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INFLUENCE OF ROLL SURFACE AND MELT TREATMENT ON THE QUALITY OF SINGLE ROLL STRIP CASTING PRODUCTION

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Abstract. *Strips made of aluminum alloy A413 were fabricated using the single roll continuous casting processing, with pouring temperature of the cast alloy (≈1300g) of about 680 ºC on the cooling slope, producing a metallic slurry that feeds the nozzle which is dragged by the roll at a rate of 0.2 m/s. Two conditions for the finishing of the roll surface were tested: 1.) Coating of the surface with boron nitride (BN); and 2.) Finishing of the surface using 1200 grit sandpaper. Further tests with the roll's surface finish obtained with a 1200 grit sandpaper were carried out: 1.) without alloy additions; and 2.) with TiBAl as grain refiner. The microstructures were observed using an Optical Microscope - OM and a Scanning Electron Microscope - SEM. The mechanical properties were obtained through tensile testing. It was found a decrease on the strength of the strips by coating the roll with boron nitride. A relevant increase in yield and tensile strength was measured on the specimen treated with TIBAL, along with a decrease on the elongation at fracture. Effects of poisoning were not found, although reported in Al-Si alloys with more than 3wt% of Silicon. More eutectic phase was formed by the addition of TIBAL. It suggests an action of the Ti and B on the coupled zone of the Al-Si eutectic.*

Keywords: *Strip Casting, Al-Si A413, TIBAL, Al-Si coupled zone.*

1. INTRODUCTION

Al-Si alloys, such as the A413 used in this research, have interesting properties such as good weldability, high resistance to corrosion and specific mechanical properties (Polmear, 1995) which favor their use in the electronic packaging industry (Jiang et al., 2018). However, Al-Si alloys show brittle and hard phases such as needle shaped silicon in the eutectic and thus making it costly to process through ingoting and rolling (Rooy et al., 1995). Therefore, research on Strip Casting as a way for processing these alloys has been made (Haga et al., 2007; Harada et al., 2011; Jiang et al., 2018; Lima Filho et al., 2019) in order to reduce the costs, emissions and time of production (Barekar and Dhindaw, 2014). The high efficiency of this process is constantly cited and could be strategic to the industrial development of countries if properly stimulated (Luiten and Blok, 2003).

Strip Casting is a manufacturing process that works with material in the semisolid state, combining fast cooling rates (around 1000 ºC/s) and rolling (Menet et al., 2001). Many recent studies have focused on increasing the quality of the strips produced by this technique in regard to microstructure homogeneity (Shi and Shen, 2018), reduction of segregation (Kim et al., 2018; Sun et al. 2017) and mechanical properties (Lima Filho et al., 2019; Wang et al. 2016) by changing the parameters of the process.

Boron nitride is a ceramic insulator often used as a lubricant in die cast aluminum production due to its low wettability on molten aluminum (Eichler and Lesniak, 2007), and thus could be used as a protective coating against oxidation on the rolls of the Strip Casting resulting from the contact with the worked material in high temperatures.

Although this process can lead to a fine grain structure, defects such as uneven microstructure, segregation and coarse grains have been reported (Barekar et al., 2016; Shi and Shen, 2018). These problems could be dealt by additions of grain refiners such as TIBAL and even increase the mechanical properties of the product (Kashyap and Chandrashekar, 2001).

Despite the common usage of TIBAl, for Al-Si alloys above 3wt% silicon content, TIBAL has shown poor refining power when conventional casting is performed, a phenomenon called poisoning (Lee et al. 1999; Qiu et al. 2007). In order to explain the phenomena, Easton et al. (2014) suggested a mechanism but highlighted that the poisoning effect of silicon remains elusive, which can be explained by the many different mechanisms of poisoning proposed in the literature (Easton et al. 2014; Qiu et al. 2007; Quested et al. 2006). However, the drawback of TIBAL can be bypassed employing other refining alloys such as Nb and B based nuclei, which also provides powerful nucleation sites (Apparao et al. 2018; Bolzoni et al. 2016; Sigworth et al. 2007).

The final microstructure will then be a junction of parameters, such as alloy composition, chemical additions and solidification rates. This last effect can be directly related to the formation of the eutectic phase out of equilibrium on eutectic alloys (e.g.: Al-Si A413) as will be shown in this work. For this alloy, the formation of a pure eutectic structure can be achieved at hiper-eutectic alloy compositions, due to the difference in growth characteristics: 1. Diffuse growth for Al-α; 2. Faceted growth for Si. In fact, in eutectic Al-Si system, Al-α dendrites can be found at the exact eutectic composition at high solidification rates (Magnin and Kurz, 1978). Therefore, in the eutectic Al-Si system, quenching must be applied to hiper-eutectic alloys to obtain only Al-Si eutectic phase. This phenomenon of eutectic growth in the coupled zone (Kurz and Fisher, 1979) has deep influence on the control of the microstructure depending on the application of the product.

This work aims on obtaining A413 strips using the Single Roll Strip Casting technique, comparing the efficiency of the roll's surface finishing under two conditions (i.e. NB coated and uncoated using 1200 grit sand paper) and grain refiner TIBAL (Al-5Ti-1B). The effect of the B as a promissory element to amplify the Al-Si coupled eutectic region is suggested in this work.

2. METHODOLOGY

The composition of the aluminum alloy A413 utilized is shown in the Tab. 1. 1.3 g (around 0.1 wt.%) of TIBAL (Al – 5% Ti – 1% B) alloy was added for grain refinement.

Table 1. Chemical composition of the A413 aluminum alloy (wt.%).

Si	Fe	Ti	Sr	Mn	Mg	Cr	Ni	Ga	V
11.3	0.1	0.11	0.02	0.02	0.001	0.001	0.004	0.003	0.008

The manufacture of aluminum strips was carried out on a laboratorial Strip Caster using the Single Horizontal Roll method. This machine has a carbon steel roll with a diameter of 105 mm and a working face of 100 mm. The schematic diagram of the Single Roll Horizontal Strip Caster is shown in Fig. 1. Aluminum strips with width of around 45 mm were cast with a roll surface speed of 0.2 m/s and pouring temperature of approximately 680 °C. For each procedure, 1300 g of A413 was melt in an electric resistance furnace and strip cast under three conditions: 1.) NB coated roll with no addition alloys to the cast material; 2.) no coating on the roll with a surface finish done with 1200 grit sand paper (a finish which guaranteed both a good wettability of the molten material with the steel roll and also a good finish of the surface of the strip solidified on the roll) and no addition alloys to the melt; and 3.) no coating on the roll with a surface finish done with 1200 grit sandpaper and 1.3 g TIBAL added to the melt using a steel bell to manually stir the molten alloy.

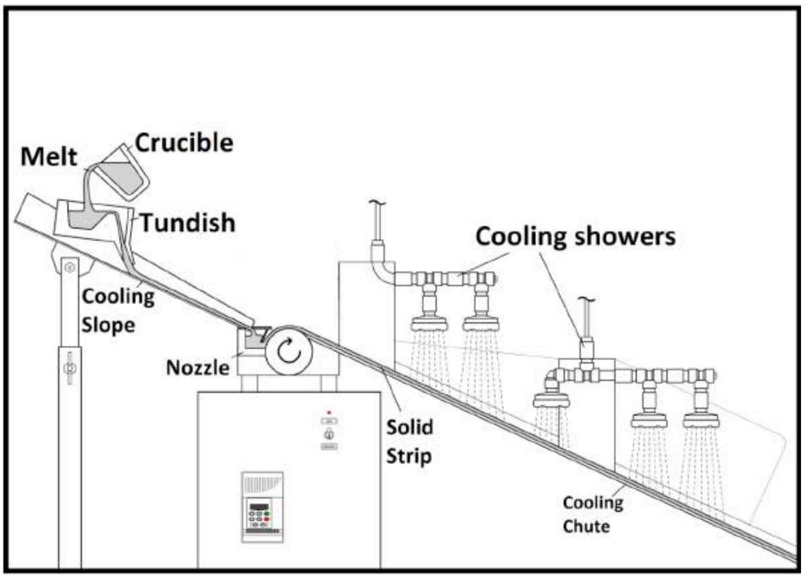

Figure 1. Schematic diagram of the machine used for manufacturing the strips.

In order to analyze the microstructure of the strips produced on each condition, optical microscopy was carried out using an Olympus BX51 microscope with specimens grounded and manually polished with abrasive alumina and finished with colloidal silica, no chemical reagents were used to reveal the microstructure. To observe the solidification structure on the strip surface a scanning electron microscopy (SEM) was used (Carl Zeiss Electronic microscope – model EVO LS15). To evaluate yield strength, tensile strength and elongation at failure, a tensile test machine EMIC – model DL 100kN was used according to the ASTM E8M (Fig. 2). Just one specimen available was tensile tested for the first and second condition and for the third condition, three samples were tensile tested.

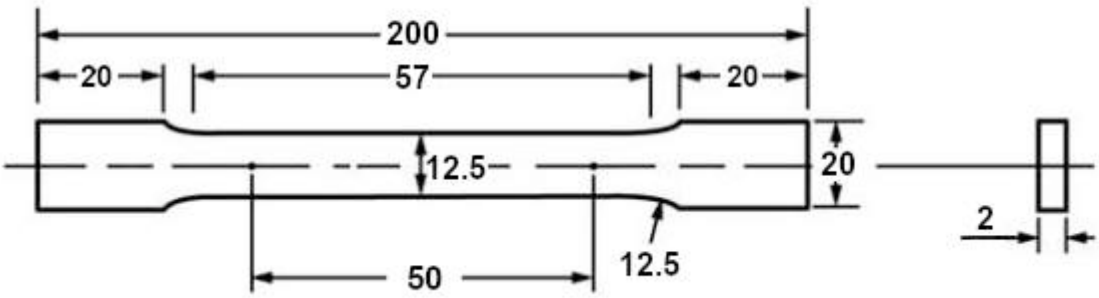

Figure 2. Schematic drawing of the tensile samples (ASTM E8M). Unit: mm.

3. RESULTS AND DISCUSSIONS

For the first condition three procedures to produce a strip were needed. Due to the low wettability of the molten aluminum on the NB surface, the roll showed poor heat exchange, which resulted in an incomplete solidification and the dragging of liquid material occurred, as can be seen in Fig. 3 (a) for the first condition during the first run. At the second run of this same condition, the same effect took place and no strip was produced. At the third run, probably due to the wear of the NB layer caused by the other tests, it was possible to cast a small piece of strip. In fact, this can be explained by the better contact between the molten aluminum and the steel roll surface promoting a better wettability. Thus, a strip was produced (with a length of about 50 cm) enough for one coupon for tensile test. The microstructure of this strip revealed several flaws (Fig. 3 (b)) and a compromise of the surface texture, in comparison with the other conditions.

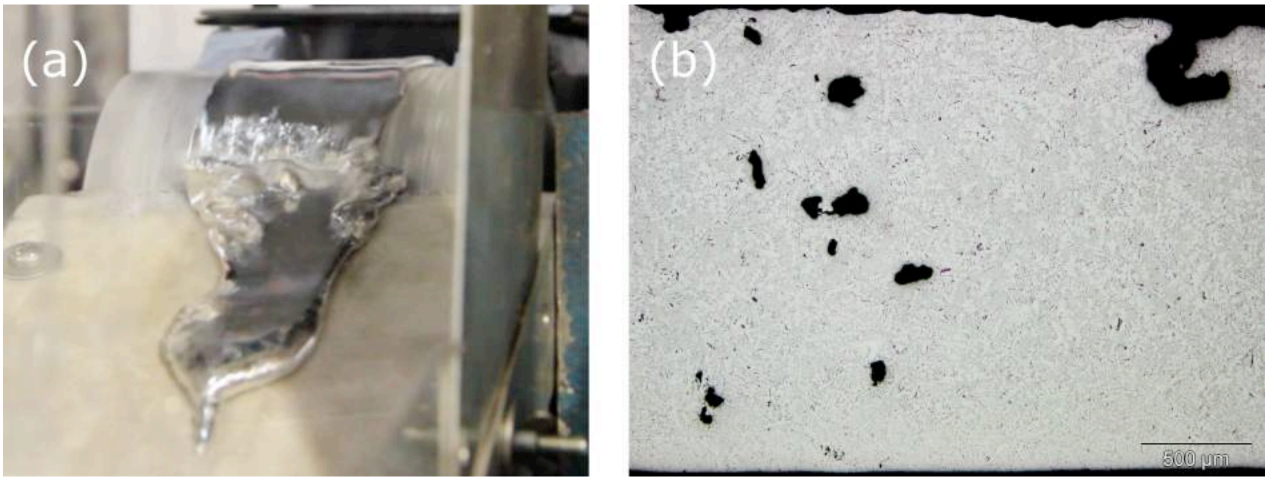

Figure 3. Liquid leaving the NB coated roll caused by the poor wettability of the molten aluminum on the NB surface with a width 45 mm (a) and microscopy of the strip produced at the first condition showing several voids (b) (the direction of rolling is from left to the right, and the lower part of the microstructure is the one in touch with the roll, as with all the other microstructures).

At the second condition an oxidized layer on the uncoated roll surface was formed, Fig. 4a. A continuous strip with approximately 2 mm thickness and length 11 m approximately was obtained. A blue layer formed characterizing a blue brittleness of the steel by heating from 205 ºC to 370 ºC) (Cotell, 1994).

At the third condition air spray was used in a tentative to cold down the roll surface to avoid oxidation. The dragging of the semisolid material did not occur properly to produce a complete cast strip. However, a small cast strip was obtained. The rest of the metallic slurry infiltrated between the roll and the Teflon plate used to direct the strip to the cooling showers and a casing formed around the roll, Fig. 4(b). This suggests that an air bed formed between the roll surface and the metallic slurry when the nozzle was completely full interrupting the production.

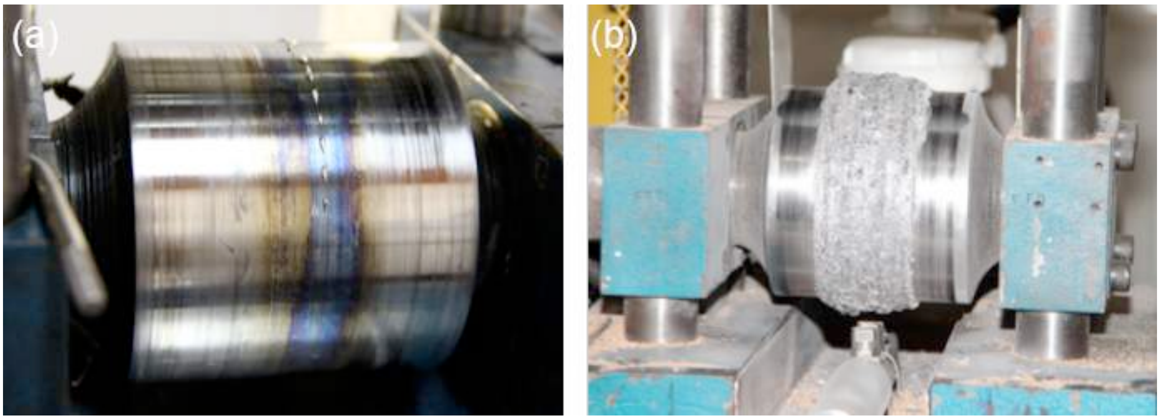

Figure 4. Oxidized roll surface for the second condition (a) and strip stuck on the roll surface after running approximately 10 seconds at the third condition (b).

Fig. 5 shows the micrographies for the three conditions taken transverse to the rolling direction of the cast strip. The samples analyzed here are in contact with the lower roll surface and hence suffers the highest heat extraction by conduction in comparison with the layer facing the atmosphere. Fig. 5 (a) shows the first condition that resulted in a coarse Al-ɑ surrounded by needles of Si in some areas. This could be related to the poor heat transfer the metallic slurry on the coated roll surface. However, few regions indicate the modification of the eutectic Al-Si can also be observed. In addition, the poor wettability of the Al-Si alloys on the NB is in accordance with the work of Eichler and Lesniak, 2007. In contrast, a fine grain structure is seen on the specimens cast without the coating on the roll, Fig. 5 (b) and (c) indicating a high heat exchange. A thorough analysis between these two microstructures suggests that the specimen with TIBAL has a fine non banded eutectic structure. Hence, the columnar structure was not formed in comparison with the sample without TIBAL addition. In other words, a more isotropic structure formed, probably due to the refining action induced by this addition (Kashyap and Chandrashekar, 2001).

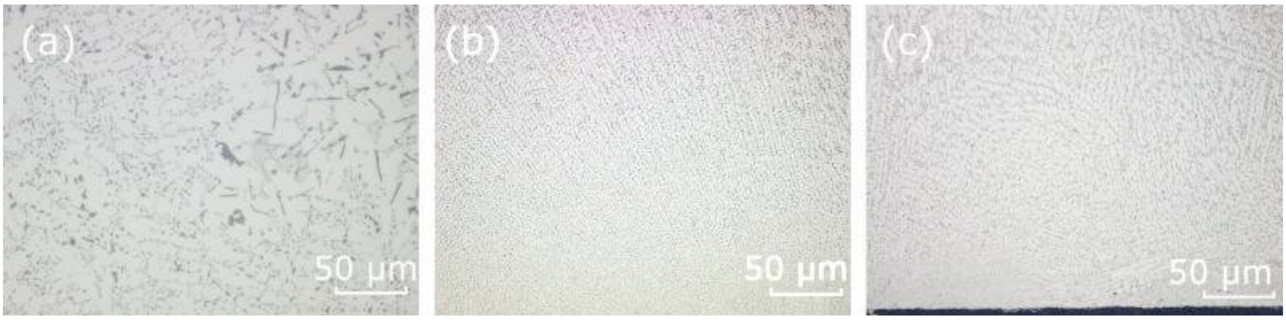

Figure 5. Specimen cast on a BN coated roll without additions to the melt (a), roll grounded with sandpaper without addition alloys (b) and uncoated roll with TIBAL added to the melt (c). Samples facing to the roll surface.

Figure 6 shows the microstructures at the region of the strip facing the atmosphere. A refined eutectic structure as well as finer dendrite Al-α are observed in Fig. 6 (c) in comparison to the other strip cast situations (Figs. 6 (a) and (b)). The poisoning effect did not happen when using TIBAL in this case, suggesting that the poisoning reaction kinetics need a time to occur. Therein also seems that the additions of Ti and B have enlarged the coupled zone of the formation of Al-Si eutectic which reduced the Al-α phase during the solidification of the strip, Fig. 7. Fig. 6 (b) shows some spots of coarse Al-ɑ with some silicon needles, although regions with fine eutectic grains are also observed. This fine structure is very rare at Fig. 6 (a) with coarse grains of Al-ɑ. These structures are related to the low solidification velocity on the layer of the metallic strip facing the atmosphere.

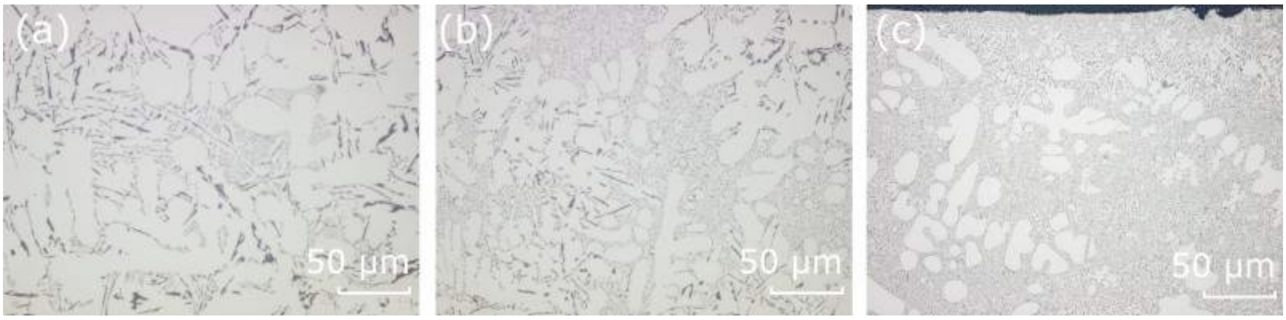

Figure 6. Coarse grains visualized at the strip cast on the BN coated roll without additions to the melt (a), spots of refined grain structure as a result of the rapid solidification on the uncoated roll without TIBAL (b) and a lower fraction of Al-α structure at the alloy treated with TIBAL on the uncoated roll (c).

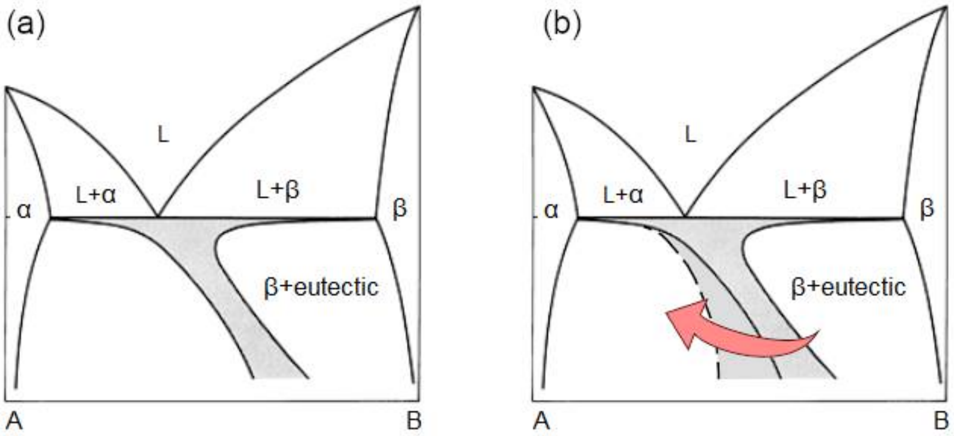

Figure 7. Eutectic coupled zone in Al-Si alloys (a) and suggested enlargement of the zone by the Ti or B (b).

SEM images of the specimen treated with TIBAL at the region in the beginning of the cast strip formation at the roll surface, Fig. 8. The structure shows when the liquid phase rich in silicon fill the Al-α phase, Fig. 8 (a). Figures 8 (b) and (c) make evident the superior quality of the structure as a result of both the high velocity of the solidification (naturally expected from the Strip Casting technique) and the refining grain effect of TIBAL. Dendritic structures in degeneration are observed being coated by the eutectic phase. This isotropic growth due to the high solidification rates resulted in a globular structure.

Table 2 shows mechanical properties obtained by the tensile test of the three conditions studied. The data demonstrates an increase on the yield strength and tensile strength as a result of the refined structure shown previously. However, the elongation at the fracture did not show this same behavior. The highest elongation was shown by the specimen with no additions to the alloy cast on uncoated roll. The lowest elongation was observed on the strongest specimen. This might be related to an increase in the generation of the eutectic phase observed in Fig. 6, resulting in a loss of ductility. On the other hand, it was observed intermediary elongation on the specimen cast on the BN coated roll, probably due to a more facilitated generation of eutectic around the Al-α phase. The sample with no TIBAL addition suffered a natural refining effect on some parts of its eutectic phase due to the high solidification speed, which occurred between the relatively coarser Al-α (i.e. in comparison with the sample treated with TIBAL). This corroborates with the higher ductility and intermediary strength as shown in Tab 2.

Table 2. Mechanical properties of the strips cast under the three conditions.

Specimen	**Yield Strength (0,2 %)**	**Tensile Strength**	**Elongation (%)**
BN	71,0 MPa	87,3 MPa	1,5
No Additions	80,9 MPa	121,5 MPa	2,8
TiBAl	100,9 MPa	136,4 MPa	1,0

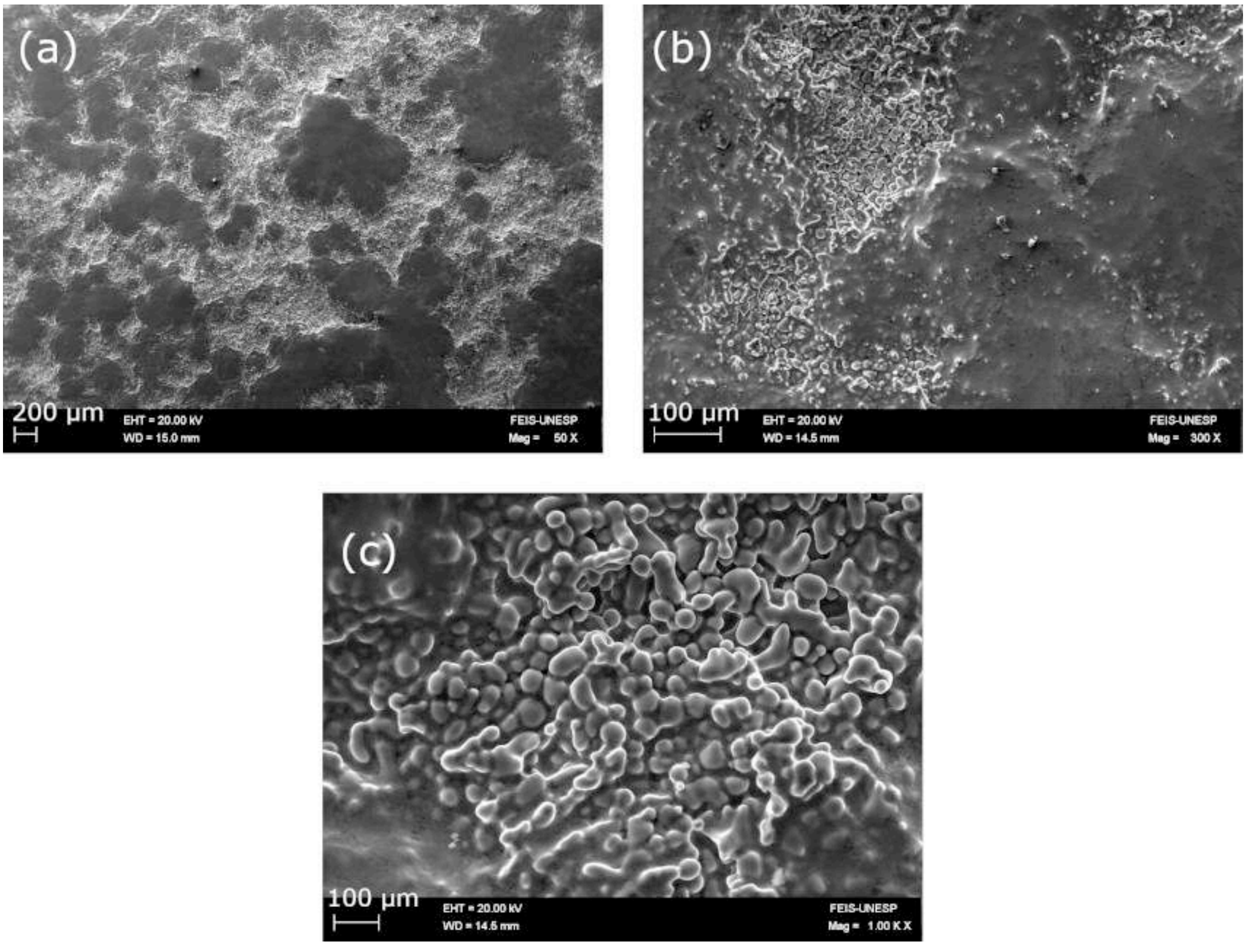

Figure 8. SEM images of the specimen cast on the uncoated roll treated with TiBAl in three magnifications: 50x (a), 300x (b) and 1000x (c).

4. CONCLUSIONS

The microstructures and mechanical properties of the Al-Si A413 strips as achieved can lead to the following conclusions:

1. Coating the roll with boron nitride protected it against oxidation which could lead to a higher life equipment. On the other hand, coarse grain structure throughout the entire thickness of the strip was obtained and the overall procedure showed to be unpractical due to the poor wetting.
2. There was a relevant increase on the strength (e.g. from 71,0 to 80,9 MPa in yield strength) and elongation (from 1,5% to 2,8%) of the strip by using an uncoated roll.
3. TIBAL promoted a bigger increase on the strength of the strip, but lowered the elongation. Further research is needed in order to obtain optimal alloy properties.
4. The action of Ti and B could be important on the shape of the coupled zone of the eutectic growth of the Al-Si system.
5. The grain refiner addition developed a more isotropic microstructure at the upper layers of the strip and modified the columnar zone.
6. Although it was reported that poisoning could affect eutectic Al-Si alloys through addition of TIBAL, this effect was not observed and needs further investigations about the poisoning kinetics mechanism.

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