Influence of injection parameters on the final surface quality of Al-Si-Cu die cast components

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ABSTRACT

In foundry practice the occurrence of solidification defects limits the production and the performance of cast components. In high-pressure die casting (HPDC) the most common defects are shrinkage or gas porosities and bifilms.

Thin sections, typical of HPDC components, are the most susceptible to casting defects, and these microstructural imperfections can be detrimental to both the mechanical and aesthetic properties. Even though laminations are not as harmful as internal defects, die cast components with this kind of superficial defects are always rejected by customers, thus requiring further machining operations.

The aim of this study is to analyse the lamination defects that occur on the surface of some Al-Si-Cu cast covers produced by means of HPDC. In order to evaluate the influence of the different injection parameters on the final quality of the die casting products, melt temperature, plunger speed and upset pressure have been varied within a range of suitable values. The obtained castings have been studied by performing visual inspections and metallographic analyses by means of optical microscopy (OM), revealing the presence of many bifilms spread over the entire cross section of some cast parts.

The presence of laminations, bifilms and cold shuts has been correlated to the considered processing conditions, proposing a new criterion parameter for the quantification of surface quality, called Lamination Ratio (LR).

RIASSUNTO

Nella pratica di fonderia, il verificarsi di difetti di solidificazione limita la produttività e le prestazioni dei componenti colati. In particolare, i difetti più comunemente riscontrati nel processo di pressocolata (HPDC) consistono in cavità da ritiro o da gas e bifilm.

Le sezioni sottili, tipiche dei componenti pressocolati, sono le zone maggiormente suscettibili ai difetti di colata. Tali imperfezioni microstrutturali possono influenzare negativamente sia le proprietà meccaniche sia quelle estetiche superficiali del pezzo. Nonostante le laminazioni non siano dannose quanto i difetti interni, i componenti che presentano questo tipo di difettologia sono sempre respinti dai clienti, e richiedono pertanto un'ulteriore fase di finitura.

Questo lavoro si propone di analizzare le laminazioni che si verificano sulla superficie di coperchi pressocolati in lega Al-Si-Cu. Al fine di valutare l'influenza dei differenti parametri di iniezione sulla qualità finale dei prodotti pressocolati, la temperatura del fuso, la velocità di iniezione del pistone e la pressione di mantenimento sono stati variati all'interno di un intervallo di valori compatibili con le specifiche della macchina. I componenti ottenuti sono stati studiati attraverso tecniche di analisi visiva e metallografica (OM), mettendo in luce la presenza di numerosi bifilm distribuiti sulla sezione trasversale dei componenti.

La presenza di laminazioni, bifilm e gocce fredde è stata in seguito correlata alle specifiche condizioni di processo, ed è stato pertanto proposto un nuovo parametro, detto Lamination Ratio (LR), per cercare di quantificare la qualità superficiale del pezzo

KEYWORDS

Aluminium alloys, HPDC, Injection parameters, Microstructure, Surface defects.

INTRODUCTION

The High Pressure Die Casting (HPDC) manufacturing process is commonly used to obtain net shape components of complex geometry. The proper adjustment of some process parameters allows the production of nearly defect-free parts at high production rates.

In general, the most common defects of HPDC components are shrinkage or gas porosities and bifilms. According to Campbell [1], bifilms are oxide layers which form on the surface of the melt and are entrapped into the liquid metal because of surface turbulence. The folding action caused by foundry operations, e.g. degassing or mould filling, creates a double folded dry surface, whose faces are opposite but do not bond. Although the bifilm can be considered to act as a crack, it constitutes a harmless defect into the melt. However, the bifilm can unfurl during the solidification and cooling of cast components into the die, becoming a major crack that can severely reduce mechanical properties and fatigue behaviour [2-4]. In addition, the formation of hydrogen porosities in aluminium alloys does not come from a nucleation process, either homogeneous or heterogeneous, but it is related to bifilms. Hydrogen diffuses in the bifilm during the solidification and starts to expand it to form a pore [5].

Even though several test methods have been developed to determine both inclusion and hydrogen content, the most widely used test for a quantitative assessment of metal quality is the standard Reduced Pressure Test (RPT). In their works, Dispinar and Campbell [6] have focused on this method and investigated the effectiveness of some quality index in order to quantify metal quality. Since RPT enanches the conditions of pore formation that are met in real castings, they proposed a “Bifilm index” based on the sum of the maximum lengths of the pores estimated from the sectioned surface of pressure test samples.

Mechanical and aesthetic properties of thin sections, typical of HPDC components, are deeply affected by these castings defects. Lamination is one of the most common surface defects in die cast components. It consists of a thin surface metallic layer having a separation surface from the bulk metal almost parallel to the component surface, with imperfect adhesion to the inner metal. It forms when a relatively warm metal vein at low viscosity flows between the steel die and another cooler and partially solidified flow. The metallic discontinuity can cause the partial or complete skin detachment along the above interface when even relatively low stresses arise or are externally applied (machining or finishing operations) [7]. Although laminations are not as harmful as internal defects, die cast components with this kind of superficial defects are always rejected by customers, thus requiring further machining operations.

The die casting process is controlled by several variables. The main involved factors are mould temperature, injection parameters, as well as chemical composition and temperature of the liquid metal. In recent years, some authors [8-10] started using an experimental DOE (design of experiment) methodology in order to determine how these parameters influence the die casting part quality. With this information, the parameters can be adjusted, and the manufacturing of the casting optimised.

In this work, the DOE methodology has been employed to study the influence of three process parameters on the surface quality of a die cast Al-Si-Cu component. In the standard manufacturing conditions, the cast part presents several laminations causing unacceptable aesthetic defects, expecially after shot peening. Melt temperature, plunger speed and upset pressure were varied and their effects on surface quality before shot peening have been investigated using a new definition of bifilm index.

EXPERIMENTAL PROCEDURE

Fig. 1 shows the cast part studied in the present work. It is a cover for electric motors in AlSi11Cu2 alloy, presenting lamination defects on three critical regions after shot peening. The chemical composition of the aluminium alloy is presented in Tab. 1. The castings were manufactured by means of a 300t hot chamber die casting machine. The casting extraction and the application of the lubricant spray were done automatically.

Melt temperature, plunger speed and upset pressure have been selected due to their easy handling during the casting process. Each casting parameter was varied twice within a range of values that could be tolerated by the die casting machine without any damage, including the values normally used for the casting production, thus obtaining 7 different combinations; all the investigated combinations are collected in Tab. 2. The plunger speed has been expressed in terms of number of valve revolutions and the parameters varied respect to the standard manufacturing parameters have been typed in bold. Critical values of casting parameters were considered to prove the capability of the proposed definition of bifilm index to take into account the differences between standard and modified casting conditions. Since the present paper is a preliminary work elaborated to verify the effectiveness of the proposed parameter in evaluating lamination defects, just one sample for each experimental condition has been analised.

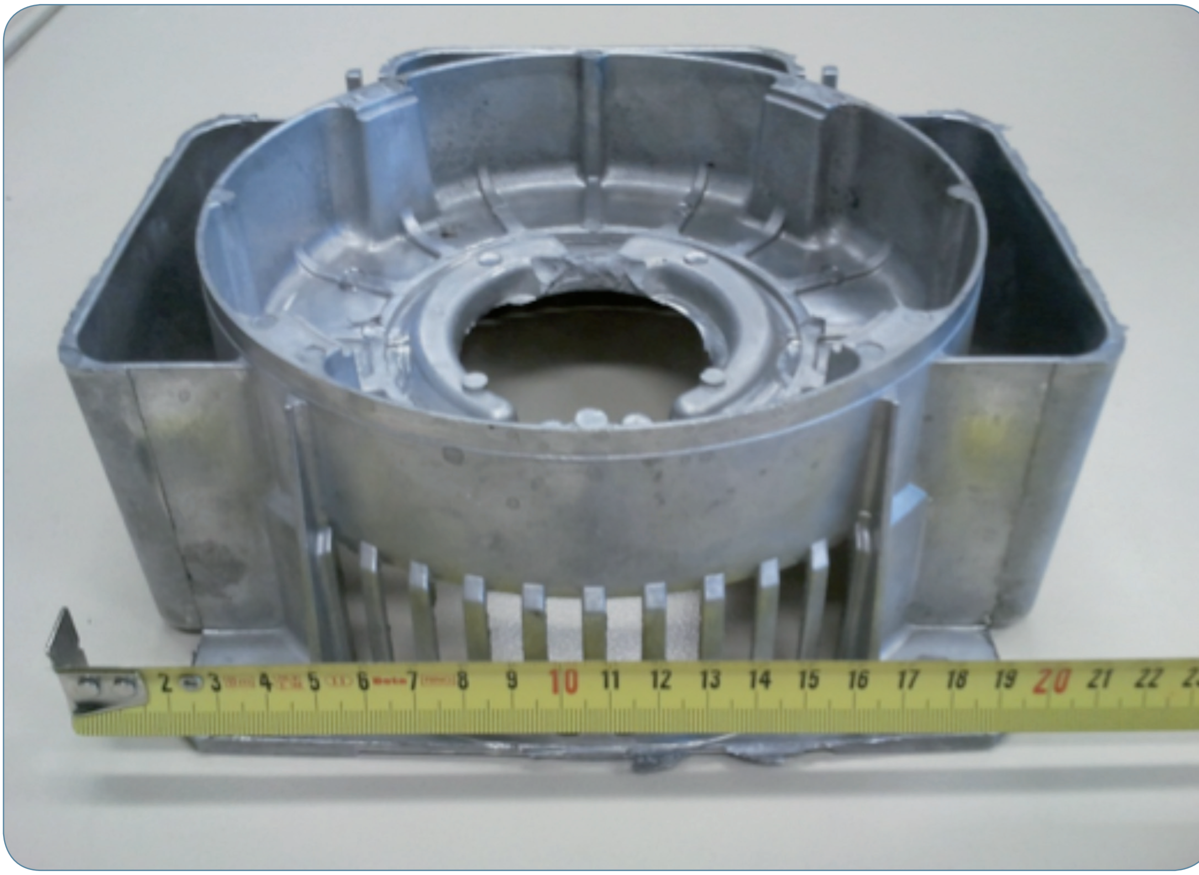

Fig. 1: Cast component manufactured by HPDC process.

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

	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Pb	Sn	Ti	Al
Min	10.0	0.45	1.50									Bal.
Max	12.0	1.00	2.50	0.55	0.30	0.15	0.45	1.70	0.25	0.25	0.20	

Table 2. Setup parameters using a DOE methodology

Experiment	Melt Temperature [°C]	Plunger Speed [n° of valve revolutions]	Upset Pressure [bar]
REFERENCE SAMPLE	690	2	300
S1	690	**1**	300
S2	690	**5**	300
S3	690	2	**120**
S4	690	2	**320**
S5	**720**	2	300
S6	**650**	2	300

Two distinct criteria have been used for the determination of the castings surface quality. In the first one, liquid penetrant inspection was performed in order to highlight whether laminations were present even before the shot peening. The castings were then observed using a LEICA MZ6 stereo microscope. The second criterion was the quantitative analysis of the bifilms length. The evaluation was carried out by measuring the bifilms on the cross sections of three selected critical regions, within a distance of 300 μm from the surface. This distance was selected due to a previous investigation performed on a shot peened defective casting, and it was found to be the depth at which the defect can be still considered as a surface one. In Fig. 2 and Fig. 3 the three analysed critical regions, named A, B and C, are shown.

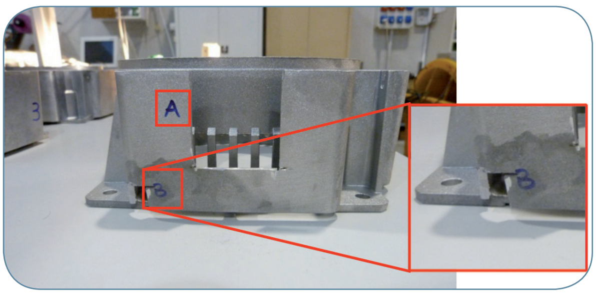

Fig. 2: Regions A and B.

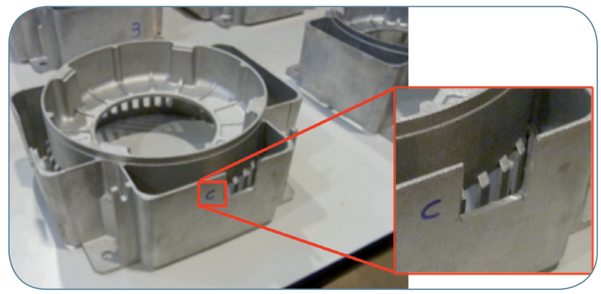

Fig. 3: Region C.

Test samples drawn from the three different regions were ground with SiC paper down to 1200, polished, etched with Keller's reagent and finally polished again for 2 minutes, in order to clear the microstructure and to highlight bifilms and cold shuts. The observation was performed by using a LEICA MEF4M optical microscope (OM), and the micrographs were subjected to image analysis.

A new criterion parameter, defined as the ratio of the total length of bifilms to the area of the cross section (calculated as the product between the length of the test sample and the selected distance from the surface), has been proposed and called Lamination Ratio (LR). This parameter has been then normalised to 1 for the reference sample, and the other castings' LRs have been compared to it.

RESULTS AND DISCUSSION

The liquid penetrant inspection has revealed evidence of lamination defects even before the shot peening, but only on two samples, as shown in Fig. 4. As a consequence, the inspection only points out that laminations can arise on these covers, but its results are not useful for a detailed quantification of the occurrence of this surface defect.

After liquid penetrant inspection, samples were drawn and observed by means of OM. Measured areas and total bifilms lengths, as well as the LRs, are summarised in Tab. 3. The LR parameter is based on a concept similar to the one proposed by Dispinar and Campbell in [6]; in their work they consider the opening of pores during solidification and cooling in die cast parts, whereas LR takes into account the length of bifilms. Therefore, Lamination Ratio is calculated as the sum of bifilms' lengths, measured on the polished cross sections within 300 μm from the surface, per unit area. The amount of laminations varied depending on the region and the specific experimental conditions. However, not less than six lamination defects were detected and measured. Thus, with this proposed parameter, the surface nature of lamination defects can be easily evaluated.

In Figs. 5-7, the Normalised Lamination Ratio of the reference sample is compared to the others for each cross section obtained from the critical regions.

The results show that the die casting parameter combinations for samples S1, S3, S5, S6 should be avoided in the casting process. Even if these combinations decrease the amount of bifilms near the surface on Sections B and C (apart from sample S1 in Section B), their effect is detrimental for the surface quality on Section A. Low plunger speeds and low filling temperatures (S1, S6) cause only a slight deterioration of surface quality compared to the reference sample RS0. Conversely, low upset pressures values cause an insufficient filling of the die, thus leading to an increase in gas porosities and density of bifilms. Considering the process temperature, it seems that the highest melt temperature for S5 realises the worst effects on the surface quality for Section A. This could be linked to the faster heat removal that occurs between the melt liquid and the die when filling temperatures are higher than those normally used in the die casting process for the considered alloy [11]. Moreover, at

Table 3. Measured areas, total bifilms lengths and LR parameters

		RS0	S1	S2	S3	S4	S5	S6
Areas ($x10^7$) [μm^2]	*Section A*	1.20	0.99	0.95	1.12	1.03	1.04	1.11
	Section B	0.90	0.62	1.02	1.16	1.11	1.35	1.25
	Section C	0.57	1.04	0.93	1.24	0.99	1.01	1.14
Bifilms Length ($x10^4$) [μm]	*Section A*	0.56	0.63	0.19	1.52	0.44	2.14	0.77
	Section B	1.28	1.10	1.08	1.18	1.04	1.48	0.96
	Section C	1.20	1.05	0.99	1.01	1.06	1.00	0.90
Lamination Ratio ($x10^{-3}$) [μm^{-1}]	*Section A*	0.47	0.64	0.20	1.35	0.42	2.05	0.69
	Section B	1.41	1.76	1.06	1.02	0.93	1.10	0.77
	Section C	2.10	1.01	1.07	0.81	1.08	0.99	0.79
Normalised Lamination Ratio	*Section A*	1.00	1.37	0.43	2.91	0.91	4.40	1.48
	Section B	1.00	1.25	0.75	0.72	0.66	0.78	0.55
	Section C	1.00	0.48	0.51	0.39	0.51	0.47	0.38

high temperatures the melt becomes less viscous and the filling more turbolent. These two combined effects lead to the formation of many cold shuts and bifilms, decreasing the surface quality of the casting. This detrimental effect related to both temperature and pressure has been observed only on Section A. Conversely, according to the calculated LR parameters, Sections B and C seem to be characterised by an improvement in the surface quality for almost any sample.

Samples S2 and S4 give the best results in terms of LRs, which are both below the reference value. Although the increase of both the plunger speed and the upset pressure seems to be the best solution to prevent laminations, these dangerous processing conditions should be avoided. In high pressure die casting, the duration of the mould is strongly affected by these two parameters. As a result, if the parameters exceed the limits of the die casting machine, the mould may be damaged or deformed. Nevertheless, a small increase in these two parameters should improve the quality of the parts without compromising the duration of the mould.

These observations prove that the quantitative analysis of bifilms and cold shuts, as well as the establishment of the Lamination Ratio, are efficient and can lead to a better knowledge of the parameters involved in the die casting process.

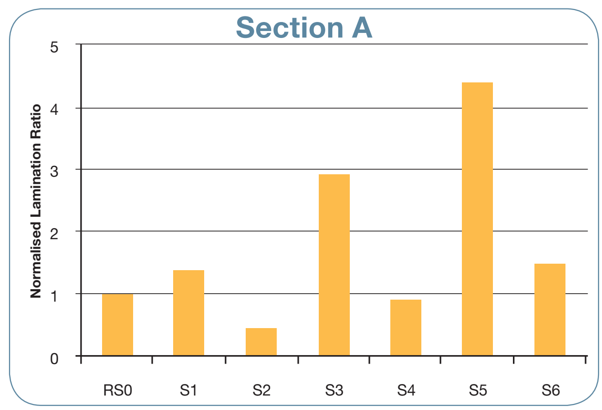

Fig. 5: Comparison among Lamination Ratios in Section A.

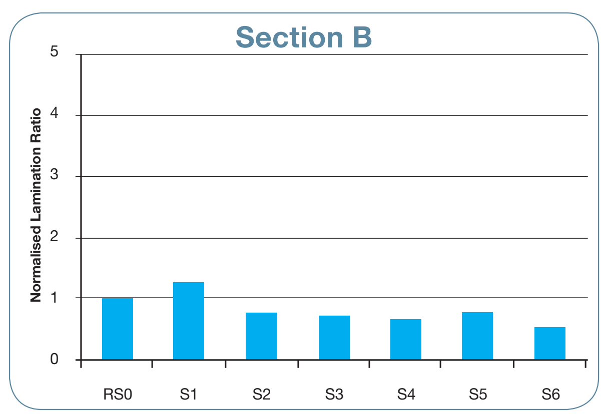

Fig. 6: Comparison among Lamination Ratios in Section B.

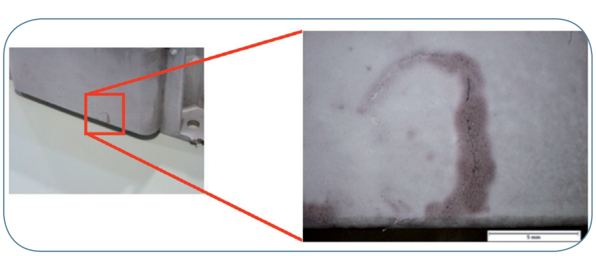

Fig. 4: Lamination revealed by liquid penetrant inspection in sample S6.

The microstructural analyses show a non homogeneous structure in all the three critical regions of the castings. Depending on the cooling conditions, dendrites of different sizes and shapes (nearly equiassic or columnar dendrites) can grow one close to another. The eutectic phase is very fine near the surface, but the size of eutectic silicon particles becomes larger and more platelet-like going towards the inner areas. The micrograph in

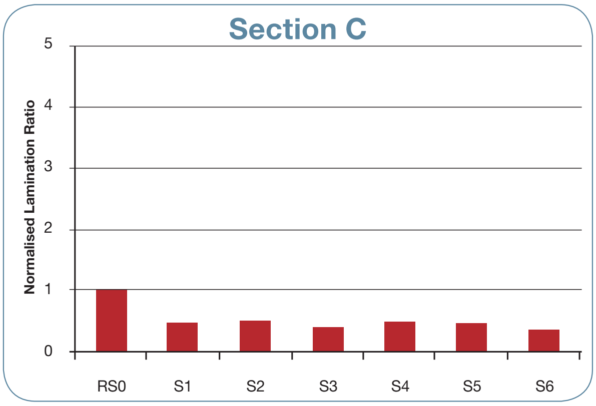

Fig. 7: Comparison among Lamination Ratios in Section C.

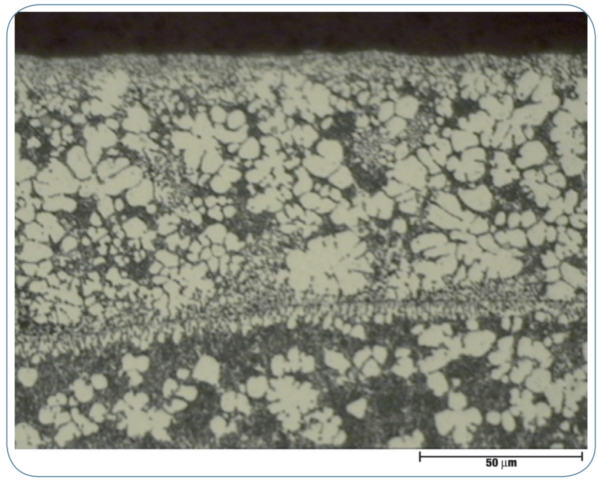

Fig. 8: Evidence of bifilm in Sample S4.

Fig. 8 shows an alumina oxide film acting as an etherogeneous nucleus for dendrites in the inner areas of the thin section.

The optical micrograph in Fig. 9 shows a continuous bifilm and cold shuts, which create a metallic discontinuity between the skin of the casting and the inner areas. These defects are often caused by a succession of arrests and floodings in particular zones of the castings, e.g. thin sections, each new flood entrapping a double oxide film [11]. The shot peening treatment detaches this skin from the casting, and shows the underlying material.

Bifilms, depending on the solidification and cooling conditions, can also unfurl, inflate and create a web, which consists on planar areas among dendrite arrays (Fig. 10). Moreover, Figs. 11-12 show evidence of cold shuts, which have occurred due to the use of a metal mould, accelerating the solidification process. The meniscus loses so much heat that it becomes partially or completely solid during the die filling, being then entrapped by the new liquid front. These surface defects, if shot peened, can also reveal the material beneath, decreasing the surface quality of the castings.

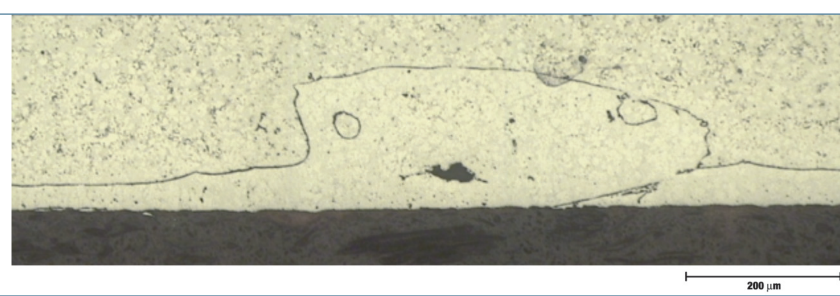

Fig. 9: Presence of continuous bifilm along the surface of Sample S5.

Fig. 10: Presence of continuous bifilm along the surface of Sample S6.

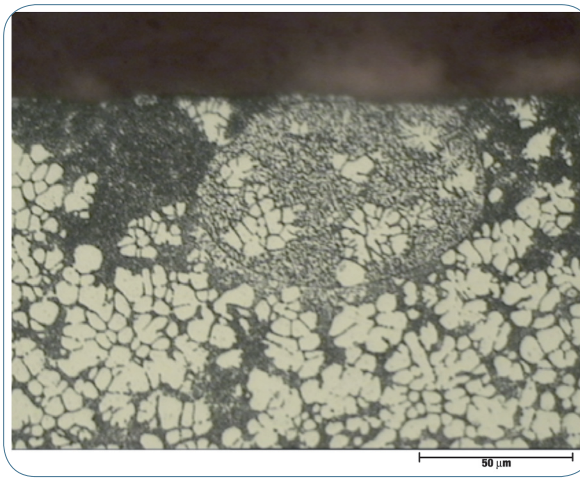

Fig. 11: Cold shut near the surface of Sample S2.

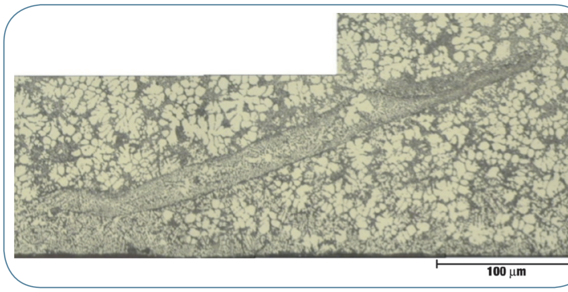

Fig. 12: Cold shut near the surface of Sample S4.

CONCLUSIONS

In the present study lamination defects, occurred on the surface of Al-Si-Cu as-cast covers produced by means of HPDC process, have been investigated. In particular, different process parameters, such as melt temperature, plunger speed and upset pressure, have been considered. A new criterion parameter, called Lamination Ratio (LR), has been evaluated by means of microstructural investigation and subsequent image analysis. This parameter has been proposed in order to correlate the injection parameters to the occurrence of surface defects in the castings. According to LRs, the increase of both the plunger speed and the upset pressure seems to decrease the occurrence of laminations in the as-cast components, whereas the increase of the melt temperature with respect to the reference process conditions is detrimental for the surface quality of the castings. These preliminary results need to be confirmed performing microstructural analyses on a larger amount of castings. Moreover, the effectiveness of the proposed parameter will be verified studying the same castings in the shot peened condition.

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