

Effect of Coating-thickness on the Formability of Hot Dip Aluminized Steel

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Abstract

The influence of coating thickness on the formability and ductility of hot-dip-aluminized steel has been determined using a 3-point bend test and optical metallography. The ductility / formability was estimated from the 3-point bend test wherein the angle of bend at which the cracks start to appear on the surface of the aluminized sheet during bending, was taken as an index of the formability / ductility. It was observed that as the amount of silicon in the aluminizing melt was gradually increased the measured ductility of the sheet sample also increased. Metallographic examination has shown that as the amount of silicon in the aluminizing melt was increased the thickness of the intermediate compound layer, between the outer aluminum coat and the substrate steel, decreased. It was thus indicated from these experiments that the formability / ductility of the sheet was inversely related to the thickness of the interlayer.

Keywords: coating thickness; formability; 3-point bend test; interlayer

1. Introduction

Hot-dip-aluminized steel products are used in applications where heat and oxidation resistance are the primary requirements. Individual components are aluminized by dipping into molten aluminum for a specific period of time, while hot dip aluminizing of sheets and wires is carried out on a continuous line [1] involving rolls and equipment similar to that used for galvanizing.

The reaction between molten aluminum and the steel surface during hot-dip-aluminizing results in the formation of Fe-Al intermetallics at coating/substrate interface [1]. These inter-metallic compounds are highly brittle, and therefore, it is always intended to keep the thickness of the interlayer to a minimum [2,3] so as to achieve better mechanical properties as well as a reasonable formability in the aluminized steel sheets.

The formability of steel sheets is markedly affected by the thickness of intermetallic layer, while the thickness and the morphology of interlayer are influenced by the composition of the molten aluminum [2,4,5], and also by that of the steel being coated [2,5]. Additionally, the dipping time and the temperature of the molten aluminum have to be closely monitored in order to control the thickness of the interlayer [1].

In case of pure aluminum the interlayer produced

during hot-dip-aluminizing is comparatively 'thick', and the interface between coating and substrate is very un-even [2,3,6,7]. With the additions of silicon into the aluminizing melt, the thickness of the intermetallic layer decreases rapidly and the coating/substrate interface becomes 'smoother' as the silicon content is increased to about 3.0%. A further increase in silicon content has a limited effect in reducing the thickness of interlayer [1].

The ductility/formability of the coating increases with the decrease in interlayer thickness, with the result that relatively severe fabrication of the sheet can be carried out without peeling of the coating [1,8]. Steel sheets, hot-dip-aluminized with Al-Si alloy can withstand moderate forming, drawing, and spinning operations without flaking or peeling of the coating. Steel sheet aluminized in pure aluminum can only withstand restrained brake and roll forming operations and may also be spun or embossed, but is not suitable for drawing [1,8].

The present work aimed at establishing a relationship between the silicon-concentration of the aluminizing-melt (and thereby the thickness of the interlayer) and the 'formability' of the aluminized steel sheets. For the purpose of quantification, the 'Angle of Bend' to which the aluminized sheet could be bent before any cracking is observed was taken as a measure of the formability of aluminized steel sheets.

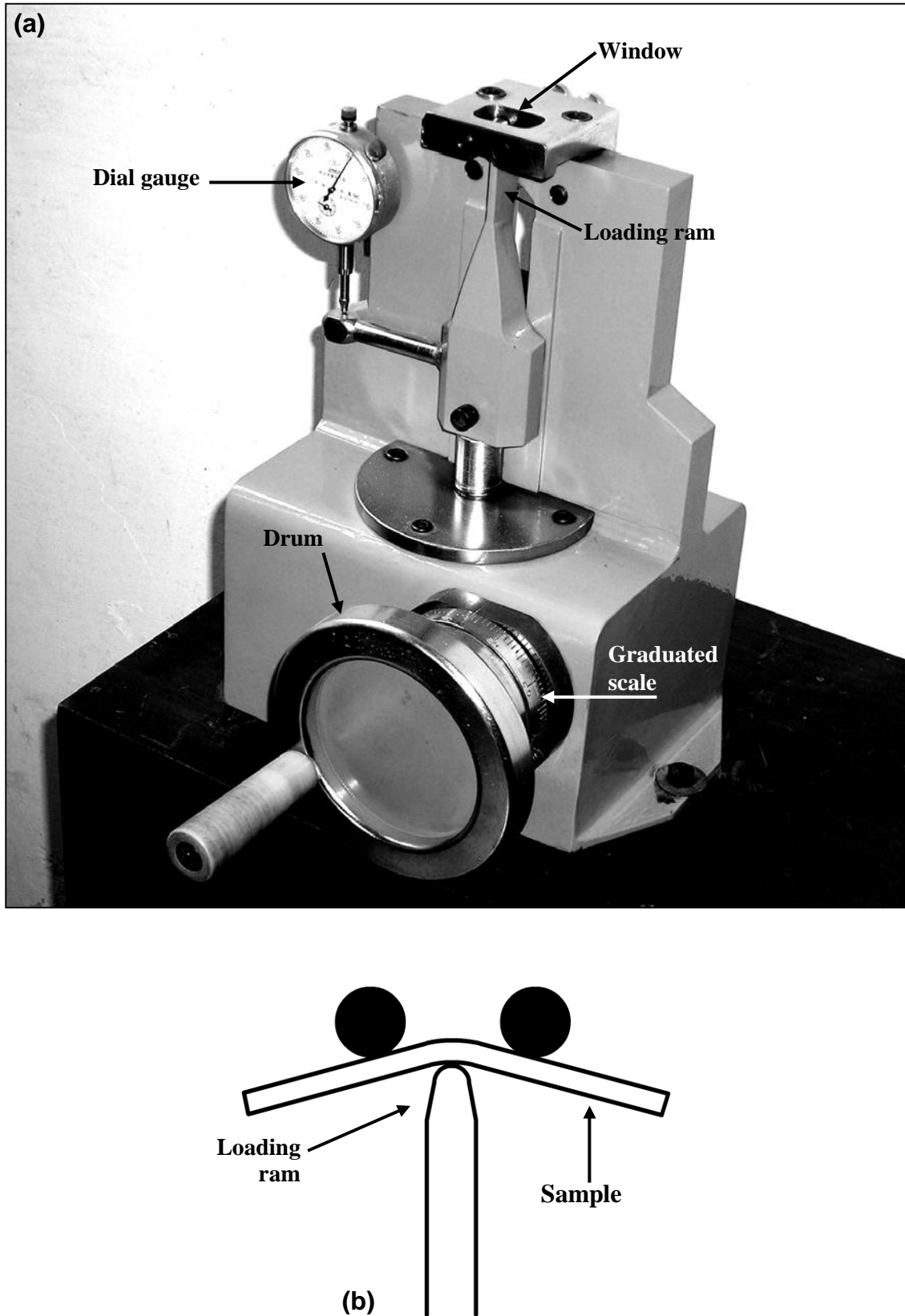


Figure 1: (a) Bending machine used for carrying out the bend type test on aluminized samples, (b) the schematic illustration of the 3-point bend test.

2. Experimental

Steel samples which were studied during the present investigation, were hot-dip-aluminized by following the conventional methods which have been described in various references [1, 8, 9].

Flat hot-dip-aluminized steel samples, which were about 50x20x2.5 mm in size, were subjected to a 3-point bend type test, in order to compare the relative 'ductility' of the samples aluminized in pure aluminum and various aluminum-silicon melts. The bend test was conducted on a bending machine which was especially designed for the present experimentation. A photograph of this 'Bending machine' is given in Figure 1 (a), while a schematic illustration of 3-point bend test is given in Figure 1(b). For carrying out the test, a 2-inch long piece of strip cut from the hot-dip-aluminized sample was subjected to the 3-point bending in the manner schematically shown in Figure 1(b). The start of the cracking on the aluminized sample, during bending, was observed through the viewing 'window' on the top of machine, Figure 1a. The bent samples were suitably sectioned at right angle to the cracks, mounted in bakelite, and then metallographically prepared before etching in 2% Nital solution. Microscopic examination of the polished and etched samples was carried out on an Olympus GX-1 camera microscope and a Hitachi S-3000H scanning electron microscope.

3. Results and Discussion

Aluminized samples were subjected to a 3-point bend-Test, in the device shown in Figure 1. During

the test, the surface of the aluminized sample (on the outer side of the bend) was closely observed with a magnifier of x10 magnification, for the start of the formation of cracks, and the angle at which the cracks just began to appear was noted.

The results obtained from the bending of the samples which had been aluminized in aluminum-melts containing different silicon concentrations were plotted against the silicon-content of the aluminum-melt. The graph shown in Figure 2 summarizes the results obtained from these experiments. It is clear from Figure 2 that with an increase in the silicon-contents of the aluminum-melt, the angle of bend at which the start of the cracking on the surface was observed, increased. It must be remembered that, the silicon additions into aluminum are known to cause a reduction in the thickness of the Fe-Al interlayer [3,4,6]. Accordingly, it would follow that the thinner the interlayer, the greater shall be the angle to which the aluminized flats or sheets could be bent without cracking. The cracking essentially constituted the formation a large number of cracks which were more or less parallel to each other (see Figure 3), and were oriented perpendicular to the tensile stress established in the surface layer of the specimen by the applied bending moment.

Sections were taken from the bent samples across the cracks so as to examine the morphology and the distribution of cracks as well as their relationship with the interlayer. The cracking pattern in the samples aluminized in pure aluminum was distinctly different from that observed in the samples aluminized in Al-Si alloys. A detailed description of the cracking patterns in the two types of samples is given below.

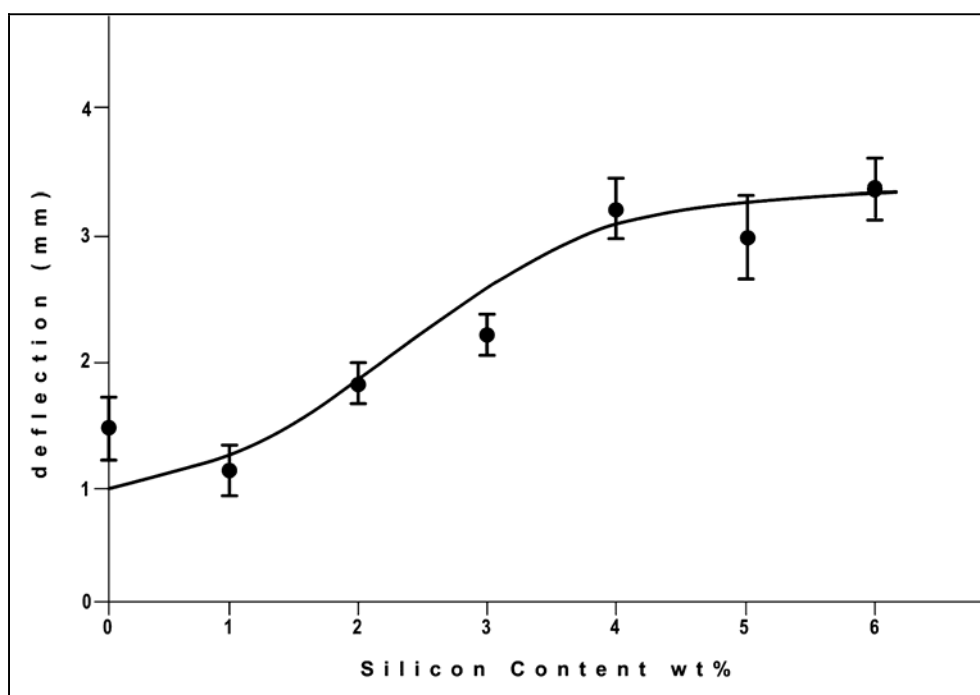


Figure 2: Graph showing relationship between silicon contents (wt%) and the deflection in (mm).

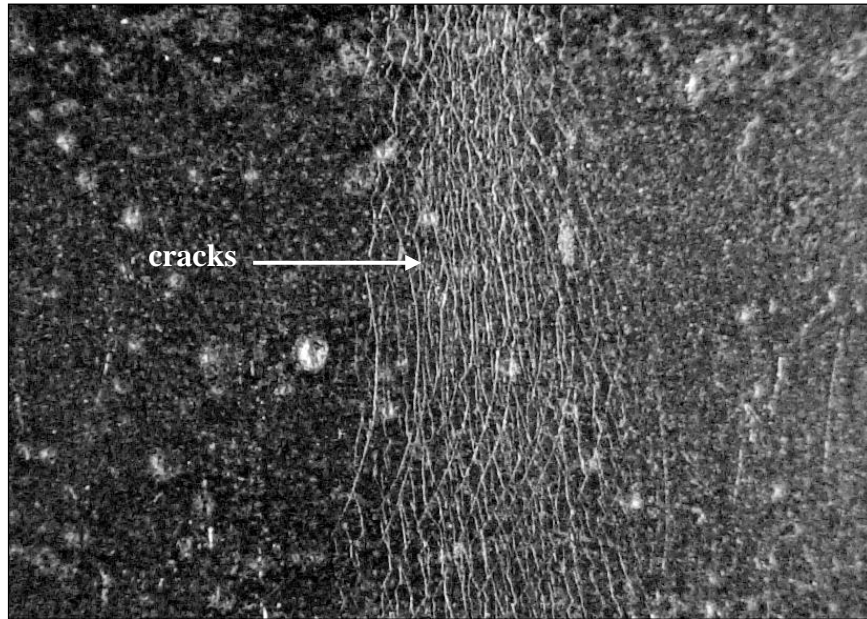


Figure 3: (a) Showing the start of the cracking during the bend-test as observed with a magnifier.

3.1 Metallographic examination of bent samples: Samples aluminized in pure aluminum

Typical microstructures of samples aluminized in pure aluminum and those aluminized in Al-Si melt are shown in Figure 4 (a and b).

Micro-sections taken from the outside and inside surfaces of bent samples (hot-dip-aluminized in pure aluminum) are shown in Figure 5. It may be noted in Figure 5 (a) that, at the outside of the bend, the brittle Fe_2Al_5 [3] layer has cracked through its entire depth, while the cracks have not been able to penetrate into the tougher steel substrate. It was also observed that as the bend angle was further increased, the already-existing cracks opened up to become more 'wide' instead of the formation of new cracks. This effect can be appreciated through a comparison between the micrographs given in Figure 5 (a) and (b). Nevertheless, it is possible that at larger bend angle, new cracks may also start to form in addition to the pre-existing cracks.

The pattern of the cracking of brittle interlayer on the inside of the bent samples was quite different from that on the outside of the bend. As shown in Figure 5 (c), on the inside of the bend, the cracking had occurred through the interlayer and parallel to sheet surface causing the aluminum coating to separate or 'flake-off' from the substrate. Also, at greater bend angles, the aluminum coating tended to buckle outwardly after separating from the substrate, Figure 5 (d).

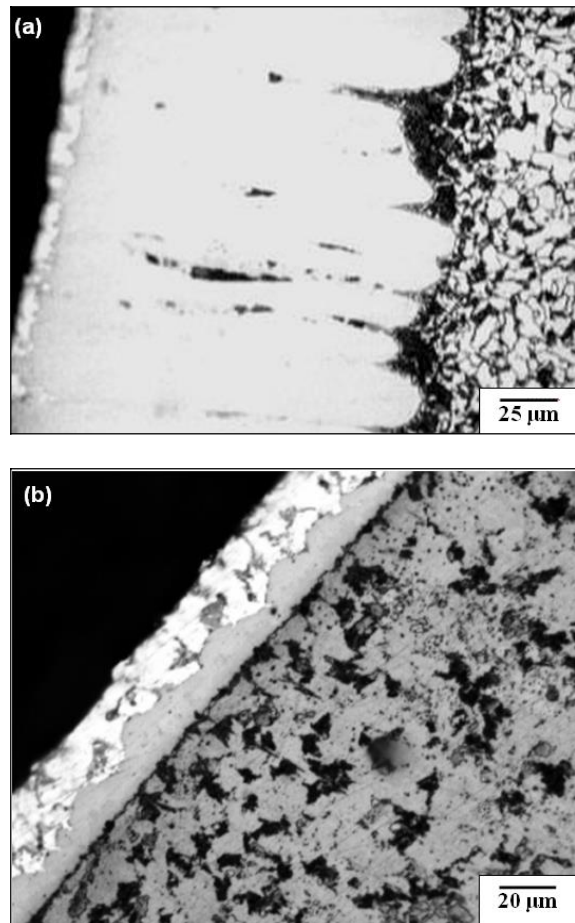


Figure 4: Microstructures showing the morphologies of the interlayer in case of aluminizing with pure aluminum (a), and with Al-Si alloys (b).

The behavior of the hot-dip-aluminized sheets in pure aluminum as observed through the metallographic examination of the bent samples clearly showed that the interlayer is highly susceptible to cracking whether it is stressed in tension (on the outside of the bend), or compression (on the inside of the bend). It should also follow from the above observations that a predictable and reliable formability cannot be expected from the sheets aluminized in pure aluminum; it shall be difficult to make sure that during the forming operation the

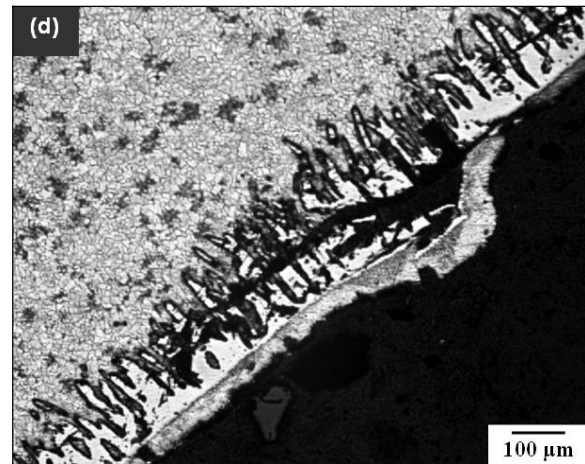
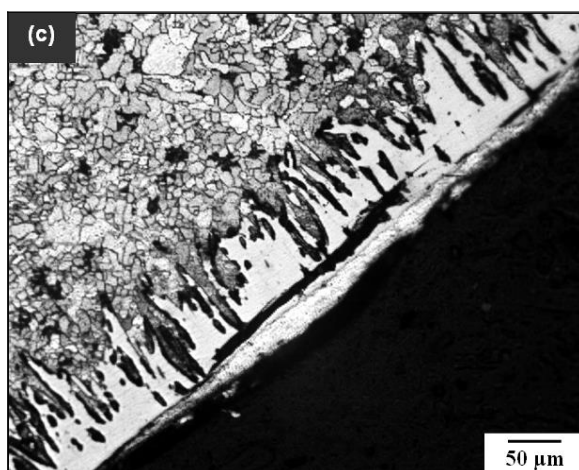
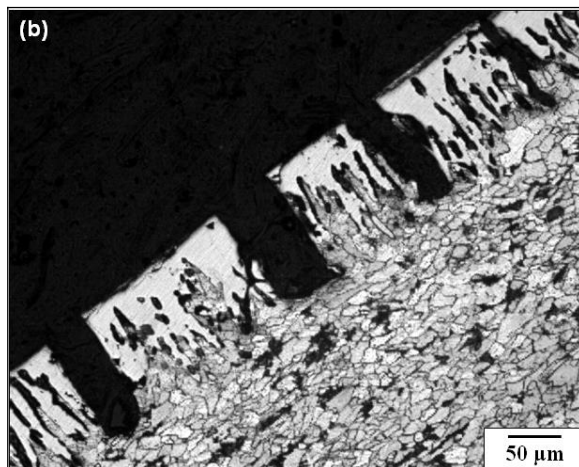
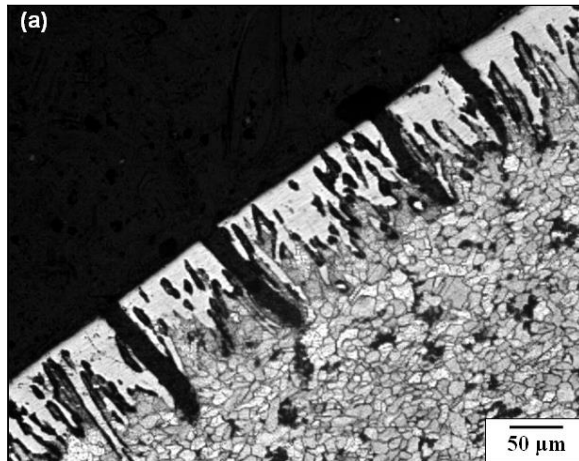


Figure 5: Microstructures showing (a,b) the outside surface of the bent samples, (c,d) the inside surface of the bend samples aluminized in pure aluminum.

interlayer does not develop any cracking. However, it can also be debated that even if minor cracking had occurred in the interlayer, as long as the outer aluminum coating is not damaged, the sheets (or the formed shape) may be acceptable for some applications.

3.2 Metallographic examination of bent samples: Samples aluminized in Al-Si alloy

Bending experiments conducted on flat samples aluminized in Al-6%Si alloy melts showed interesting results. As may be seen in the metallographic section taken across the cracks, given in Figure 6 (a and b), that at many places the cracks had formed in the inter-metallic compound layer while the outer aluminum layer is still quite 'healthy' and continuous.

It can be easily appreciated that during the bend test, the cracks in the interlayer had formed much earlier than when they were first noticed at the outer surface of the sheet. Accordingly, the results of the bend test as presented in Figure 2, may be regarded as debatable.

It can be argued that the early cracking of the interlayer may cause a stress-concentration at the surface of the sheet, which then may affect the tensile strength of the aluminized steel. The reduction in the tensile strength of steel wires and sheets upon aluminizing has been understood [1,8,9] to be caused by the 'tempering' of the steel during the dipping into molten aluminum above 650°C. However, on the basis of the present work, it appears that a possible cause for the deterioration of the tensile strength may lie in the early cracking of the interlayer.

Further, as reported in the published literature [1,8] the wires and sheets coated in aluminum-silicon alloys exhibit relatively better drawability and fabricability compared to the wires and sheets aluminized in pure aluminum. The present work provides support to these observations as reported by ASM Committee [1]. The present work clearly shows that smaller the thickness of the interlayer the smaller would be the length of the cracks in the interlayer and therefore the smaller shall be the consequent degree of stress-concentration. And thus as a result, the observed drawability and the fabricability shall also show an improvement.

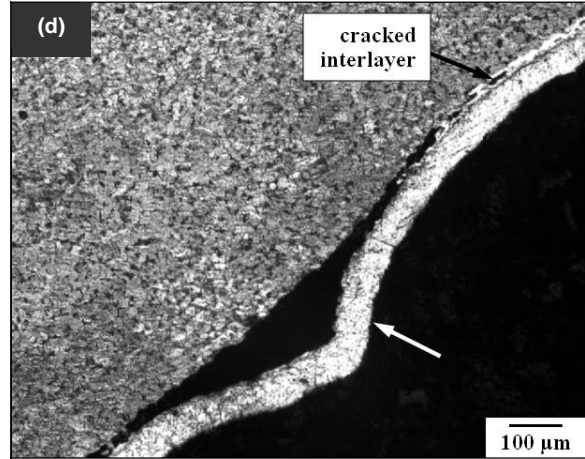
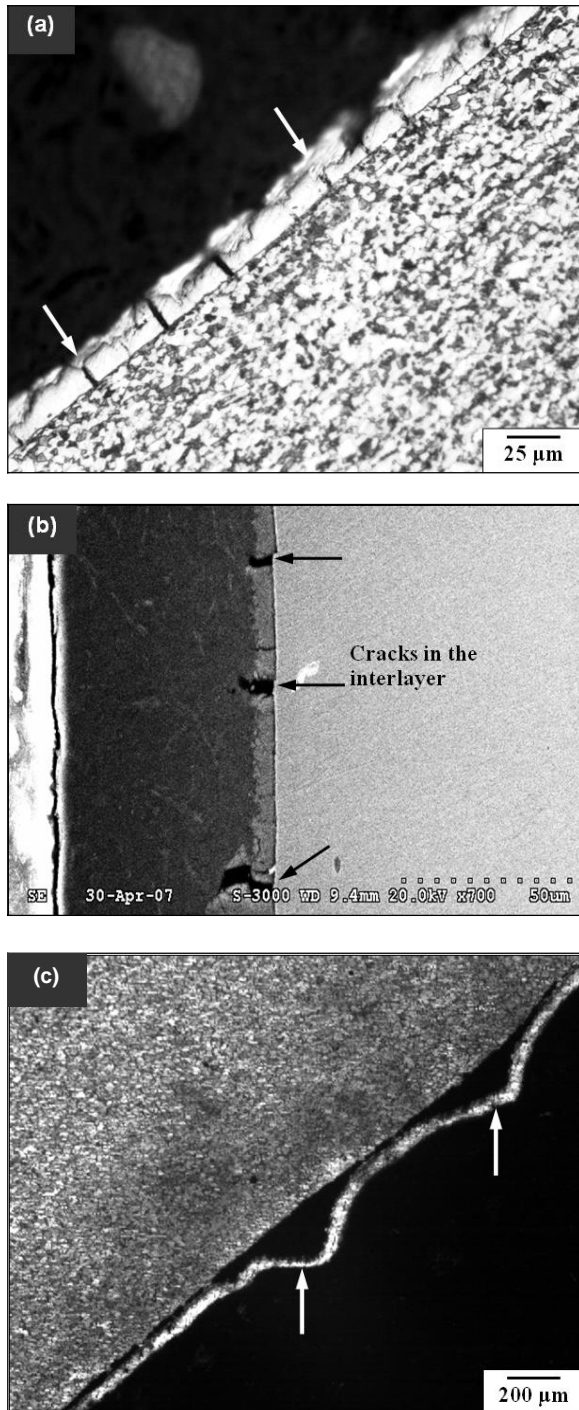


Figure 6: (a,b). Microstructures showing the outside surface of the bent samples aluminized in Al-Si alloy. The cracks in the interlayer are indicated by the arrowheads, (c,d) Microstructures showing the inside surface of the bent samples aluminized in Al-Si alloy. The locations where the aluminum coating has buckled/flaked-off are indicated by the arrowheads. In Figure 6d, the cracking through the intermetallic compound may also be noted.

To sum up, it must be stated that the presence of the brittle layer of inter-metallic compound just beneath the surface can affect, by means of early cracking and stress-concentration, various mechanical characteristics including the strength, the drawability, and the fabricability.

The behavior of the inside of the bent samples aluminized in Al-6%Si alloys is shown in Figure 6 (c and d). It may be noted that similar to the samples aluminized in pure aluminum (Figure 5 c and d), the cracks are formed parallel to the sheet surface. The cracking occurs through the interlayer causing the outer aluminum coat to separate or flake-off from the substrate and buckle outwardly.

The ‘flaking’ of the aluminized sheets during forming or fabrication has also been reported in the published literature [8,9]. It is logical to believe that such flaking must have been observed at those locations where compressive stresses had developed during the bending or fabrication. The present work clearly shows that whereas the appearance of ‘cracks’ on the surface is related to the tensile stresses, the ‘flaking’ appears to be related to the compressive stresses.

It is not very common to use aluminizing-melts containing more than 6-7% silicon. However, the published literature reports that some researchers [4] have made use of the ‘eutectic’ composition (i.e., Al-13%Si) for conducting aluminizing experiments. Accordingly, during the present work, a limited

number of samples were aluminized using Al-13%Si alloy, and subjected to the Bend-Test. The bending experiments conducted on the samples aluminized in Al-13%Si melts showed a fairly inconsistent behavior in terms of the 'angle of bend' for the start of cracking. In order to see the pattern of cracking in these samples, the bent samples were metallographically examined.

Before describing the results obtained from the metallography of these samples, it is relevant to point out that Al-13%Si alloys are known to suffer from 'over-modification' wherein isolated regions containing large plate-like precipitates of silicon start to appear in a well modified fine eutectic matrix. These plate-like precipitates can be of the order of 100 microns in size and exhibit a variety of orientations with the aluminum matrix [10,11]. Accordingly, it was of interest to explore whether the 'over-modification' of silicon precipitates inside the aluminum coating was responsible for the inconsistency of results observed during the Bend-Test.

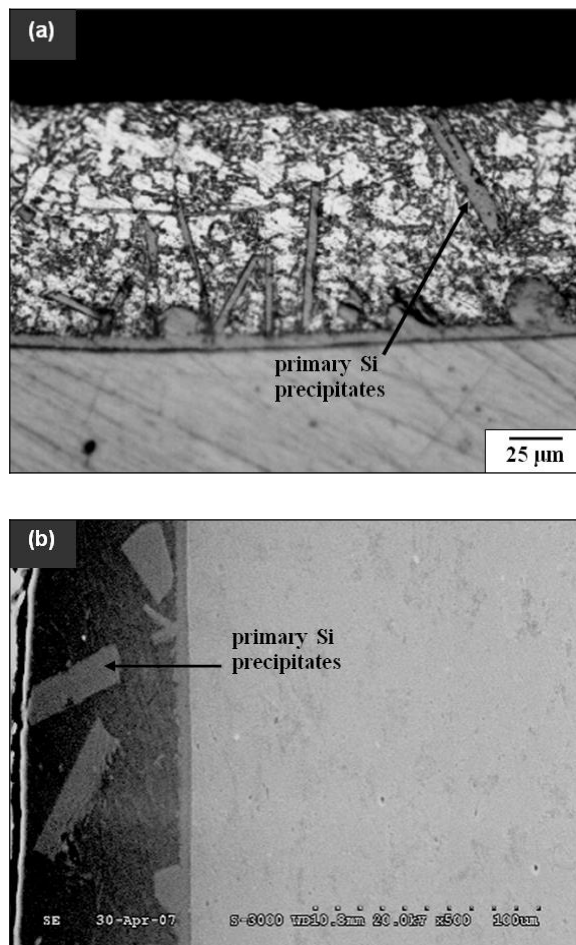


Figure 7: (a & b). Microstructures showing the randomly oriented primary silicon precipitates inside the outer Al-13%Si alloy coat.

Microstructure given in Figure 7 shows the distribution of silicon precipitates in the outer aluminum layer in aluminized steel sheets. It may be noted that whereas most of the silicon precipitates exhibit a fine and uniform distribution, some precipitates are relatively quite large as compared with the others. Further, some precipitates have formed as large plates and that these plates exhibit random orientations. Also, that some of these large plates may be relatively thicker compared with the rest.

It was also noted that the large plates of silicon may sometimes be so oriented that during the bend-test these plates would be perpendicular to the applied tensile stress. The micrograph given in Figure 7 shows that some of the plates are oriented almost normal to the sheet surface such that these plates can easily develop cracks under a tensile force applied parallel to the sheet surface and perpendicular to the precipitate plates.

The microstructures of sections taken from the bent samples aluminized in 'over-modified' melts are

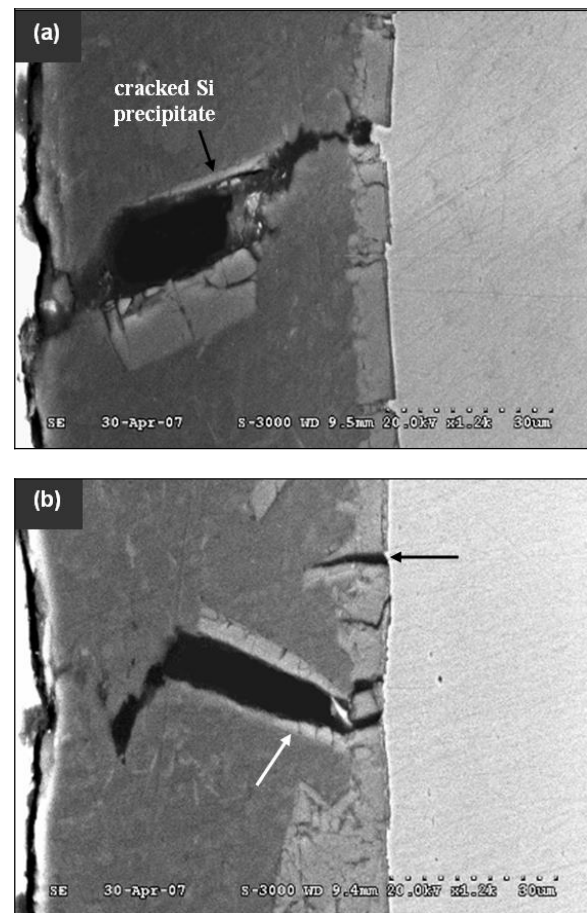


Figure 8: (a & b). Scanning electron micrographs of bent samples showing the preferential propagation of cracks through the primary Si precipitates, as indicated by the arrowheads.

given in Figure 8. It may be noted that whereas the interlayer had cracked at many locations, the cracks which had reached the outer surface, had propagated through the large silicon precipitates. It can be easily appreciated from these observations that when large plates of silicon are present in the outer aluminum-coat (as in the over-modified case) the cracks shall show up at the surface earlier than when there were no large silicon precipitates present.

4. Conclusions

Bending experiments conducted on aluminized samples showed that the presence of the brittle interlayer beneath the outer aluminum coat can affect, by means of early cracking and stress-concentration, various mechanical characteristics including the strength, drawability, and fabricability. The sheets and wires aluminized in Al-Si alloys exhibit better fabricability and drawability than those aluminized in pure aluminum because the thickness of the interlayer is comparatively much smaller in the case of aluminizing with Al-Si alloys.

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