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EFFECT OF HOT DIPPING ALUMINIZING ON THE TOUGHNESS OF LOW CARBON STEEL

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Abstract
Steel that has been aluminized said as hot dipping aluminizing has better protection against corrosion and can protect against temperatures as high as 800°C. In hot dipping aluminizing, Steel is immersed into a molten aluminium for certain dipping time. The research aims to know the effect of preheating and dipping time on the toughness of low carbon steel. The method research was started by cutting the low carbon steel plate, according to ASTM E23 (Charpy test sample) into 16 pieces samples. Then the samples were grouped into four groups. Group-1 was initial samples. The Group-2 was directly immersed into molten aluminum 700 ^{0}C, for dipping time 5 minutes. The Group-3 was preheated at 700 ^{o}C for 30 minutes and then to be aluminized (700 ^{o}C) for dipping time 5 minutes. The Group-4 was preheated at 700 ^{o}C for 30 minutes and then to be aluminized (700 ^{o}C) for dipping time 10 minutes. Finally, all groups were tested by the Charpy test at room temperature. The results show that the aluminizing increases the toughness of low carbon steel from 228.125 KJ/m^2 to 312.5 KJ/m^2. The preheating process before aluminizing increases sharply the toughness of low carbon steel from 228.125 KJ/m^2 to 512.5 KJ/m^2. The increasing dipping time from 5-minute to 10-minute increase gradually the toughness from 512.5 KJ/m^2 to 556.25 KJ/m^2.

Keywords:
Aluminizing;
Hot Dipping;
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INTRODUCTION

Hot-dip aluminizing associates a reaction between solid Steel or iron and liquid aluminum. The steel surface to be aluminized is immersed in a bath of molten aluminum or its alloy. Depending on the aluminum bath's temperature, dipping time, Steel's chemical composition, thickness of the aluminide layer, and the phases formed will be different [1].

The hot-dip aluminizing is an effective and inexpensive coating process to protect steels from oxidation and impart a good surface to Steel [2][3]. The quality of coating depends on the properties of the intermetallics layer forming at the interface. A brittle intermetallic layer may peel off from the surface during forming operations [4][5]. Some parameters of aluminizing are temperature (700–900 ^{o}C) and dipping time (300–2400 seconds) [1,5,6,7]. Since aluminizing involves high temperatures and times as parameters, the effect of aluminizing parameters on the mechanical properties of Steel is interesting for investigating [8, 9, 10, 11, 12, 13].

The research aimed is to investigate the effect of aluminizing on the toughness of low carbon steel.

METHOD

The material is low carbon steel with composition, as shown in Table 1. The molten aluminium for aluminizing was Al 6061.

The research flow chart is shown in Figure 1. The Steel was machined to be 16 Charpy impact test samples as ASTM E23, as shown in Figure 2. Next, the samples were precleaned using 10% Hydrochloric acid, followed by washing distilled water and drying.

Table 1. Chemical Composition of Low Carbon Steel

C (%)	Si (%)	Mn (%)	P (%)	S (%)	Cr (%)	Mo (%)
0.054	0.218	0.448	< 0.003	0.006	0.2	< 0.005

Ni (%)	Al (%)	Cu (%)	Nb (%)	Ti (%)	V (%)	Fe (%)
< 0.005	< 0.001	0.11	< 0.002	< 0.002	0.006	bal

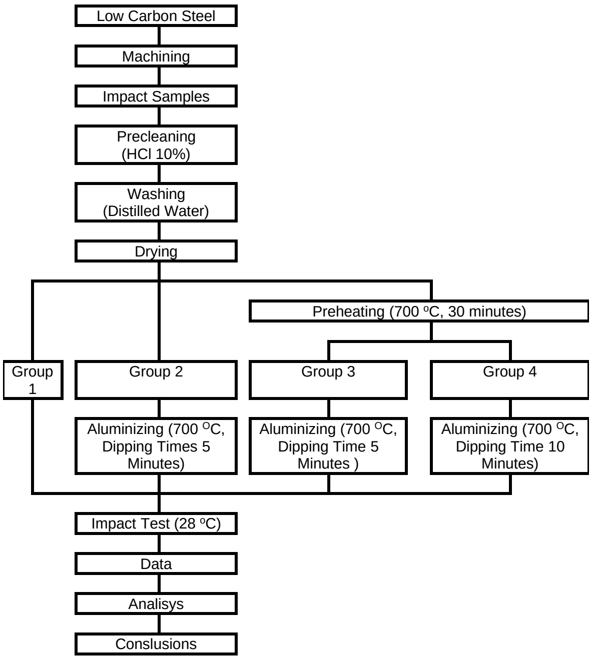

Figure 1. Research Flow Chart

Then, the samples were grouped into four groups. Group-1 was direct to impact testing. The Group-2 was aluminized by immersing the samples into the molten of aluminum at 700 ^{0}C, for 5 minutes. The Group-3 was preheated at 700 ^{o}C for 30 minutes and then to be aluminized at 700 ^{o}C for 5 minutes. The group-4 was preheated (700 ^{o}C, 30 minutes) and then to be aluminized at 700 ^{o}C for 10 minutes. Finally, all the groups were tested on the impact test. The variables of the experiment for each group are shown in Table 2.

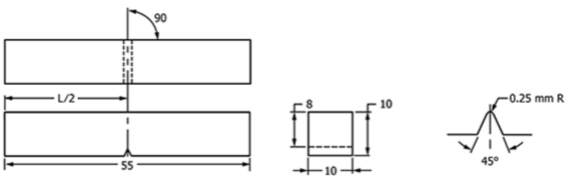

Figure 2. Impact Test Sample [14]

Table 2. The Variables of Experiment

Name of group	Preheating 700 ^{0}C, for 30 minutes	Aluminizing	
		Temperature (^{0}C)	Dipping time (minutes)
1	No	No	No
2	No	700	5
3	Yes	700	5
4	Yes	700	10

RESULTS AND DISCUSSION

Performance Samples After Aluminizing

After aluminizing, it founds a white solid layer that sticks on the surface of samples (Group-2, Group-3, and Group- 4), as shown in Figure 3. The white layer is very thin and thus is very easy to pull out and broken. The white layer is also found on the surface of Steel die in the aluminum die casting process. It is called the "die soldering" phenomenon [15].

Figure 3. A White Solid Layer Sticks on The Samples

Based on the previous research, the white layer is a thin layer of solid aluminum, as shown in Figure 4, the morphology of the layer is divided into "three-zone." The outer zone is the layer of solid aluminum, which is brittle. The middle zone is an intermetallic (Al-Fe) where the aluminum diffuses into the surface steel. The predominant intermetallic layer is Fe_2Al_5. Table 3 shows the thickness of various intermetallic phases as a function of time and temperature [1]. The rate of growth intermetallic is constant at (0.1483 mm/h$^{1/2}$) for general steel [15], but 0.57 μm/s$^{1/2}$ is for a low carbon steel [6]. The inner zone is the base metal (Fe).

The mechanism dies soldering are as follows as depicted in Figure 5. Firstly, the molten aluminum meets the steel surface. Second, molten aluminum attacks from grain boundaries as the weak intergranular area of Steel. Thirdly, the phase boundary attack results in the loosing of the steel grains. Thus there are some pits on the steel surface. Fourthly, the iron from these pits and the loosened grains start to diffuse out, resulting in intermetallic compounds between aluminum and iron. Next, the initial intermetallic phases in the erosion pits are formated and grow. Finally, soldered aluminum was mechanically stripped off the steel surface [15].

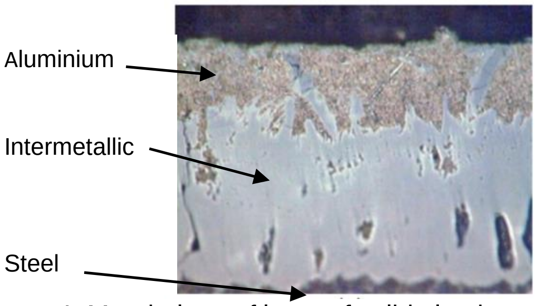

Figure 4. Morphology of layer of solid aluminum. Magnificient 500x

Impact Test Result

Figure 6 shows the appearance of the fracture of the specimen. The specimen of Group-1 and Group-2 is broken. Some specimens of Group-3 and Group-4 are unbroken.

The impact test results are shown in Table 4. Figure 7 shows the average toughness for each group. The toughness of initial low carbon steel (Group-1) is 228,125 KJ/m^2 while the Group-2 is 312,5 KJ/m^2. The toughness of the unbroken specimen is indefinite [14]. Thus the toughness value of Group-3 and Group-4 for each group is taken from the average toughness of broken specimens. The toughness of Group-3 is 512,5 KJ/m^{2,} and Group-4 is 556,25 KJ/m^2.

Table 3. The thickness of Intermetallic Phase as Function of Time and Temperature [1]

Time in seconds	Temperature °C 700 °C	800 °C	900 °C	1000 °C
900	A:130, B, and C; ND	A:125, B, and C; ND	A:115, B: 25, C;20,	A:107, B:45, C;45
3600	A:135, B, and C; ND	A:145, B, and C; ND	A:90, B: 22, C;35,	A:30, B:75, C;80
10,800	A:140, B and C; ND	A:135, B : 15, C;20	A:90, B:60, C;70,	A:30, B;125, C;120
21,600	A:125, B and C; ND	A:105, B: 25, C;20	A:60, B:65; C;90	A:20, B:125 C;230

A: Fe_2Al_5; B: $FeAl_2$; C: Al difused layer; ND: Not Detected

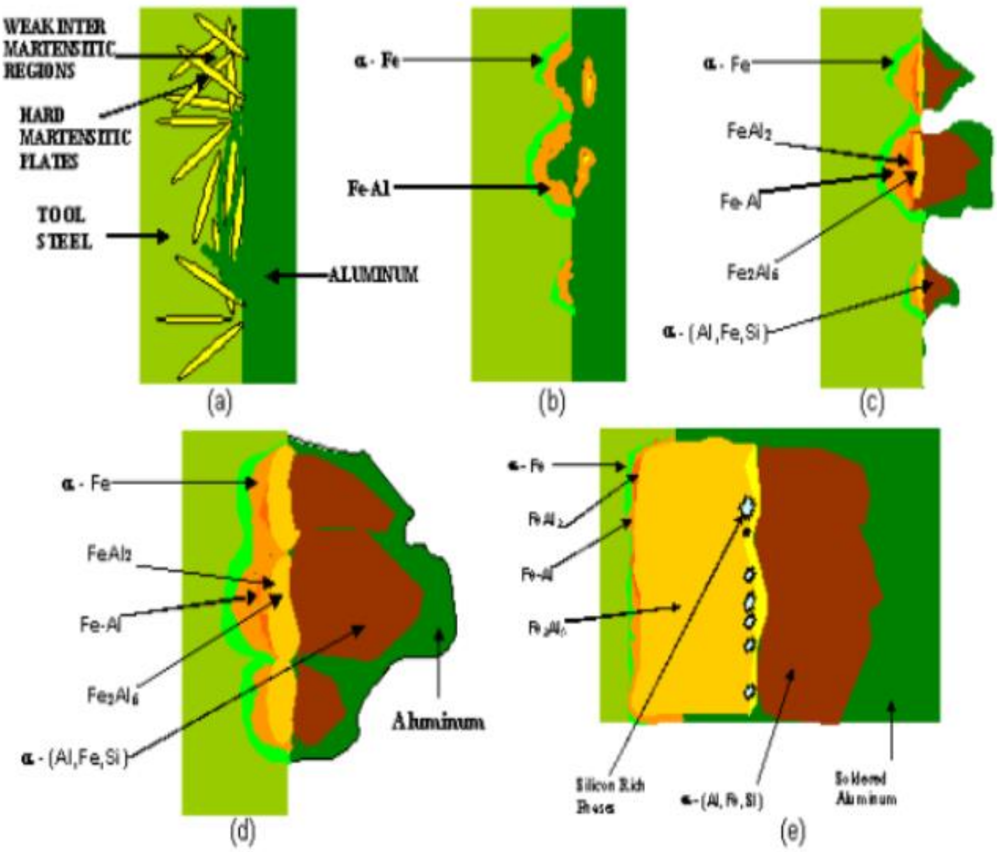

Figure 5. Illustration of Die Soldering [15]

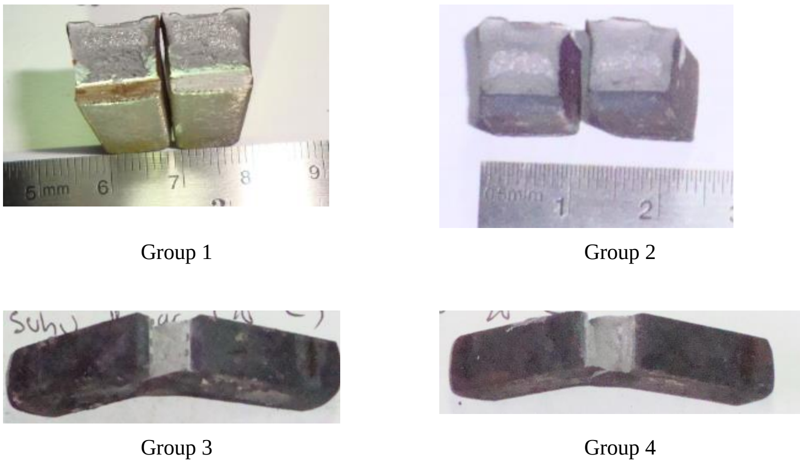

Figure 6. Fracture Appearance

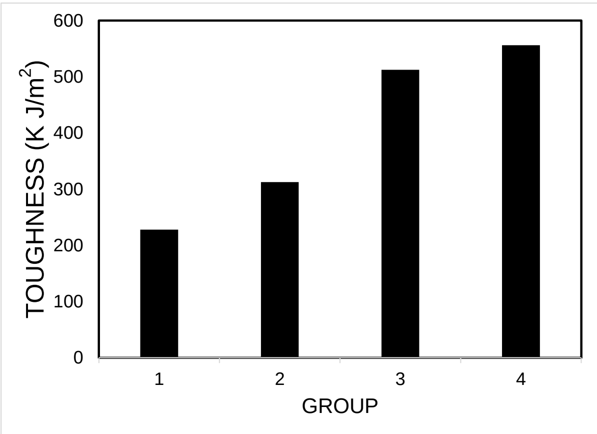

Figure 7. The Impact Test Results

Table 4. Impact Test Results

Group	No Sample	Toughness (KJ/m^2)	Explanation
1	1	225	Broken
1	2	262,5	Broken
1	3	212,5	Broken
1	4	212,5	Broken
1	average	228,125	===
2	1	262,5	Broken
2	2	375	Broken
2	3	362,5	Broken
2	4	250	Broken
2	average	312,5	===
3	1	Undifinite [14]	Unbroken
3	2	Undifinite [14]	Unbroken
3	3	512,5	Broken
3	4	Undifinite [14]	Unbroken
3	average	512,5	===
4	1	Undifinite [14]	Unbroken
4	2	Undifinite [14]	Unbroken
4	3	600	Broken
4	4	512,5	Broken
4	average	556,25	===

Since the low carbon steel is directly aluminized by immersing into the molten of aluminum at 700 ^{0}C for 5 minutes, the low carbon steel toughness (Group-1) increases from 228,125 KJ/m^2 to 312,5 KJ/m^2 (Group-2). The aluminizing increases the toughness of low carbon steel.

Based on previous research, the aluminizing effect of reducing the hardness of low carbon steel [11,12,17]. Meanwhile, almost metal shows that reducing hardness increases toughness [18,19, 20, 21].

The toughness of Group-2 is 312,5 KJ/m^2 that is smaller than Group-3 (512,5 KJ/m^2). The preheating process (700 ^{o}C, 30 minutes) before aluminizing increases low carbon steel's toughness. An explanation is as follows :

There are two equations, i.e., (1) and (2), that show a relationship between time and diameter of grain since Steel is heated for a certain time [22][23].

$$Dn - Do = A.\exp(-Qgg/RT).t \qquad (1)$$

where Do and Dn are initial diameters of prior austenite and final diameter (m); t is a time (second); T is a temperature (K); A and R are constants; Q_{gg} is an energy of activation for grain growth (Kcal/mol). For low carbon steel: n = 2; A = 4,27 x 10^{12}; Qgg = 278,4 kcal/mol.

$$d = 198.98\ Hr^{-0,201} \cdot t^{0,057} \quad (2)$$

where

d : diameter of grain (μm)

Hr : heat rate (^{0}C/minute)

t : holding time (minute)

Based on (1), it is known that preheating for 30 minutes at 700 ^{0}C will increase the activation energy of grain to grow bigger. Meanwhile, increasing in diameter of the grain effects to reduce the hardness. Reducing hardness will increase toughness [18, 19, 20, 21, 24, 25, 26].

The toughness of Group-3 (512,5 KJ/m^2) is smaller than the Group-4 (556,25 KJ/m^2) It means that increasing in dipping time from 5 minutes to 10 minutes increases the toughness of low carbon steel about 8 %.

Then, (2) is for low carbon steel [24]. Since an assumption of heat rate of this research is 10 ^{0}C/minute, thus the diameter of a grain of Group-3 and Group-4 can be calculated as follows:

The diameter of grain for Group-3.

$$d = 153.33\ \mu m. \quad (3)$$

The diameter of grain for Group-4.

$$d = 155.5\ \mu m. \quad (4)$$

Based on the calculation results, the diameter grain of Group-3 is smaller, about 0,7 % than the Group-4.

CONCLUSION

Aluminizing increases the toughness of low carbon steel from 228.125 KJ / m2 to 312.5 KJ / m2. The preheating process before aluminizing increases sharply the toughness of low carbon steel from 228.125 KJ/m^2 to 512.5 KJ/m^2. The increasing dipping time from 5 minutes to 10 minutes in the aluminizing process increases the toughness of low carbon steel gradually from 512.5 KJ/m^2 to 556.25 KJ/m^2.

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