On the quality of A354 ingots and its impact on cast product

[1]S. Akhtar, [2]R. Molina, [3]M. Di Sabatino, [1]L. Arnberg
[1]Department of Materials Science and Engineering, NTNU, NO-7491 Trondheim (NORWAY)
[2]Teksid Aluminum, Carmangnola (ITALY)
[3]SINTEF Materials and Chemistry, NO-7465 Trondheim (NORWAY)

ABSTRACT

A study in an automotive casting plant was targeted to address the problem of high rejection rate of a cylinder head casting made from an A354 alloy. Ingots of an A354 alloy from three different suppliers, A, B and C, were analyzed by the reduced pressure test (RPT) and the pressure filtration (PREFIL) test, individually as well as in combination. Hydrogen measurements during casting trials was carried out with an ALSPEK H® analyzer. The results have shown a good agreement with the scrap rate data of the final cast product, and the problem of higher scrap rate was significantly reduced when the ingots of an A354 alloy with the highest oxide content from supplier C were replaced. In order to study the influence of transfer and de-gassing on the melt quality, reduced pressure tests were also conducted along the production line. The effect of melt holding time on the quality of the cast product is also presented. The results from these trials shows that the bi-film index data from the RPT has a potential to be used in an industrial environment for routine melt quality control as the cause of high scrap was successfully identified with this technique.

RIASSUNTO

Questo studio, condotto presso una fonderia di componenti automobilistici, ha analizzato il problema di un elevato livello di scarto rilevato su di una tipologia di teste cilindri prodotta, per colata a gravità, con una lega della famiglia A354. Lingotti di lega A354 provenienti da diversi fornitori, denominati A, B e C, sono stati analizzati e confrontati con i metodi RPT (solidificazione a pressione ridotta) e Prefil (filtrazione sotto pressione). Il livello di idrogeno nel bagno metallico è stato misurato e monitorato con ALSPEK H®. La lega prodotta dal fornitore C ha fatto evidenziare livelli più alti di inclusioni/ossidi e i risultati dei controlli sul prodotto hanno mostrato che la percentuale di scarto si è ridotta notevolmente quando questo fornitore è stato sostituito. Inoltre, per studiare l'effetto delle pratiche di trasferimento e degasaggio della lega liquida sulla qualità dei getti, il metodo RPT è stato applicato in vari punti della linea di produzione. Nel presente lavoro sono anche presentati gli effetti sulla qualità dei prodotti finali del tempo di permanenza della lega liquida nel forno di mantenimento, prima del suo utilizzo. I risultati delle prove effettuate hanno mostrato che un nuovo parametro, definito come "indice bi-film" che misura la quantità di doppi film di ossido (ripiegati su se stessi) presenti nel bagno metallico, può essere impiegato a livello industriale per monitorare la qualità della lega e ridurre gli scarti di produzione.

KEYWORDS

A354 alloy, melt quality, RPT, PREFIL, hydrogen, bi-films.

INTRODUCTION

A need for improved properties, lower production cost and greater strength/weight ratio has forced the replacement of cast or forged ferrous parts by aluminium alloy castings in many critical applications [1]. The high property requirement of aluminium castings has required superior melt quality and melt treatment processes and a more stringent control on melt cleanliness with respect to inclusions and hydrogen content to minimize microporosity [2]. The molten metal quality must be monitored and controlled at all stages of the manufacturing process [3]. To obtain high performance castings, the quality of molten metal must be optimized prior to final pouring operation, i.e., the melt must be free from inclusions, impurities and dissolved gases. There are two main groups of techniques for controlling and monitoring the cleanliness of the molten metal [4] respectively:

1. Inclusion removal techniques such as fluxing, flotation, sedimentation and de-gassing [4].
2. Inclusion measurement techniques, which include filtration systems such as

PoDFA (Porous Disc Filtration Apparatus), PREFIL, and non-destructive such as the ultrasonic and LiMCA (Liquid Metal Cleanliness Analyzer) techniques [4].

The two important interactions that take place between an aluminium melt and its environment are the absorption of hydrogen and the formation of oxide films. It is impossible to prevent the formation of oxide on the liquid aluminium surfaces. The formation of the alumina oxide film is an important part of the melting process for the reason that it protects the metal beneath from further oxidation. The problem occurs when an oxide film is entrained in the melt during foundry operations like charging, fluxing, and degassing, skimming, transferring, mould filling. The entrainments events are surface folding actions in which a non-wetting surface film is folded over against itself with gas trapped in between two halves. This constitutes a defect that will act exactly like a crack in the liquid and is known as double oxide film defect or a bi-film [1]. The most commonly used technique for bi-film index measurements is the RPT which is fast, simple and low cost. The RPT can be used to measure the effect of both detrimental defects i.e., hydrogen and bi-films, but it cannot be used to quantify the hard inclusions, so for good assessment of melt quality RPT must be combined with PREFIL or PoDFA tests [5, 6]. Di Sabatino et al. [7] and Kwon and Lee [8] have studied the effect of oxide inclusions on fluidity, with the conclusion that increasing oxides content decreases fluidity. An extensive review of inclusion measurement methods has been presented by Dispinar and Campbell [9]. More details about the procedure and use of the RPT test to measure the bi-film index and its acceptance criteria are given in the References [10-11]. Dispinar and Campbell [12-13] have shown that high quality castings can be made even without de-gassing provided that there is a (i) minimization of turbulence at tapping, (ii) minimized fall of liquid and (iii) filling conditions to reduce turbulence in the mould.

For the aluminium alloys, the first source of bi-film and inclusions is at the aluminium smelter. This first addition of bi-film is supplemented by a second population introduced by pre-alloying. Several more populations follow in the foundry by melting, pouring into a transfer ladle, holding furnace and finally pouring into the mould [10, 14]. These cracks like defects remain suspended in aluminium melts for a long period of time. If frozen into the casting, they can severely reduce the mechanical properties. Therefore, the potential for improving aluminium casting lies principally at the melting and casting stages where hydrogen gas and oxide films may be removed from the melt [1].

The work presented in this study focuses on the investigation of the problem of high rejection rate at an automotive casting plant associated to a cylinder head casting. In foundry the castings under investigation were usually made from the mixture of an A354 alloy from three different suppliers in an uncontrolled proportion. In an attempt to solve this problem, a number of systematic experiments were carried out to assess the melt quality with RPT, PREFIL tests and an ALSPEK H® analyzer was used for hydrogen measurements. This paper presents the results of the characterization from these castings trials.

EXPERIMENTAL PROCEDURE

The chemical composition of an A354 alloy from the three different suppliers (A, B and C) is given in Table 1.

Table 1: Chemical composition in wt (%) of an A354 alloy from different suppliers

Supplier	Si	Cu	Mg	Mn	Fe	Ti	Sr	Na	Al
A	9.04	1.124	0.422	0.005	0.116	0.023	0.0015	0.0001	Bal
B	9.37	1.085	0.499	0.012	0.152	0.010	0.001	0.0001	Bal
C	9.03	1.168	0.484	0.004	0.194	0.011	0.0006	0.0007	Bal

For the melt quality study, nine laboratory scale experiments were planned. The ingots were investigated individually or in combination, and with or without scrap additions. The details of the design of experiments are given in the Table 2.

For all the experiments, the casting parameters were carefully controlled to ensure the same set of casting conditions for each experiment. The casting parameters were:

- Melting and casting at a constant temperature of 740°C in a 10 kg electric resistance furnace.
- Similar pouring procedures.
- RPT at the pressure of 100 mbar.
- Coating of the PREFIL crucibles and RPT cups with boron nitride.
- Pre-heating of the PREFIL crucible and RPT cups at the same temperature.

Furthermore, scrap casting of an A354 alloy made mainly from the suppliers B and C were also re-melted and subjected to similar tests. Melt quality tests were conducted along the production line (from the taping of the melting furnace till the final pouring station) to observe the change of melt quality during the transfers procedures and de-gassing treatments. The RPT and PREFIL test samples were also taken after one day and two weeks from the holding furnace to study the effect of the melt holding time on the melt quality. In all the experimental trials hydrogen measurement was carried out with an ALSPEK H® analyzer. The principle of operation of an ALSPEK H® analyzer is given elsewhere [15]. In order to study the possible difference in solidification path of an A354 alloy from three different suppliers, thermal analysis was also carried out by using K-type calibrated thermocouples.

Table 2: Design of experiments of the melt quality study

Experiment No	Combination (wt %)
1	A (100)
2	B (100)
3	C (100)
4	A+B (50+50)
5	A+C (50+50)
6	B+C (50+50)
7	A+B+C (33+33+33)
8	A+B+C (23+23+23) Scrap (30)
9	Scrap (100)

RESULTS AND DISCUSSION

The thermal analysis curves of an A354 alloy from the supplier A, B and C are shown in Figure1 (a). The derivative of the curve from supplier A material is shown in Figure 1 (b).

The temperature where the dendritic network starts to grow is approximately 583 ± 3 °C for all three alloys, and the eutectic growth temperature is 566 ± 1 °C, which show that they are similar in terms of solidification path.

The results from the RPT in terms of bi-film index are shown in Figure 2a for an A354

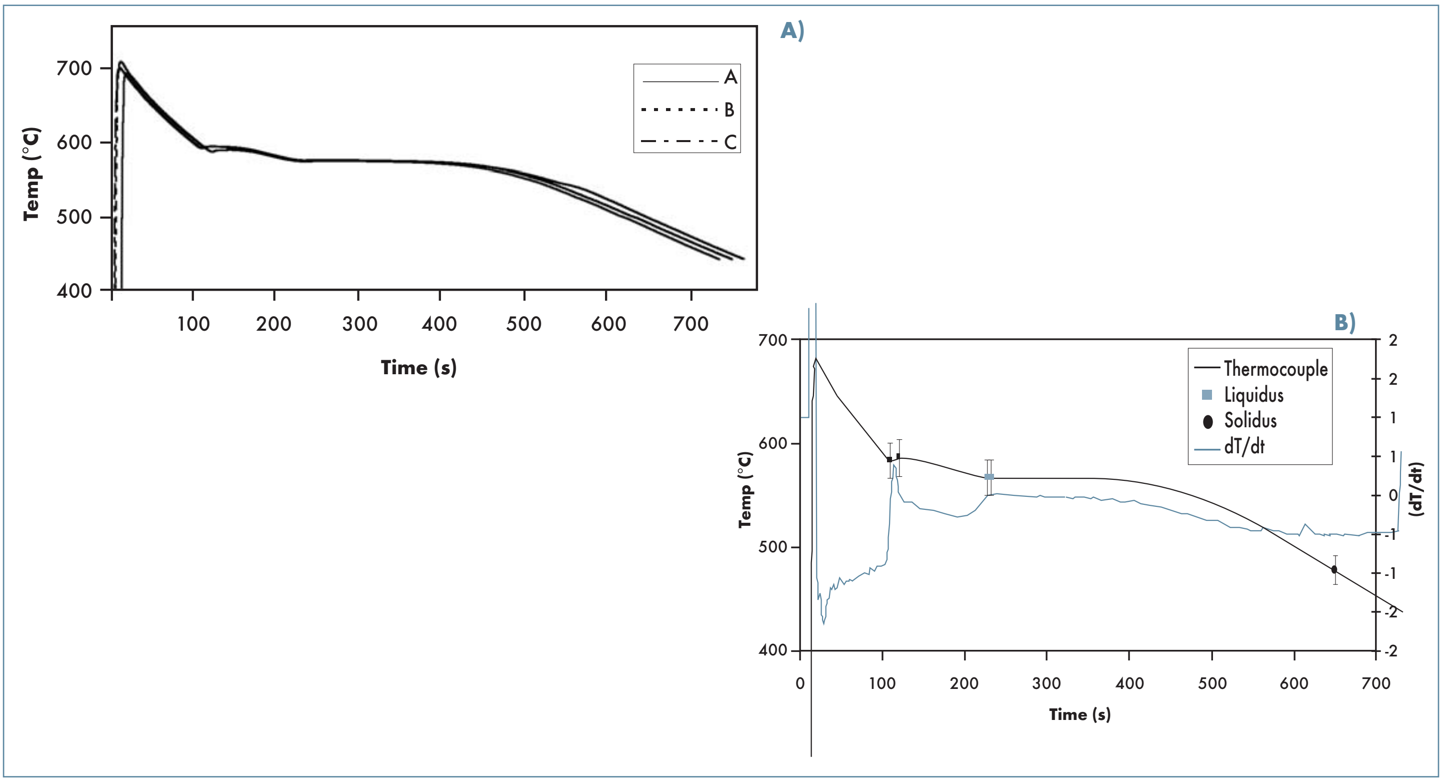

Fig. 1: (a) and (b) Cooling curves for an A354 alloy from three different suppliers and corresponding derivative for curve A.

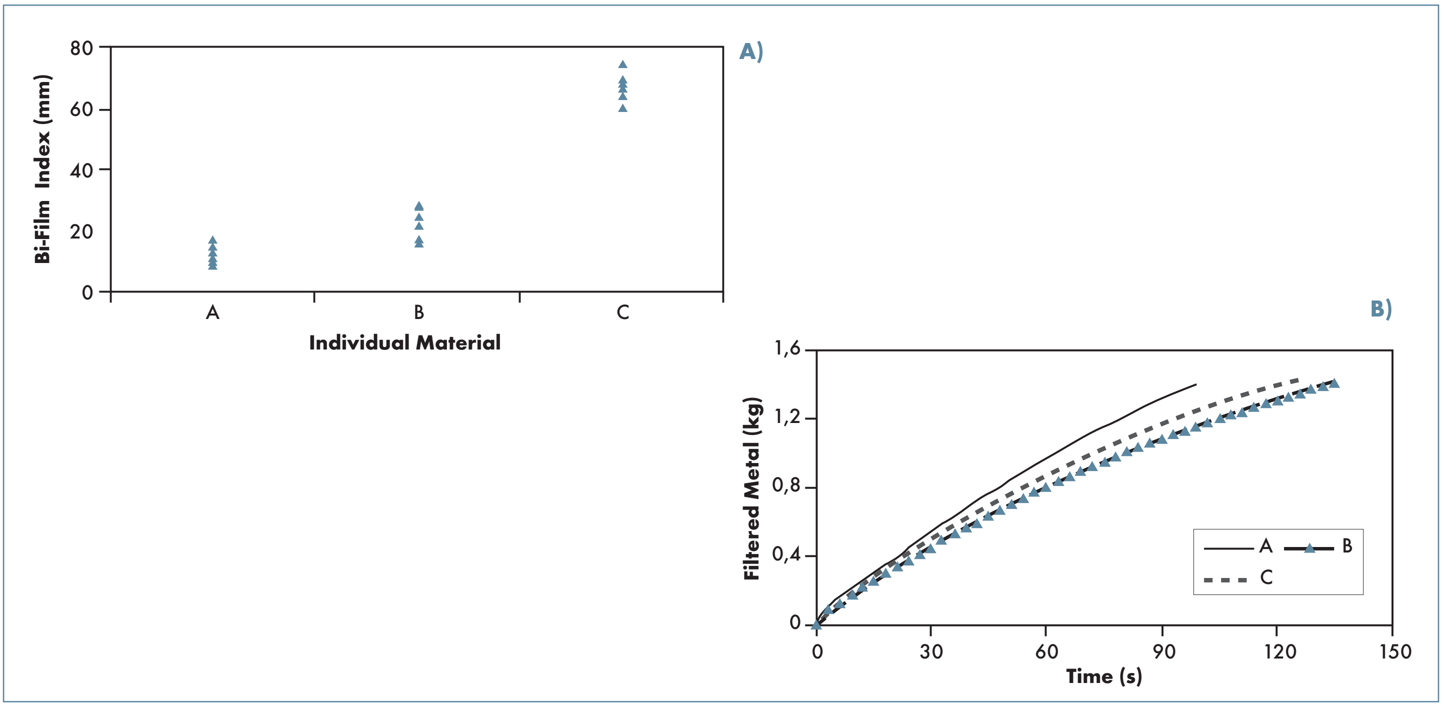

Fig. 2: (a) Bi-film index measurement and (b) PREFIL flow curves for the individual ingots of an A354 alloy from the supplier A, B and C.

alloy from the three different suppliers, when melted and tested individually. The corresponding PREFIL flow curves from the same melts are shown in Figure 2b.

The bi-film index of the ingots from the supplier C is the highest amongst all. The average bi-film index values are 70, 13, and 23 mm for the suppliers C, A and B, respectively. The PREFIL flow curves in Figure 2 (b) also show that the ingots from the supplier A are the cleanest while the material from the supplier B and C have lower melt quality.

The metallographic analysis of the filters from the PREFIL tests in Figure 3 showed the presence of common inclusions like thin and thick oxide films, magnesia and spinel in the starting raw materials.

The bi-film index and the PREFIL flow curves for the ingots mixed in equal proportion by weight in different combination from three different suppliers are shown in Figure 4. When ingots from the supplier C were mixed with the ingots from supplier A and B the average bi-film indexes were 51 mm and 64 mm, respectively. The average bi-film index was 22 mm when the ingots from the supplier A and B were mixed. The same trend is also predicted by the PREFIL flow curves as shown in the Figure 4 (b).

The bi-films index and the PREFIL flow curves were calculated for the 100% scrap (which was mainly from the supplier B in the form of a risers and gating). The mixture (A+B+C) of the ingots from all the suppliers was also tested individually as well as with addition of 30% scarp. These results show similar behaviour in all the cases as shown in Figure 5 (a) and (b) for bi-film index measurements by RPT and the flow curves from PREFIL tests, respectively.

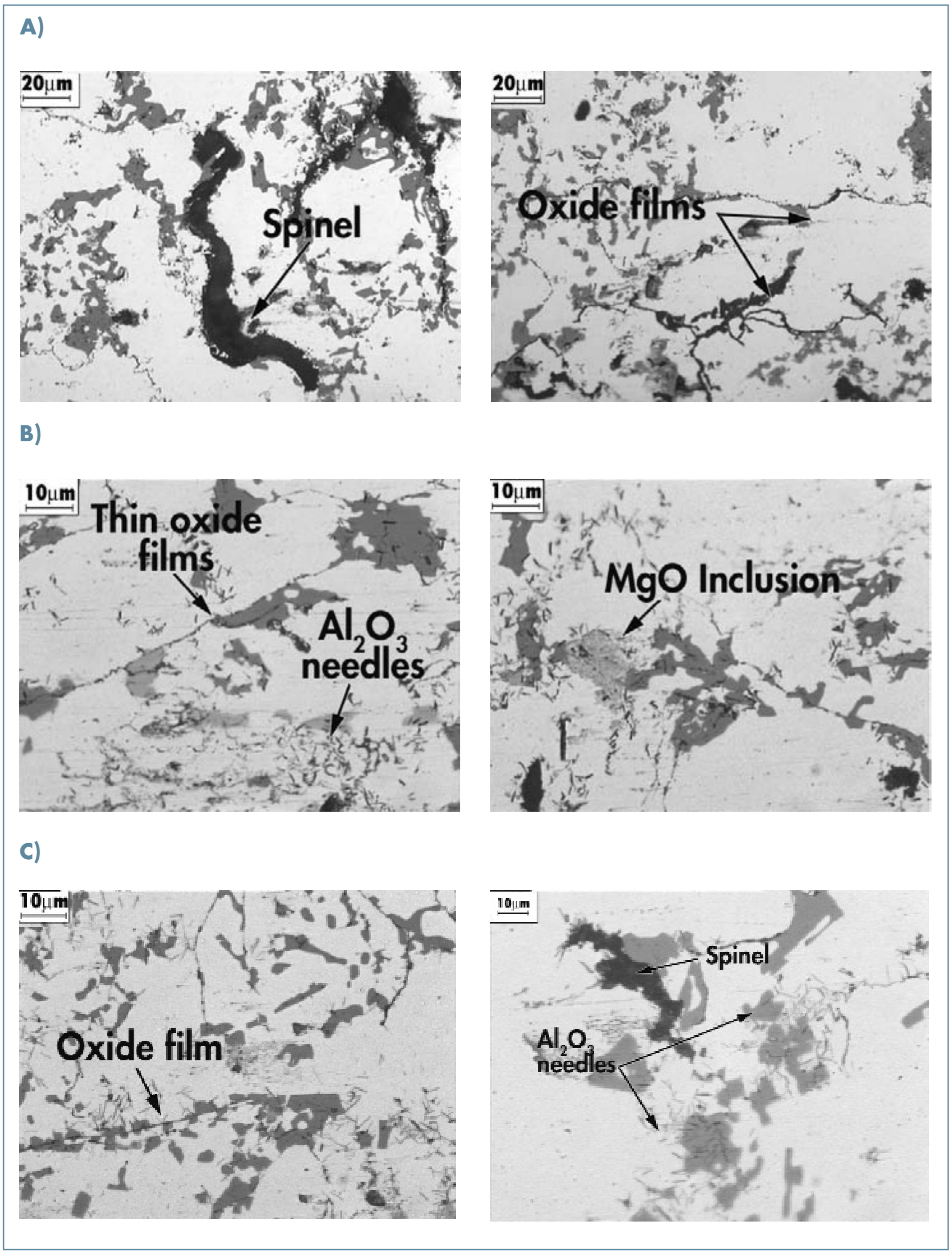

Fig. 3: Micrographs of the filters obtained from PREFIL test of the individual ingots from the suppliers (a) A, (b) B and (c) C.

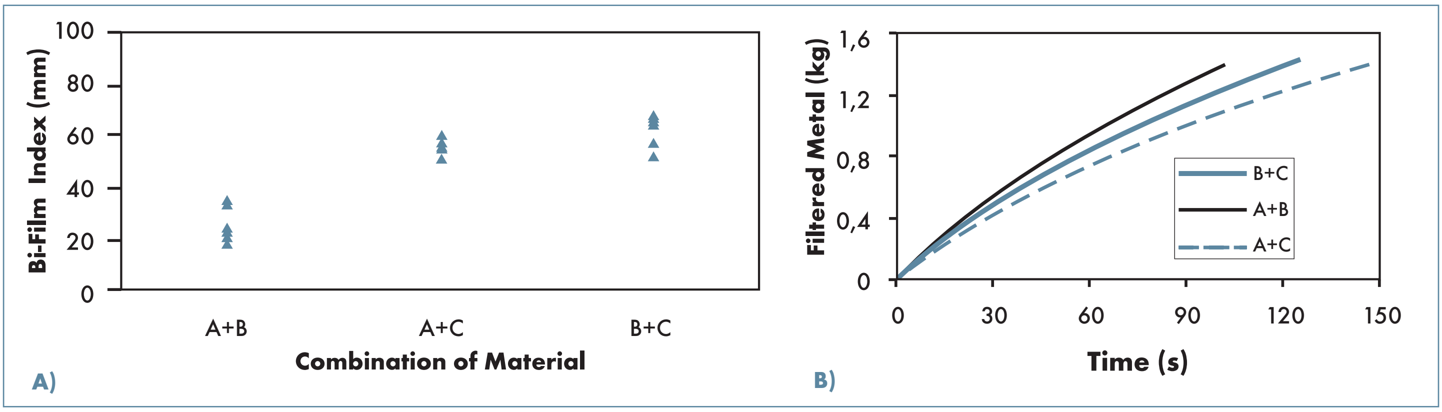

Fig. 4: (a) Bi-film index measurement and (b) PREFIL flow curves for the mixture of the ingots from supplier A, B and C.

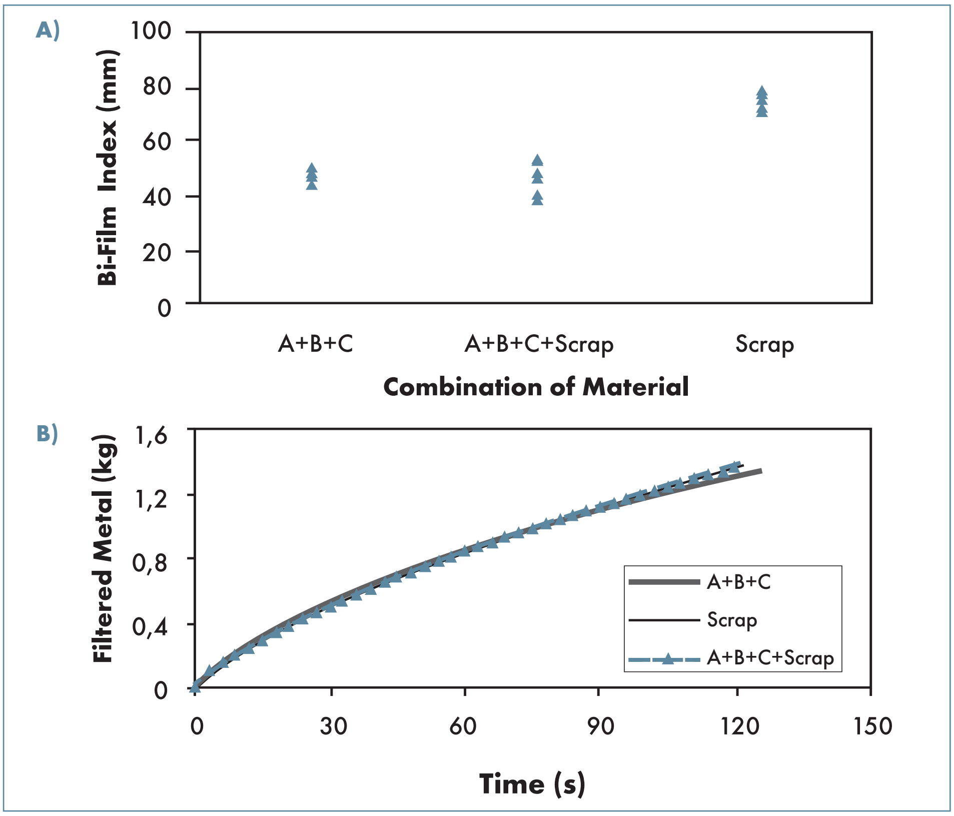

Fig. 5: (a) Bi-film index measurement and (b) PREFIL flow curves for 100% scrap as well mixture of an A354 alloy ingots from supplier A, B and C with and without 30% scrap addition.

Similar tests were also conducted on the scrap castings from the supplier B and C. The starting average bi-film index of the material from the supplier B was 23 mm, and it reached to the value of 74 mm after all the transfer procedures from melting to the holding furnace. In case of the material from the supplier C, the bi-film index reached the average value of 224 mm from the initial value of 70 mm. The bi-film index and the PREFIL flow curves from the scarp castings of the material from the supplier B and C are shown in the Figure 6. The change in the oxide length from the start to the end of the operation for these scrap castings is also illustrated with the images from the sectioned RPT samples in Figure 7.

The EDX analysis on fracture surfaces of the scrap casting from the ingots from the supplier C shows the presence of oxide layers and plate-like Al-Fe-Si crystals. The SEM images and the corresponding EDX spectra are shown in Figure 8. The long, needle-shaped iron rich intermetallic plates are reported to cause severe feeding difficulties during the solidification, due to

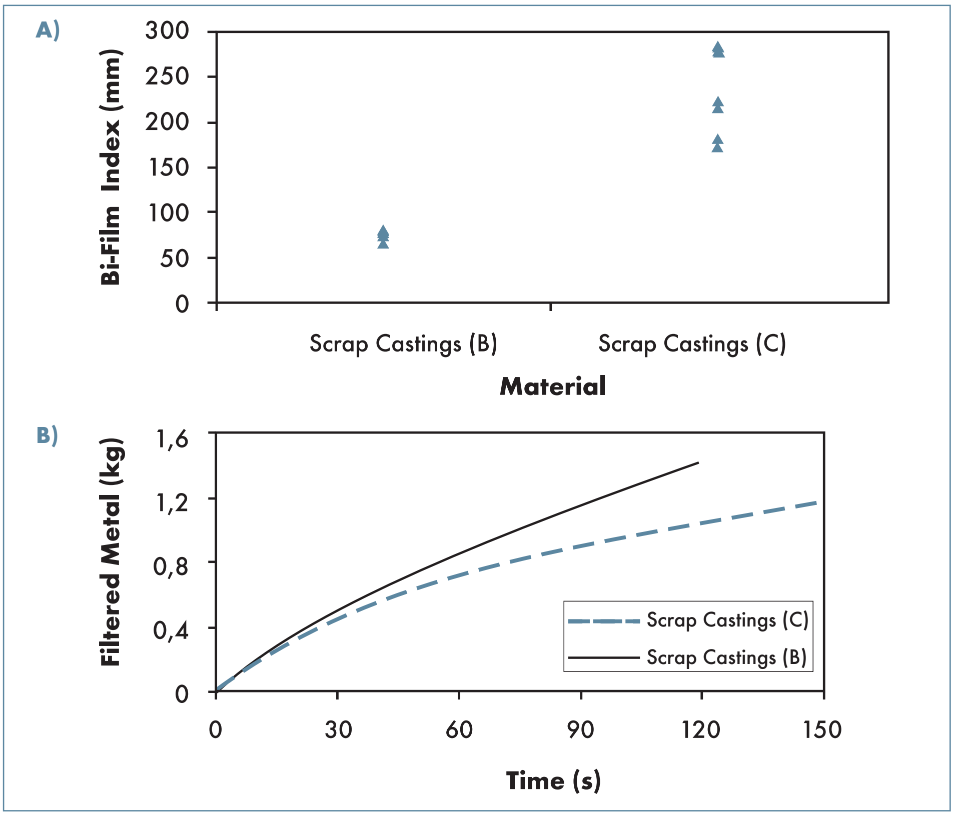

Fig.6: (a) Bi-film index measurement and (b) PREFIL flow curves of an A354 alloy scrap castings from the supplier B and C material.

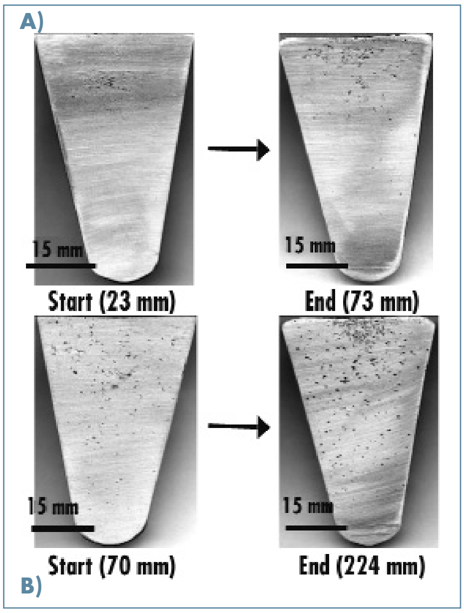

Fig.7: Sectioned RPT sample images for the alloys from the supplier (a) B and (b) C, respectively, from the individual ingots (Start) and from the scrap castings (End).

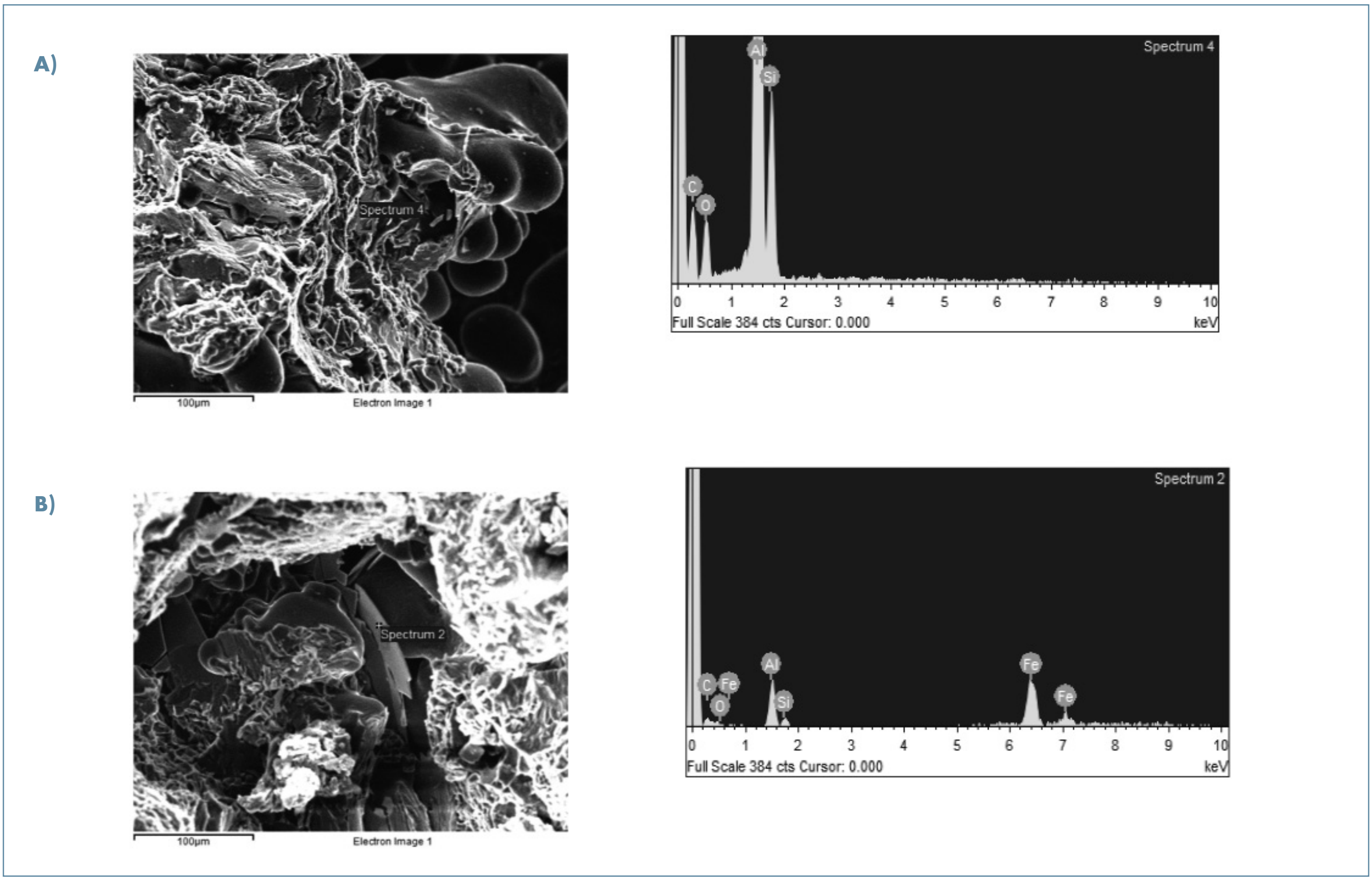

Fig.8: (a) and (b) SEM image and the corresponding EDX spectra show the presence of oxides and the Fe-plate.

the blockage of the interdendritic flow channels, which may lead to the shrinkage porosity [16].
The PREFIL and RPT tests were conducted on the melt from the holding furnace containing the ingots from the supplier B. The melt holding time was one day and two weeks at 740 °C. The results of the bi-film index measurements and PREFIL flow curves are shown in the Figure 9. The average bi-film index for one day and two weeks holding time was 100 and 297 mm, respectively. This indicates that the melt quality detoriates with the increase of the melt holing time. This might be caused by the air in the gap between the two halves of the bi-films that further oxidize the bi-film, thicken it and make it an inclusion type

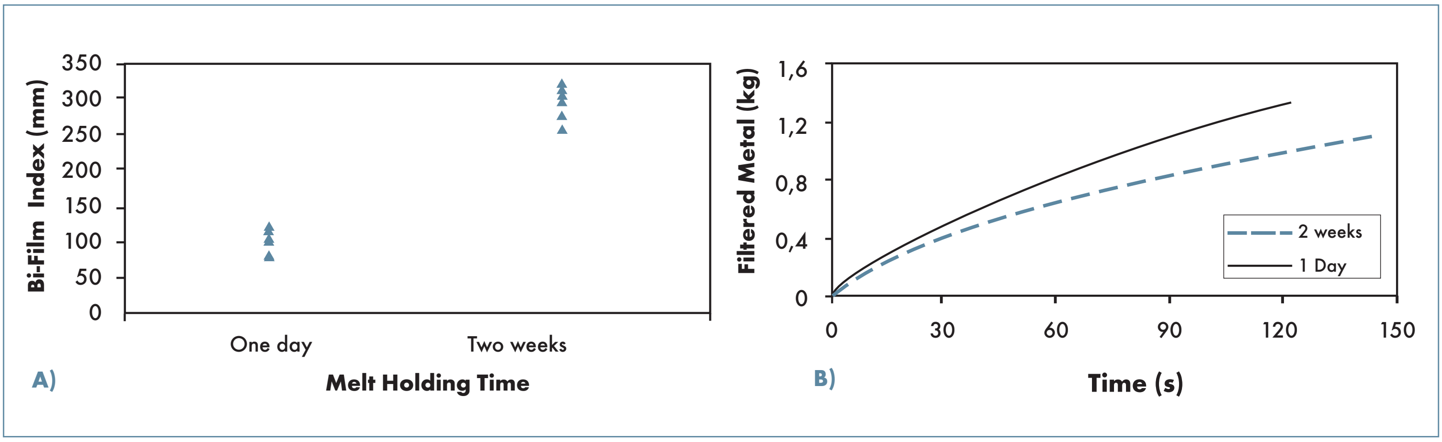

Fig.9: (a) Bi-film index measurement and (b) PREFIL flow curves for the one day and two weeks holding time for an A354 alloy melt from the supplier B.

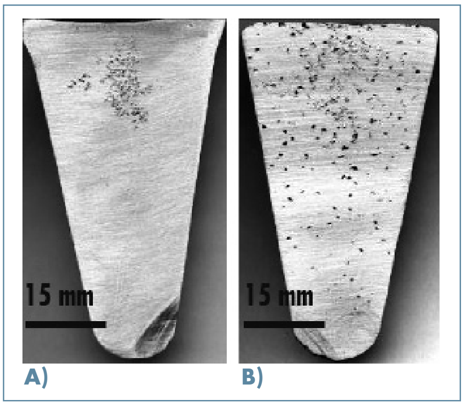

Fig.10: Sectioned RPT sample images for (a) one day and (b) two weeks holding time for the ingots from the supplier B.

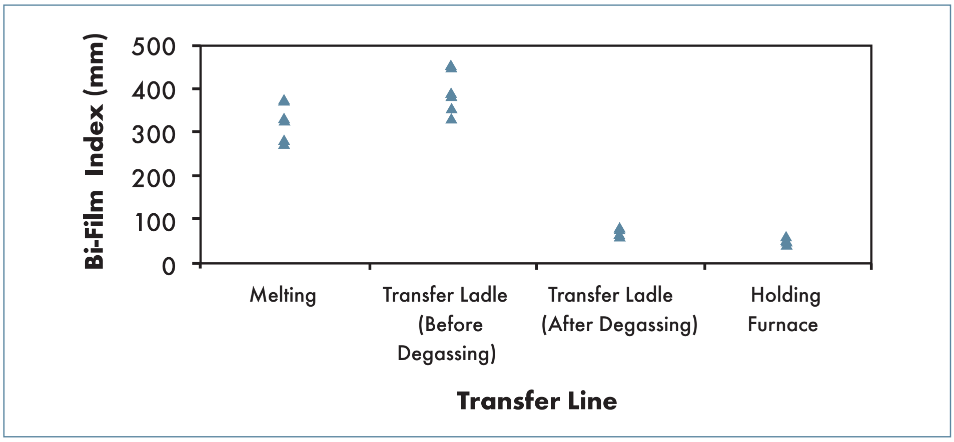

Fig.11: Change of the bi-film index from melting to the holding furnace for the melt from supplier B.

defect [6, 17]. The images from the sectioned RPT samples for one day and two weeks holding time are shown in Figure 10. The bi-film index measurements were also made on the RPT samples taken along the production line with the melt from the supplier B. The results are shown in the Figure 11.

Very high values of the bi-film index were observed when the melt was transferred from the melting furnace to the transfer ladle. After the nitrogen de-gassing in the transfer ladle for six minutes, the melt quality considerably improved in terms of the average bi-film index. In the transfer ladle after de-gassing, the bi-film index was reduced to 66 mm from an initial average value of 389 mm. The images of the sectioned RPT samples from the melting furnace, from the transfer ladle after nitrogen de-gassing and from the holding furnace are shown in Figure 12. These results show that it is important to degas the alloy when the transfer procedures are turbulent along the production line. The rising bubbles in the de-gassing process collect the bi-films/inclusions and raise them to the surface where they are removed [18-19]. Thus, the so-called de-gassing process cleans the melt from bi-films/ inclusions with simultaneous reduction in gas content. The RPT test can be used to assess the detrimental effect of both, the hydrogen content as well bi-films [6, 9]. However the hydrogen content tends to influence or somehow increase the bi-film index values by contributing toward the growth of oxide films and making them more visible in RPT sectioned surface [20].

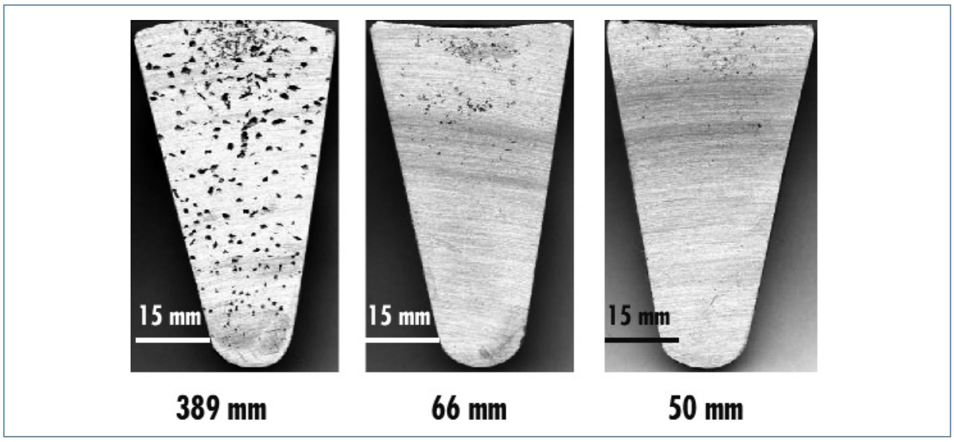

Fig.12: Sectioned RPT samples images showing the change of the bi-film index from melting to the holding furnace.

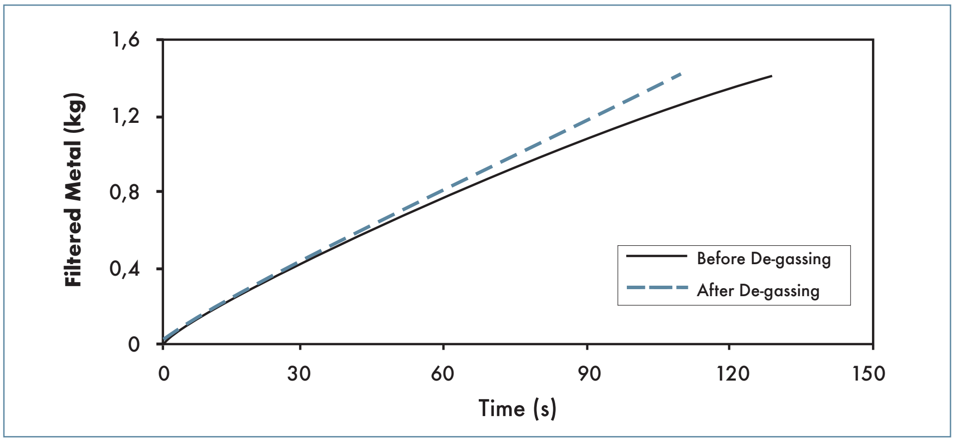

Fig.13: PREFIL flow curves before and after de-gassing.

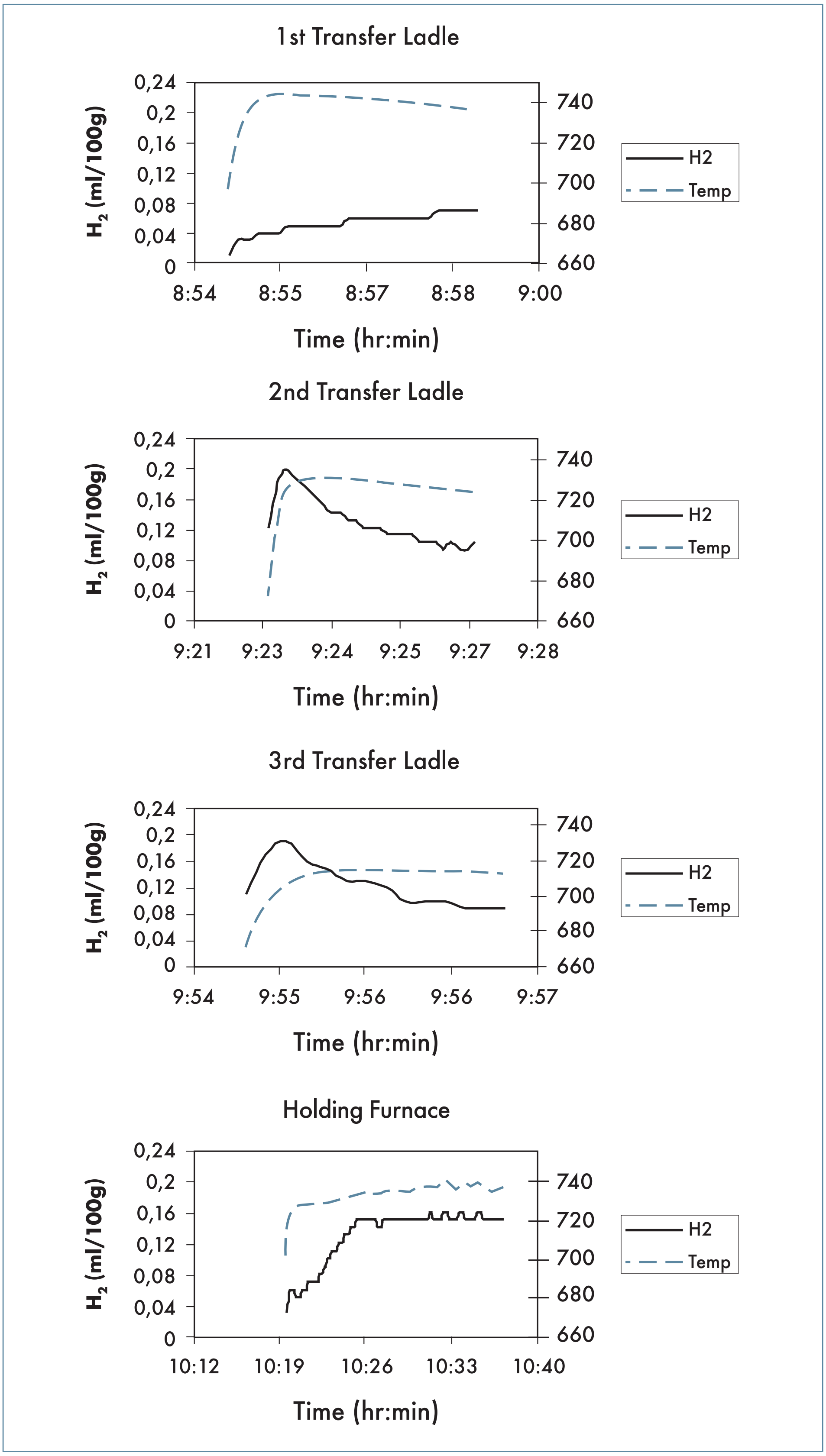

Fig.14: Hydrogen measurement in the transfer ladle and holding furnace (after nitrogen de-gassing).

It is difficult to assess here how much of the reduction in bi-film index is due to the hydrogen removal and how much is the effect of removal of oxides, both due to the de-gassing process. The PREFIL flow curves in Fig 13 show that the melt quality before and after de-gassing is similar.
The example of the hydrogen measurement in Figure 14 using an ALSPEK H® analyzer from three different transfer ladles after the nitrogen de-gassing and in the holding furnace shows the hydrogen content varied around 0.10-0.14 ml/100 g after the de-gassing operation.

CONCLUSIONS

- Rejection rate of the cylinder head sharply decreased when the alloy supplier C was replaced by the supplier B.
- Quality of the starting material has a strong impact on the final cast product.
- De-gassing is an important part of the casting process when the transfer operations are turbulent, since it helps for the removal of bi-films with the simultaneous reduction in gas content.
- Bi-film index is a useful parameter to assess melt quality.

ACKNOWLEDGMENT

The European Project Nadia- New Automotive components Designed for and manufactured by Intelligent processing of light Alloys (NMP-2004-SME 3.4.4.5, contract n.026563-2) is gratefully acknowledged for financial support. The authors would like to thank Mr. Renzo Galvagno, Mr. Roberto Di Matteo , Mr. Giovanni Amione, Mr. Marco Angiari, and Mr. Paolo Amalberto of Teksid Aluminum for there help during the casting trials as well sample preparation. The help of Dr. Giulio Timelli (DTG- University of Padova, Italy) for the thermal analysis and of Dr. Derya Dispinar (SINTEF) for proof reading the manuscript is very much appreciated.

REFERENCE

[1] Dispinar, D., and Campbell, J. "Critical assessment of reduced pressure test Part 1: Porosity phenomenon": International journal of cast metal research, (2004), Vol 17, No 5, pp 280-286.

[2] David, V.N. "Using filters and evaluating their effectiveness in high pressure die castings",www.pyrotek.info/documents /techpapers/

[3] Simard, A., Proulx, J., and Paquin,D. "Capability study of the improved PREFIL- foot printer to measure liquid aluminium cleanliness and comparison with different techniques", AFS 6th International conference on molten aluminium processing, pp 93-112 (2001)

[4] Habibi, N., Samuel, A.M., Samuel, F.H., and Rochette, P. "Effect of grain refining and Sr modification on PREFIL measurement sensitivity in 356 alloys using electron probe microanalysis technique": International journal of cast metal research, (2004), Vol 17, No 2, pp 79-87.

[5] Dispinar, D., Campbell, J. "Critical assessment of reduced pressure test Part 2: Porosity phenomenon": International journal of cast metal research, (2004), Vol 17, No 5, pp 287-294.

[6] Haber, K., Schumacher, P., Geier, G., and Stauder, B. "Characterization of the melt quality and impurity content of an LM25 alloy", 138th TMS Annual Meeting, Shape Casting: 3rd International Symposium, San Francisco, California, USA, (February 2009), pp 181-88.

[7] Di Sabatino, M., Arnberg, L., Rørvik, S., and Prestmo, A. "The influence of oxide inclusions on the fludity of Al-7wt % aluminium foundry alloys", Material.Sci. Eng.A, Vol 413-414, 2005 pp 272-276.

[8] Kwon, Y.D., and Lee, Z.H. "The effect of grain refining and oxide inclusion on the fluidity of Al–4.5Cu–0.6Mn and A356 alloys", Mat. Sci. Eng.A, Vol 360 (2003) pp 372-376.

[9] Dispinar, D., and Campbell, J. "A comparison of methods used to assess aluminium melt quality". 136th TMS Annual Meeting, Shape Casting: 2nd International Symposium, Orlando, Florida, USA, (February 2007), pp 11-18.

[10] Campbell, J. "Materials perspective, Entrainment defects", Materials science and technology, (2006), Vol 22, No 2, pp 127-145.

[11] Dispinar, D. "Determination of melt quality of aluminium and its alloys", PhD Thesis, University of Birmingham UK, (January 2005).

[12] Dispinar, D., and Campbell, J. "Effect of casting conditions on aluminium melt quality", Materials processing technology, (2007), pp 405-410.

[13] Dispinar, D., and Campbell, J. "Melt quality studies in secondary re-melting of aluminium", The journal of institute of cast metal engineers, Vol 178, No 3612, pp78-81.

[14] Dispinar, D., and Campbell, J. "Use of bi-film index as an assessment of liquid metal quality": International journal of cast metal research, (2006), Vol 19, pp 5-17.

[15] Moores, A.W., and Froesher, A., "New device for the determination of hydrogen concentration in aluminium alloy": AFS Transactions, (2005), pp 1-10.

[16] Seifeddine, S., Torsten, S., and Svensson, I.L. "Variation in microstructure and mechanical properties of cast aluminium EN AC 43100 alloy", Metallurgical science and technology, (2007), Vol 25, No.1, pp12-22 .

[17] Personal communication with Dispinar, D., Norway, 2009.

[18] Personal communication with Campbell, J., UK, 2009.

[19] Velasco, E., Valdes, R., and Nino, J. "Degassing: A critical stage in the manufacturing of Al-Si-Cu alloys for automotive castings", 138th TMS Annual Meeting, Shape Casting: 3rd International Symposium, San Francisco, California, USA, (February 2009), pp 79-86.

[20] Dispinar, D., Nordmark, A., Voje, J., and Arnberg, L. "Influence of hydrogen content and bi-film index on feeding behaviour of Al-7Si", 138th TMS Annual Meeting, Shape Casting: 3rd International Symposium, San Francisco, California, USA, (February 2009), pp 63-70.