

Filtration efficiency of ceramic foam filters for production of high quality molten aluminum alloys

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ABSTRACT

Ceramic Foam Filters (CFF) are used extensively in aluminum cast houses to improve the metal cleanliness during the casting process. There have been numerous papers describing filtration mechanisms and efficiencies of ceramic foam filters. However, in the absence of convenient in-line monitoring methods, only limited dynamic filtration data have been made available either from research groups or production facilities. The present paper describes CFF filtration efficiencies measured with PoDFA and LiMCA techniques during standard production casts within Alcan installations. In particular, the variations of filtration efficiencies are discussed with regards to elapsed time into cast and molten metal flow variations for multiple inclusion size ranges.

INTRODUCTION

The detrimental effects arising from the presence of nonmetallic inclusions in aluminum alloys are well known. These include, for example, pinholes and stringers in light gauge foil and flange cracks in beverage containers. Over the last 10 years, requirements for alloys used in the fabrication of high quality products (containers, lithographic sheet, foil) have become very stringent; tolerable inclusion-related flange cracking in beverage container production is now around 1 per million, down from 1 per ten thousand (100 ppm) in the early 1980's.

A substantial number of methods are used in the cast house to remove inclusions from the melt, prior to or during casting. Among these, the use of ceramic foam filters (CFF) has gained very large acceptance since its commercial introduction in 1976 at Alcan's Oswego, New York, Sheet mill facility [1]; it is estimated that half of the world aluminum production was filtered using CFFs in 1992 [2]. The different types of available CFF filters have been reviewed and classified by Apelian et al. [3].

Since their introduction, the issue of filtration efficiency of CFF filters under actual production conditions has raised much controversy. Much of this controversy has hinged on what filtration mechanism is predominant in CFF filters; this has been compounded by the difficulty in obtaining on-line, process-based reliable evaluation data at the present levels of inclusion concentrations.

Initially, filtration efficiency was tracked by process performance data, such as surface roughness of extrusions [4] or pinholes per unit area of foil [5]. The advent of reliable liquid metal sampling and analysis methods such as the LAIS [6], PoDFA and LiMCA [7, 8] techniques has provided a baseline of performance data. Bases et al. [6] measured filtration efficiencies of 34-60% for 30 PPI units, in agreement with values reported since by Doutre et al. [7] and Dupuis and Dumont [8]. Metal flow rate affects filter efficiency, dropping from 60% at 29 kg/m²/s (2.5 lb/in²/min) to 45% at 43 kg/m²/s (3.7 lb/in²/min) [6]. The influence of metal flow rate on filtration performance has been discussed by Mutharasan et al. [9, 10].

The efficiency of CFF filters will be governed by the filtration mechanism under which they operate. Early on, the accumulation of inclusions on the filter to form a "cake" was believed to play a dominant role [11, 13]. While this high efficiency filtration mode can play a significant role in alloys with inclusion contents of the order of 250 ppm [12, 13], rapid improvements in metal quality in the last 10 years have brought the incoming inclusion levels down to 1 ppmV or less (roughly equivalent to 1 mm²/kg as measured by PoDFA or 100,000 inclusions larger than 20 microns per kg of metal, as measured by LiMCA (100 k/kg)). As described by Aubrey and Dore [2], deep bed filtration is clearly the dominant filtration mode for CFF operated for present-day high quality aluminum alloy production. Deep bed filtration of CFF filters has been described by Netter and Conti [14], Gauckler et al. [15] and Engh and Bathen [16, 17]. Comparisons of CFF and deep bed filter based on water models have been performed by Desmoulins et al. [18, 19]. A third mechanism, called NIFF (Near surface Interstitial Flow Controlled Filtration), proposed recently by Strom et al. [20-23] to explain increasing filtration efficiencies during casting does not appear to be supported by data (data showing decreasing filtration efficiencies will be presented in this paper) and has been criticized as superfluous [2]. Given the levels of inclusions present in the incoming metal reported by these authors (3-5,000 inclusions larger than 20 microns per kg of metal (3-5 k/kg)), the inclusion "bridging" scenario appears unlikely even if all inclusions present in 30 tonnes of metal were caught in the top first 5 mm of the CFF filter, the volume occupancy of inclusions in pores would still be less than 0.1% with the average inclusion to inclusion distance over 8 times their diameter of 20 microns.

Recent papers by Butcher and Rogers [24], Hollar et al. [25], Castillejos et al. [26] and Strom et al. [20-23] report filtration efficiencies as high as 80-95% for filtration of high quality, "clean" alloys, in contradiction with the 30-60% efficiencies reported previously.

The present paper presents LiMCA and PoDFA data gathered at Alcan during the last 15 years for 30 PPI phosphate bonded ceramic filters from two major suppliers. It will be shown that the efficiency data is consistent with the work by Mutharasan et al. [9], Netter and Conti [14], Gauckler et al. [15], Engh et al [16, 17] and Desmoulins et al. [18, 19] but cannot be reconciled with data presented by Strom et al. (20-23). Contrary to previous work, data is also presented that indicates decreasing efficiencies with increasing inclusion diameter (in the range of 20-50 μ m); this is interpreted as indication of dynamic release/agglomeration of large particles by CFF filters.

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Table 1
Range & average filtration efficiencies obtained for 30 ppi
ceramic foam filters used under various plant conditions

Specific metal flow rate (kg/m ² /s) (lb/in ² /min)	Alloys	Configuration	Number of casts	EFFICIENCY (%)		Method of evaluation
				Range	Average	
13 to 32 (1.1-2.7)	AA51 82	CFF	17	-70 to 84	36	PoDFA
14 (1.2)	AA5XXX	CFF	13	-67 to 88	38	PoDFA
15 to 19 (1.3-1.6)	AA6063	CFF	12	-29 to 60	26	LiMCA
19 to 35 (1.6-3.0)	AA3004 AA5182	CFF	15	8 to 80	48	PoDFA
25 to 30 (2.1-2.5)	AA3004	CFF + ABF	7	-18 to 81	53	LiMCA
	AA3004		13	26 to 87	72	PoDFA
32 to 38 (2.7-3.2)	AA3004	Deg. + CFF + ABF	6	-4 to 44	24	LiMCA
	AA3004		5	-6 to 48	31	PoDFA
41 to 47 (3.5-4.0)	AA3004	Deg. + CFF + ABF	7	39 to 81	60	LiMCA
	AA3004		8	-14 to 67	53	PoDFA

RESULTS

Average Performances of CFF

Efficiency and Consistency of CFF

Table I presents the filtration efficiency ranges and averages obtained for 7 distinct production campaigns in Alcan plants, representing more than 100 casts. As presented in this table, the results have been obtained using both PoDFA and/or LiMCA techniques. The first observation from these results is that under conditions used, the filtration efficiency of ceramic foam filters varies over a wide range (including negative efficiencies). The range is slightly larger based on PoDFA results in comparison with LiMCA; this comes partly from the fact that the PoDFA samples are grab samples taken only at one or two instances during the cast. Moreover, as the filtration efficiency varies with the elapsed casting time (discussed later), the filtration efficiency calculated from PoDFA results depends on the time at which the samples are taken during the cast. On the contrary, a much better average efficiency is obtained using the LiMCA data as it provides one set of data (one before and one after the CFF using a two-head system) every minute.

The spread of the filtration efficiencies can also be attributed in part to the variation on the incoming metal cleanliness level. Figure 1 shows that the filtration efficiency decreases with the inclusion content of the metal. This indicates that ceramic foam filters do not operate in a full proportional mode.

The specific metal flow rate has also been reported as one of the principal factors affecting the filtration performances of ceramic foam filters and an operating metal flow rate between 12 and 35 kg/m²/s (1 to 3 lb/in²/min) [2] is recommended. In certain instances, when ceramic foam filters have been used as pre-filtration systems before Deep Bed Filters, they have been used over the recommended metal flow rate. While this could be used as an argument for explaining the low performance and the wide range of variations of the filtration efficiency obtained, results presented in Table I show the same low average and variable performance of CFF over flow rates ranging from 13 kg/m²/s up to 47 kg/m²/s.

Filtration Efficiency vs Inclusion Size

Based on mathematical and physical modelling, it is believed that the removal efficiency of ceramic foam filters increase with the size of the incoming particles [14, 19, 27].

However, no results from liquid metal

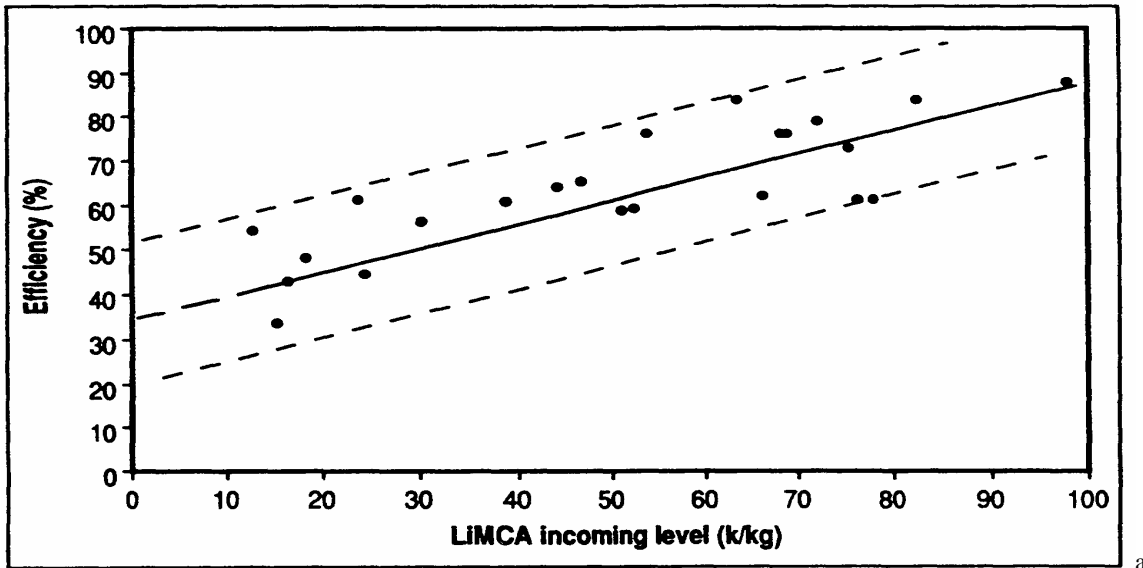


Figure 1
Efficiency vs incoming metal cleanliness (LiMCA N20 (k/kg))

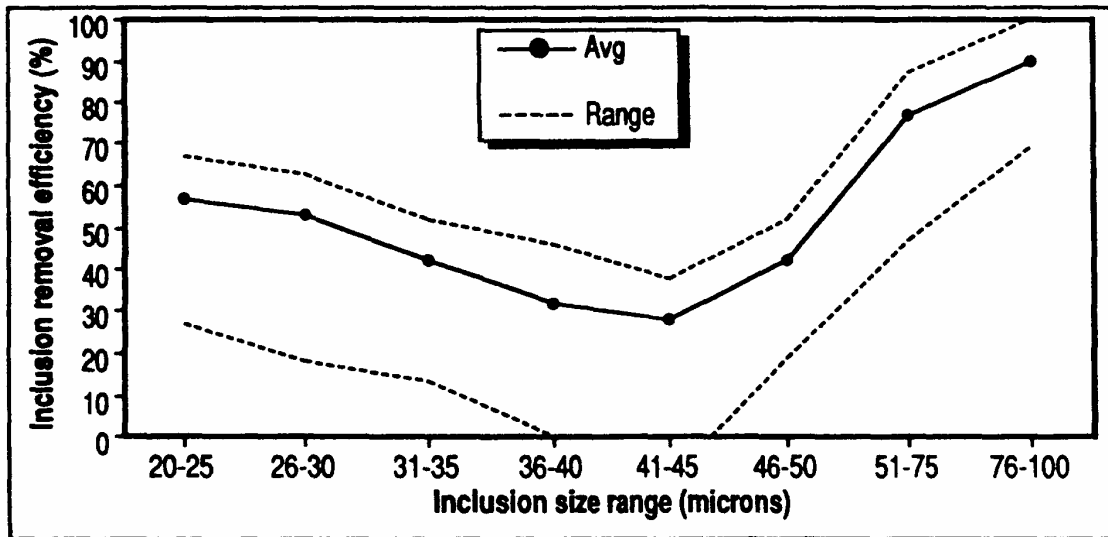


Figure 2
CFF removal efficiency vs inclusion size

experiments are available to validate these predictions. Using the LiMCA apparatus, which reports the concentration of inclusions for 5 micron-size-range for inclusions of 20 microns and over, it has been possible to precisely evaluate the removal efficiency of ceramic foam filters as a function of the particle size. Contrary to previous results, LiMCA results obtained show in all cases (i.e. for any casting center where measurements have been performed using different type of CFFs and at various incoming inclusion levels) that the removal efficiency of a ceramic foam filter decreases with the particle size from 20 microns up to 45 microns and starts to increase for particles larger than 45 microns as shown on Figure 2. In some instances, negative efficiencies have

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been measured for particle size ranges between 30 and 40 microns, meaning that more particles are measured after the CFF than before. The explanation for this situation significantly different than the results from mathematical and physical models must be that ceramic foam filters act as particle agglomerators, a phenomenon which is not taken into account in mathematical modelling and which does not occur in the physical modelling of filtration with ceramic foam filters. To illustrate the agglomeration effect of ceramic foam

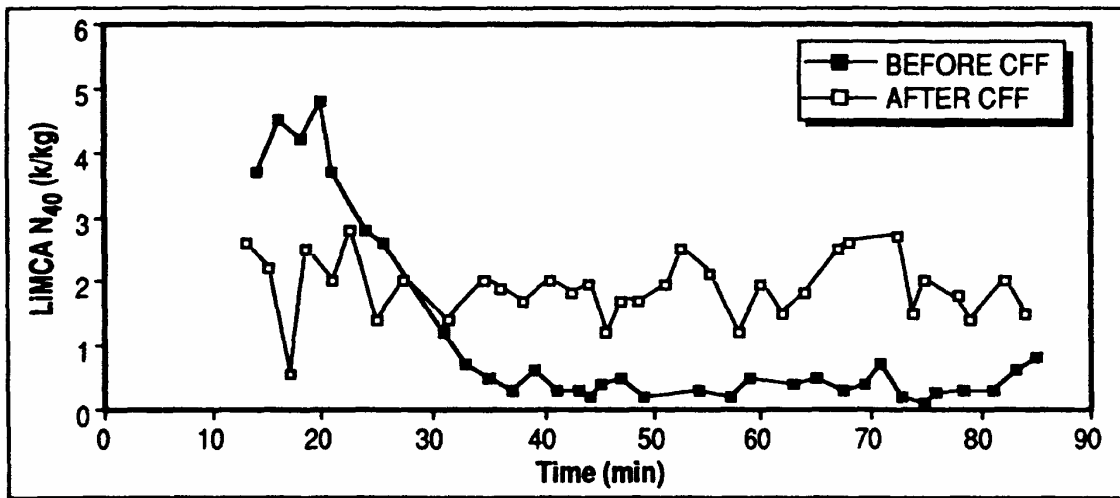


Figure 3

Concentration of inclusions larger than 40 microns (LiMCA N_{40} k/kg) measured before and after a ceramic foam filter (30 ppi)

filters, Figure 3 shows that the outgoing inclusion level for the largest particle fraction (i.e. 40 microns and over) is higher than the incoming level for a significant part of the casting period. So, it appears that small inclusions (<20 μm) are agglomerated and released as larger clusters of 30 to 50 microns in size.

Effect of Ceramic Filter Material

All the results presented in this paper have been obtained with phosphate bonded type filters sold by two of the largest CFF suppliers. However, in recent years, other manufacturers are claiming new products, improved recipes and methods of control for their ceramic filters and of course, higher filtration performances [20-26].

A recent campaign of evaluation has been undertaken to evaluate two other types of ceramic filter. One is a phosphate bonded ceramic foam filter similar to those covered in the present paper, but according to the supplier, fired at a higher temperature and the other type is a fully sintered alumina ceramic filter of the type used by Strom et al. [20-23]. Early results of this ongoing evaluation show that at a specific flow rate in the range of 30 to 35 $\text{kg}/\text{m}^2/\text{s}$ (2.5 to 3.0 $\text{lb}/\text{in}^2/\text{min}$) no improvement in the filtration efficiency has been measured. PoDFA and LiMCA values have shown filtration efficiencies ranging from 6% to 48% for the phosphate bonded ceramic foam filter and from -6% to 42% for the sintered alumina ceramic filter; again we cannot reconcile our results with those published by Strom et al. [20-23]. Further evaluations are underway.

Dynamic Performance of CFF

The information gathered in this section was made available through the usage of the LiMCA solely. Because of its in-line monitoring capabilities, it has been possible to correlate process events to the actual metal cleanliness levels measured after the CFF.

Spontaneous and Process Related Releases

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Alcan's experience with ceramic foam filters at various metal flow rates has identified CFF as limited capacity buffers (deep bed filtration through a 5 cm filtering media). Figure 4 illustrates a typical cast where the CFF cannot fully absorb incoming inclusion bursts.

Based on multiple casts performed at various flow rates, CFFs have been found to be susceptible to process induced vibrations as well as metal level in the trough [29]. An example is illustrated in Figure 5. The first of the three surges measured after the CFF was caused by an increase of the metal level in the trough. In plants equipped with stationary holders where operators adjust the metal through a tap hole, metal level fluctuations occur frequently; the effect of such process events makes the CFF release part of the inclusions it had retained before.

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The last two smaller surges observed during this cast were associated with the handling (positioning, opening and closing) of an OES horizontal mould on the top of the casting trough near the CFF. The vibrations induced to the trough system during this normal process operation were detrimental to the CFF capability of holding its filtered inclusions. Sometimes, no process related variations can be found to explain releases. Figure 4 includes typical examples of such filter instabilities. Figure 6 shows that the CFF erratic releases yield larger inclusions than the ones entering the filter. This is in line with the previously mentioned agglomeration/release phenomena measured with the LiMCA.

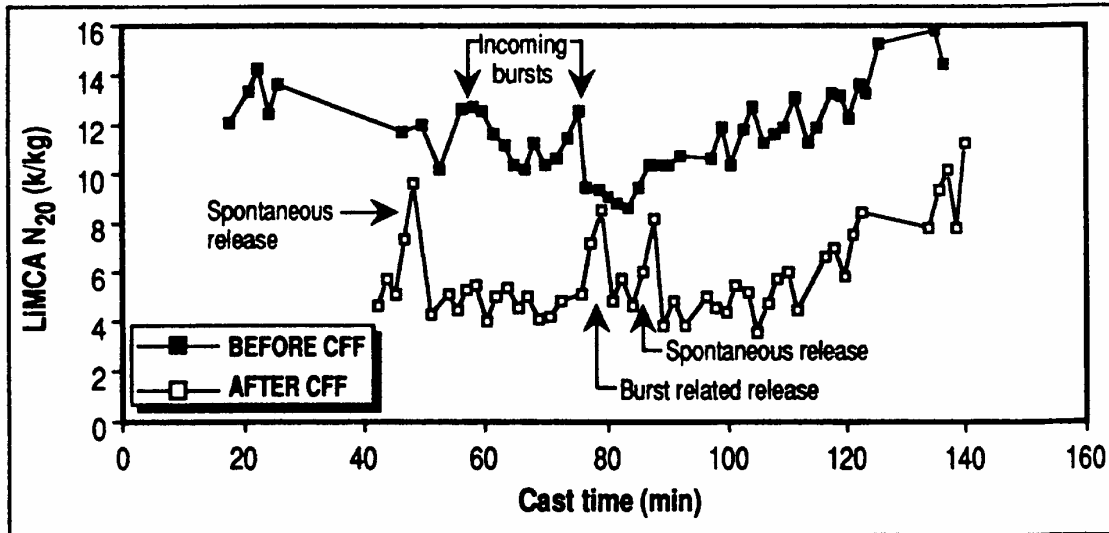


Figure 4
Spontaneous and burst related inclusion releases from CFF

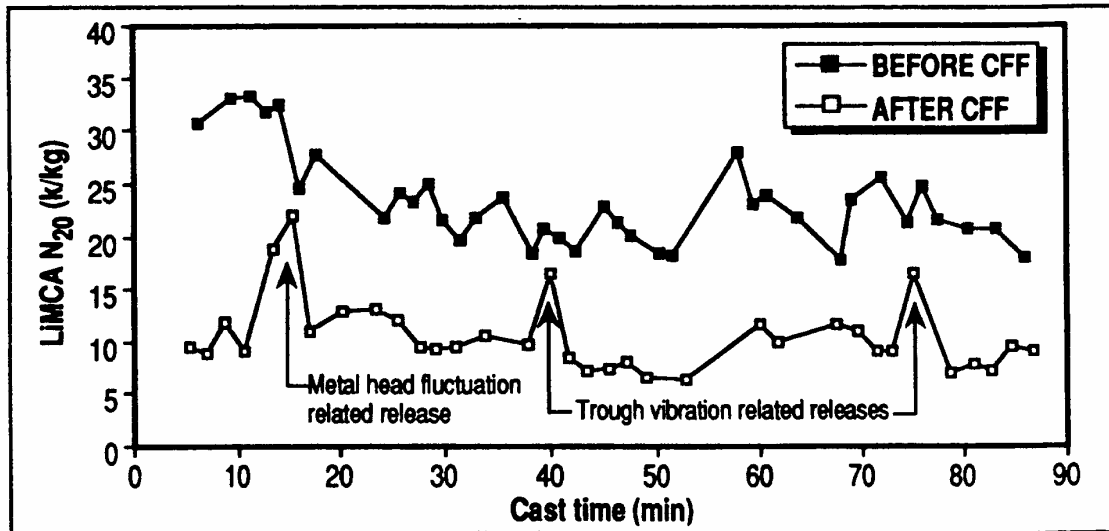


Figure 5
Typical sensitivity of the CFF to disturbances during a cast

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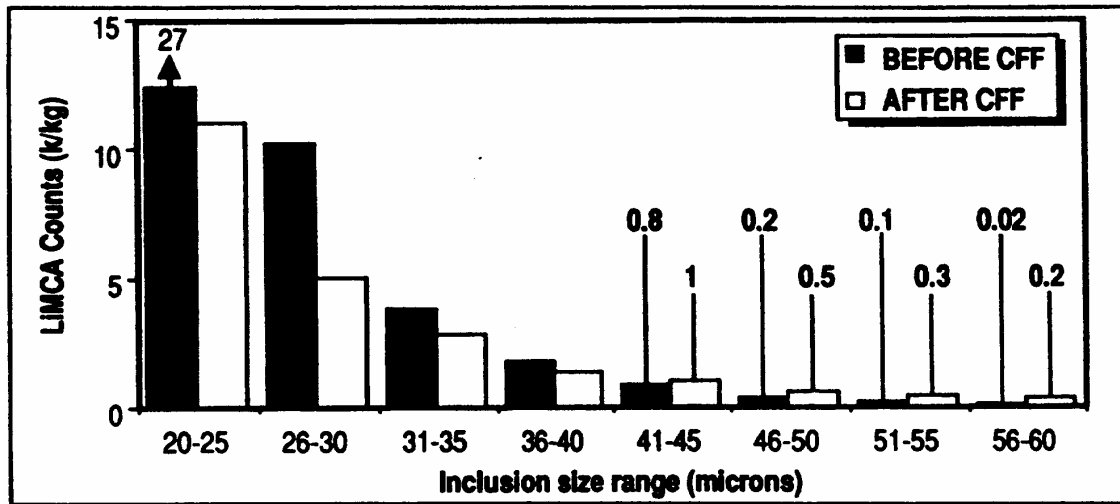


Figure 6
Inclusion size distribution for samples taken before and after ceramic foam filter (30 ppi) during release

Filter Loading

The limited inclusion holding capacity of ceramic foam filters is illustrated in Figure 7; filtration efficiency decreases as the loading increases. Loading of ceramic foam filters is also identified with surges near the end of casts.

Our evaluation of the maximum loading capacity of CFFs is around 100-120 t/m². It is clear that this decreasing efficiency trend with increasing casting length cannot be reconciled with LIMCA data published recently by Six et al. [20, 21]. However, in that study, CFF loading was light and the limit of 100 t/m² was not reached.

Based on our evaluations of the loading capacities of a CFF, a typical 40-tonne cast requires a 0.34 m² (23 x 23 inches) filter to ensure that the metal cleanliness after the CFF is consistent to the end of a single cast.

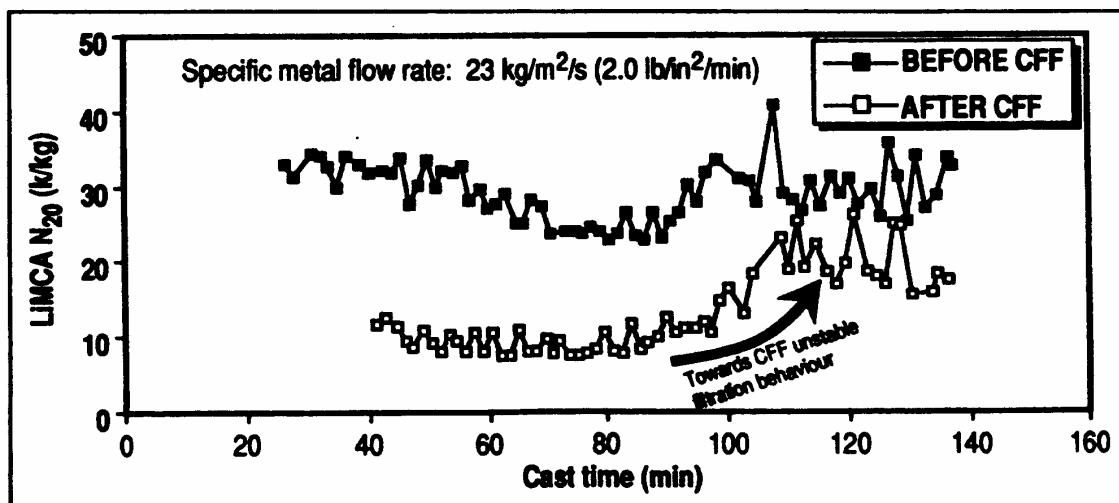


Figure 7
Effect of filter loading on final cleanliness results

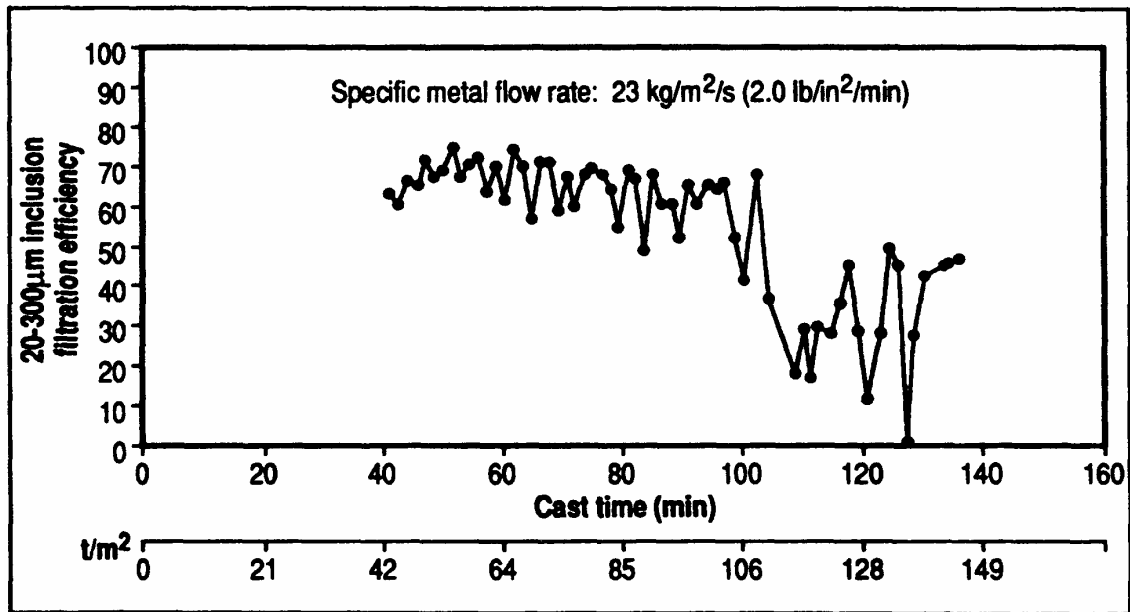


Figure 8
Variation of CFF filter efficiency with inclusion loading

DISCUSSION

Over the last decade significant improvements in the furnace preparation methods and in-line metal treatment processes – especially for high quality aluminum alloys - insure that commonly used 30 ppi ceramic foam filters operate exclusively under deep bed filtration mode. Under these conditions, the filtration efficiency (η) can be estimated quite well according to the following equation [9]:

$$\eta = 1 - e^{-\lambda L}$$

Where: L is the filter thickness

$$\text{and } \lambda = K_0 / U_m$$

$$\text{with } K_0 = K_0' + K_0'' + U_m$$

and for 30 ppi CFF filters,

$$K_0' = 0.018 \text{ s}^{-1} \text{ and } K_0'' = 0.067 \text{ cm}^{-1}$$

U_m is the metal velocity (cm/s)

For a 5 cm (2 inches) thick 30 ppi CFF, efficiency can be calculated as 40% at 0.5 cm/s (11.7 kg/m²/s – 1 lb/in²/min) and 33% at 1.5 cm/s (35.2 kg/m²/s - 3 lb/in²/min). These values we consistent with those of Gauckler et al. [15], Netter and Conti [16] and the present study (see Table I). The recently reported 90% + filtration efficiencies [20-23] cannot be supported by this analysis. For a specific CFF porosity, the only way to increase the efficiency is by reducing the metal velocity. According to equation (1), a decrease of the metal velocity into the range of operation of a Deep Bed Filter ($U_m = 0.2\text{cm/s}$) would lead to a filtration efficiency of only 58% for a 30 ppi CFF.

The use of higher ppi ceramic filters may lead to higher filtration performances as claimed by Butcher and Rogers [24]. However in a recent study, Desmoulins, was unable to observe a significant improvement in filtration efficiency using 50 ppi CFF compared to 30 ppi ones. Moreover, from a practical point of view, installations that have attempted operation of 50 ppi units have suffered early aborts due to preheat or premature build-ups, as reported, by Kakimoto et al. (28). When operated at low metal velocities, finer porosity filters may achieve filtration efficiencies comparable to Deep Bed Filters. However, the cost of these units would make this prohibitive.

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The filtration efficiency and consistency of Ceramic Foam Filters appears clearly to be limited by the limited length of these filters. Moreover, this limited length is also a limit to the loading capacity of these filters due to the low volume available for the retention of the particles (a Deep Bed Filter operates at typical metal velocities 1/8 those of CFFs and therefore requires 8 times more surface area; coupled to a thickness 8 times greater, this yields a volume available to store inclusions 64 times that of a CFF).

Finally, this limited inclusion retention of CFFs makes them extremely sensitive to inclusion releases.

CONCLUSIONS

Under present day metal cleanliness conditions, with incoming inclusion levels of the order of 1 ppmv, Ceramic Foam Filters operate in a **Thin Bed Mode**. As such, their small thicknesses lead to a triple limitation:

- a) The filtration efficiency is limited by the metal path length (filter thickness) ($\eta = 1 - e^{-\lambda L}$), especially at the high flow rates usually used (L is typically 1/8 that of a Deep Bed Filter).
- b) The ability to absorb inclusions is limited by the total media volume. A practical limit is reached around 100 t/m² of surface area (volume is typically 1/64 that of a Deep Bed Filter).
- c) The inclusions released (as clusters of larger size) within the porous media cannot be re-stabilized before they reach the end of the filter media.

Overall, because of their medium efficiencies and operational unstabilities, 30 ppi Ceramic Foam Filters, when operated alone, are not suited for the production of high quality aluminum alloys.

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