blank interface to another position inclined at an angle to the blank interface (see Figs. 7a and 11a). The thicker the chromium layer, the larger the angle (θ) of rotation is, and the interlayer blocks take over a much more bonded interface as shown in Fig. 11b, and as a result of this rotation the area fraction of the blank bond decreases ($F_b=1-F_c/\cos\theta$). Meanwhile, Fig. 12 confirms that due to the high strength of the interface, a large amount of Fe particles compared with a few Cr-fragments were pulled out by the peeled MS90 layer during the peeling test. Another factor is the bond between the flown substrate in the cracks appeared due to the fragmentation of the Cr-layer and the sides of the interlayer blocks.

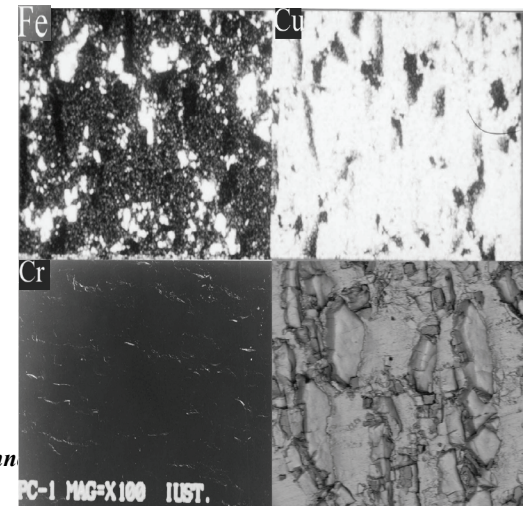

Fig. 12. X-Ray map taken from the peeled MS90 surface of the sample annealed 700°C

This area is ignored as an approximate value in the initial analysis because the bonding nature on the top of the blocks is different from that on the side of the chromium blocks in the bonding process. That is, one is a metallurgical bond and the other a mechanical bond. The sides of the chromium blocks have a smaller effect on the bond strength than do the tops of chromium blocks. Obviously, as the chromium layer thickness increases, the total block area (top and sides) increases. Moreover, as the block length increases, the blank area reduces. Thus, the situation becomes increasingly complex as the chromium layer thickness changes. The mechanism concerning the variation in the area fraction of the blank bond needs further investigation.

4. CONCLUSION

This study of the interfacial bond strength of rolled MS90 alloy strips and chromized steel sheets has led to the following conclusions:

(1) Bonding MS90 alloy strips to hard chromized steel sheets can be carried out by rolling the two components bonding together via a mechanism involving blank bonds and block bonds.

(2) In the current rolling operation, overall bond strength increases with the thickness of the interlayer up to 55 μm, but decreases at greater values. This is similar to the relationship between the area fraction of the blank bond and the chromium thickness.

(3) The bond strength of the blank bond is eight times greater than that of the block bond. This means that the total bond strength depends principally on the bond strength and the area fraction of the blank bond.

(4) There is a linear relationship between the overall bond strength and the area fraction of the blank bond.

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