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Residual stress analysis applied to HPDC alluminium components: a case study

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High-Pressure Die Casting (HPDC) is a casting process largely diffused in the aluminium foundries. By HPDC is possible to obtain aluminium castings with thin walls and high specific mechanical properties in short cycle times. Aluminium HPDC castings are commonly intended for the automotive sector: engine, covers, engine blocks and more in general the powertrain. In recent years, one of the most important focus in the automotive sector is decreasing the powertrain weight, acting on stock allowances in certain parts of the casting. This reduction can affect the dimensional features and in turn the residual stress inside the casting. Despite that, it is possible to obtain beneficial compression states into the castings by mean of post-process operations, such as shot-blasting, to reduce or remove residual stresses by mean of heat treatments. Residual stresses can be assessed by an X-Ray residual stress measurement devices, a non-destructive technique that allows observing the process parameters effect into the casting.

In this work, after a detailed analysis of the residual stress measurement available for aluminium castings, a powertrain component realized in aluminium alloy EN AC 46000 was analysed. These analyses involved both dimensional response and related residual stresses in the as-cast state and the shot-blasted-state on a valve cover, to understand and prevent the residual stress states into the aluminium castings.

KEYWORDS: RESIDUAL STRESS ANALYSIS, ALUMINIUM CASTINGS , HPDC, SHOT-BLASTING, X-RAY METHOD

INTRODUCTION

Nowadays, the aluminium market grew a lot, mainly thanks to the automotive industries that have invested heavily in both the reduction of fuel consumption and vehicles weight. The interest in aluminium alloys is attributable to their very good mechanical properties, especially if compared to their light-weight (1). In this scenario, aluminium foundries have increased their production a lot, focussing on both reducing cycle times and optimizing casting cooling (2). Particularly, processes such as sand casting (SC), gravity casting (GC), high pressure die casting (HPDC) and low pressure die casting (LPDC) are used to realize aluminium components (3). High pressure die casting is an automated manufacturing method for casting thin-walled pieces and very complex components, largely used for high production volumes. This process is characterized by a very high filling-rate of the die by the molten aluminium that solidifies under high pressure. Cycle times may change dependently on the dimensions of the pieces but are usually relatively short. This production process can lead to residual stresses into

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the casted parts, like any other manufacturing process. Residual stresses are self-balancing tensile or compressive stresses existing into the material independently from the presence of an external load. The causes that give rise to residual stresses are uneven plastic deformations, surface modifications and thermal gradients (4). These stresses are generally classified according to the quantity of material involved (5). Type-I-stresses are macro residual stresses involving millimetres of material and are typically caused by manufacturing processes. Type-II-stresses are micro-residual stresses involving micrometers of material while type-III-stresses occur at the atomic scale. The proper choice of the measurement method makes it possible to asses all types of residual stresses (4). Utilizing neutron diffraction (6), the penetration in aluminium is about 50 mm (7,8). Synchrotron x-ray (9) ensures penetration in aluminium of about 100 mm. Relaxation measurements are based on the residual stresses release during the processing of the material (10). This method leads to reach 10μm-10cm by hole drilling and 10cm-1m in deep hole drilling. The magnetic method is only suitable for ferromagnetic materials (11) and ensures penetrations of 10μm-1mm;

the ultrasonic method guarantee penetrations of about 150mm while thermoelastic and photoelastic methods 10μm-1mm. Utilizing the evaluations of the materials' hardness (12) is possible to assess the residual stress in the first 10μm-1mm of the material and, finally, by means of X-ray Diffraction, the penetration is of about tens of micrometers, raising up to 1mm by adopting electropolishing techniques for removing the uppermost layers of material. In this work, the x-ray diffraction method was adopted in aluminium valve covers for automotive usage, obtained by HPDC technique, with the aim to :

- assess the applicability of this non destructive method to complex geometries;
- evaluate the impact of design and manufacturing process change on residual stresses;
- assess the possibility to consider the technology suitable for in-process qu
ality control.

MATERIALS AND EXPERIMENTAL METHODS

The investigated powertrain components were realized in aluminium alloy EN46000 by high pressure die casting. The campaigns of residual stress measurements were conducted on the components showed in Fig. 1. For all investigated parts, the same HPDC process was carried out: (i) die lubrication; (ii) metal injection, (iii) solidification, (iv) extraction, (v) water quenching, (vi) trimming, (vii) shot blasting. Particularly, the last process step has been identified as the most significative to be investigated. X-ray analysis was performed on selected components by the portable X-ray Residual Stress Analyzer μ-X360s, equipped with Cr X-ray target. The measurement is carried out by comparing the lattice parameters of the sample to the theoretical values of the unstressed lattice for the same material, using the cosα method. The diffractometer analyses the 2θ-shift of specific diffraction peaks collecting data on a 2D detector (13) and the residual stress measurement is made by using a collimated X-ray incident beam as a probe directed to the sample surface with a specific exposure angle for a determined time. An integrated LED marker and a CCD camera make the sample positioning easier. Measurements may be carried out along two different crystal planes, [311] and [222], each crystal plane requiring different parameters (i.e. detector-sample distance, detector-sample angle). The measurement of residual stress on plane [311] is made by adopting a 25° detector inclination and a 39 mm distance from the sample surface, while for plane [222], 35° and 25 mm are chosen. The aim of the analysis was the comparison of the stress state in different components as a function of two parameters: shot-blasting and lighter design. The main parameters affecting the residual stresses in powertrain components are the wall thickness, that influences the solidification rate, and the shot blasting, that affects the surface tension state. The points selected for the analysis were chosen after performing optical scan analysis and FEM simulations, to highlight the possible critical points in terms of residual stresses involved. After performing the first residual stress measurements in the as-cast state, the covers were shot blasted and then subjected to the second residual stress measure.

Fig.1 - Components realised, tested and measured (images not to scale each other).

As thin large valve covers regard, one cover was analysed before and after shot blasting: Cover 1 (as-cast) and Cover 1S (cover 1 after shot blasting). The cover was tested only in [311] configuration because of the high numbers of points selected. Massive valve covers analysed were two, and were named after : Cover Basic (as-cast), Cover Evo (as-cast) and Cover EvoS (cover Evo after shot blasting). It is important to note that Evo weights 5% in less than Basic because Cover Basic presents different wall thickness to Cover Evo: Basic wall thickness is 4.5 mm, Evo wall thickness is 2.5 mm. Details about the lighter design are showed in Fig.2-c and d.

RESULTS AND DISCUSSION

Thin large valve cover

One thin large cover was analysed in the as-cast and trimmed state and then after shot blasting. Twenty-four possible critical points were selected where residual stress were measured (as illustrated in Fig.2-a).

Fig.3 shown some details about the measurements. Camera image depicts the analysed point. The red-LED marker visible in the figure indicates the analysed point, that must be located as much as possible into the middle of the rectangular-shaped dotted yellow-lines. The Debye ring indicates the residual stress state. As clearly noticeable from Fig.3-a, Debye ring in shot-blasted covers have smoothed edges suggesting a homogeneous stress state. Fig.3-b displayed the line chart for analysis performed on planes [311]. For points 13, 14 and 22 it was not possible to perform measurements in planes [311] because of the shape of the cover.

As point 24 regards, it becomes evident the beneficial effect of the shot blasting, that change the tensional state of the point from tensile to compressive state. Moreover, it is also clear that all parts of the cover benefit from the shot blasting, as highlighted for sample Cover 1S in both the line chart and the Debye ring. If the previous stress state is in tensile condition (point 24) or a quasi-tensile condition (as points 1, 12, 17), the shot blasting causes a strong impact on the residual stress changing it into a strong-compressive state.

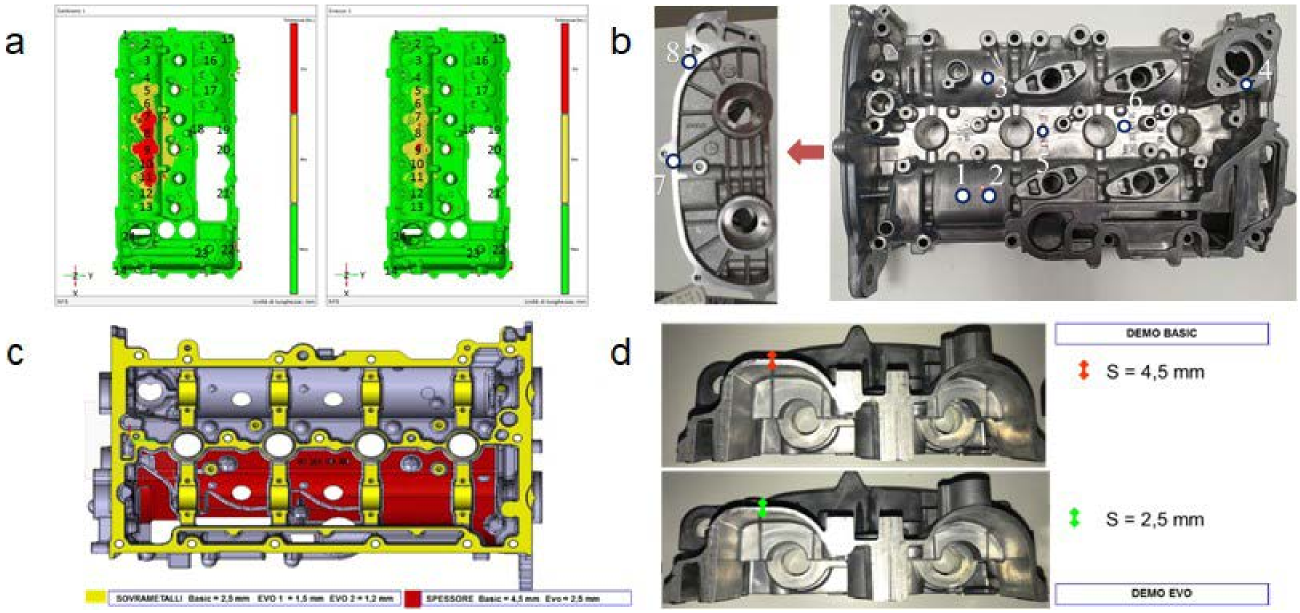

Fig.2 - a. Optical analysis in thin cover in as-cast (left) and shot blasted (right) states and analysed points; b. analysed points in massive valve cover; c. Lighter design in massive cover; d. Wall thickness in the massive cover.

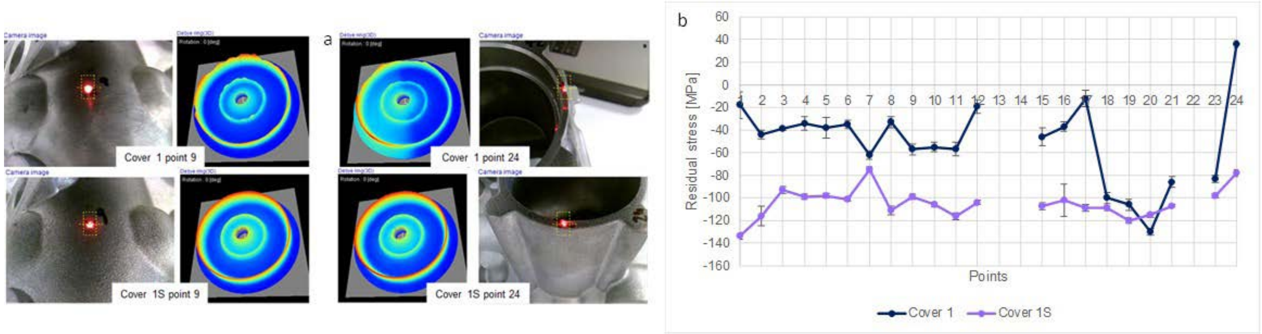

Fig.3 - a. Results obtained for 'thin large valve cover' in the as-cast state (Cover 1) and after shot blasting (Cover 1S). Upper images: points #9 and #24: Debye rings and camera images of the referred points. b. line chart of measurements performed.

The shot blasting influences the residual stresses equalizing it along the entire surface. In the as-cast cover, the average tensional stresses values based on all points analysed was -50±36.6 MPa, while after shot blasting the average was -104.6±13.1 MPa. The high standard deviation in the as-cast state was motivated by the strong variations in the measured points: from +36 MPa (point 24) to -130 MPa (point 20).

MASSIVE VALVE COVER

For these covers the wall thickness reduction contributes to weight saving and has an impact on the residual stress state. In Fig.4 residual stresses are shown for both [311] and [222] planes. From the measurements, a compressive state on the surface of Cover-Basic arises, with an average value of almost -50 MPa on [311] planes and -60 MPa on [222] planes. On the other hand, the lightened cover Evo results in a tensile or quasi-tensile state in some parts of the cover surface, with average values of -5 MPa in [311] and -35 MPa on [222]. The lateral points (7 and 8) showed similar tensional state for both Cover Basic and Cover Evo and in both planes. After the shot blasting, a general compressive residual stress results on the surface of Cover Evo S, with average values of almost -100 MPa along [311] planes and -115 MPa on [222] planes.

Further considerations can be done: first of all, the lightened cover (Evo) results in higher distortions and a light compressive state. Secondly, as attended, the shot blasting caused an increase in the compressive state, without residual tensile stress. From Fig.4 resulted that points 5 and 6 were not measurable in planes [311] because the cover shape makes impossible the approaching of the instrument at the correct distance, while in Cover Evo S on [222] planes, measurements for points 5 and 6 were not shown because of the strong distortions detected and/or the high standard deviations. The weight reduction affects the tensional state increasing the possibility of having tensile stresses or slight compressive stresses. In this respect, weight reduction caused the change from the average value of -45±28.5 MPa in Basic cover to -27±48.3 MPa in Evo cover on planes [311], and from -64.4±23.8 MPa to -47.3±29 MPa on planes [222]. The high standard deviation is motivated by the uneven tension state, typical for the as-cast products. On [311] planes maximum value was +49 MPa and minimum value -75 MPa, on [222] planes the maximum value was -8 MPa and minimum value -101 MPa. Since the lighter cover Evo presents tensile stress in point 1, the cover was further investigated in the shot blasted state founding the average values of -100.2±11.5 MPa on [311] and -120.7±15.4 MPa on [222].

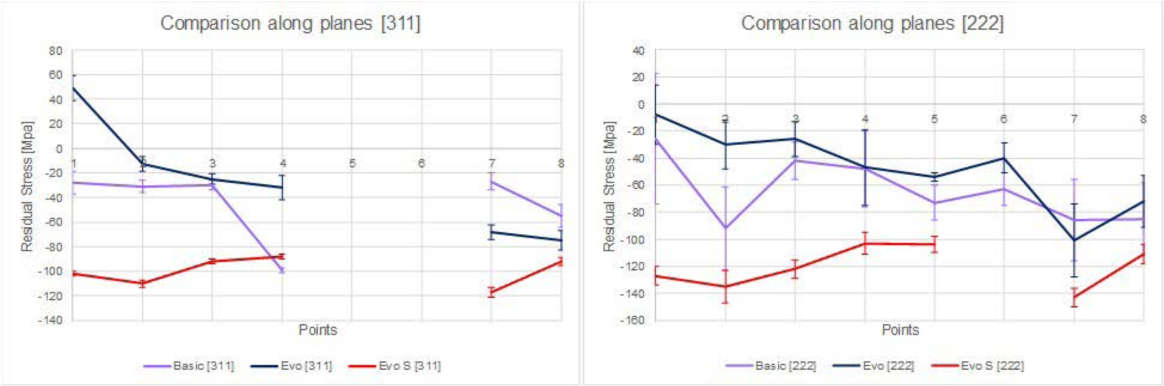

Fig.4 -Line charts for Cover Basic and Cover Evo.

CONCLUSIONS

In this work, two powertrain components were investigated in terms of residual stresses, in the as-cast and trimmed state and after shot blasting. Referring to the aims of the activity , the main conclusions follow.

1. The X-ray diffraction method (non destructive) can be applied, with some limitation in accessibility to certain area, to complex geometries.
2. The casting geometry (wall thickness) affects residual stresses. Components investigated, reported in Fig.1, are the thin large valve cover and the massive valve cover. Particularly, massive valve cover was investigated in the Basic shape and in the Evo shape, to highlight the effect of the weight reduction on the tensional state. In fact, despite the weight reduction appears as very important for both the fuel consumption reductions and the cost savings, it influences the residual stresses too. As the thin large valve regards, analysis highlight the beneficial effects of the shot blasting that has harmonized the tensional state from the average value of -50.2 ± 36.6 MPa to -104.6 ± 13.1 MPa. Measurements were performed only on planes [311]. In the massive large cover, the analysis performed on Cover_Basic evidenced a compressive state on the cover surface. Furthermore, maximum and minimum values measured in Cover_Basic are -27 MPa and -99 MPa on planes [311] and -26 MPa and -92 MPa on planes [222]. The weight reduction obtained by the thinning of the cover wall, as indicated in Fig.2, caused in Cover_Evo a variation in the tensional state. In this sense, on Cover Evo were documented stresses maximum and minimum respectively of +49 MPa and -75 MPa on [311] planes and of -8 MPa and -101 MPa on planes [222]. From these values appears quite evident the presence of an uneven tensional state more pronounced that in Cover Basic.
3. Manufacturing process steps (i.e. shot blasting) affect residual stresses. After the shot blasting, the cover presents a different tensional state, with a homogeneous compressive state having -88 MPa as maximum and -117

MPa as a minimum compressive state on [311] planes and -103 MPa and -143 MPa on [222] planes. These results evidenced the effectiveness of the residual stresses measurements, that underlined the impact of the lighter design on the tensional state in castings. Furthermore, the shot blasting process brings uniformity in the tensional state improving the quality of the powertrain components, reducing the possibilities to triggering into fractures during the assembling of the engine components.

4. The X-ray diffraction (non destructive) technology is suitable for in-process quality control to be adopted during new products development phase. In particular portable X-ray measurement to evaluate the residual stresses in the casting parts is a very interesting source for quickly evaluating both the residual stresses due to casting process and the beneficial effect of the shot blasting, allowing the analysis of various shapes of the castings.

AKNOWLEGMENTS

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