CONDITIONS FOR THE EARLY ONSET OF BLISTERS DURING HEAT TREATMENTS OF Al-Si-Cu CAST PART

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The evolution of subsurface pressurized pores, originating blisters during heat treatment cycles, on High Pressure Die Cast components made of Al-Si-Cu alloys was studied using a Finite Element Model in order to understand under which conditions blister form even below 400°C. The initial defect geometry, depth, inner pressure and the maximum temperature of the thermal cycle were varied in limited ranges, while the material was modelled as elastoplastic, considering creep effects negligible. Results suggested that blisters develop as a result of high plastic strain accumulation in localized regions lying between the pore and the outer surface and that blisters can form even at temperatures of 350-370°C. The simulations were experimentally validated by two sets of experiments carried out on cast parts, monitoring the surface and volume evolution of subsurface defects coupled by optical microscopy and microtomography analyses.

KEYWORDS: BLISTERS, HIGH PRESSURE DIE CASTING, ENAC AlSi11Cu2(Fe), HIGH TEMPERATURE BEHAVIOUR, RESIDUAL STRESSES, MICROTOMOGRAPHY.

INTRODUCTION

After solidification, high pressure die-cast (HPDC) parts can meet several practical situations where their surface is free to expand outward due to the expansion of a subsurface gas porosity. As temperature increases pore pressure can become so high to plastically deform the covering surface layer, which yield stress is oppositely affected by temperature. The small amount of material blown up with respect to the surrounding surface is referred to as blister [1]. This surface defect can make unusable cast parts for esthetical or functional reasons. Examples of situations that can lead to blister formations are: the early extraction of parts from the die, heat treatments [2] and, in general, all industrial processes leading to thermal cycles, even localized to the cast surface. At least three groups of factors affect blister formation at microscopical level: gas pressure inside the pore, geometrical initial discontinuity features (i.e. shape and location) and mechanical properties of the alloy in the temperature range of interest. These factors have been discussed in detail by the authors in in [3]. While their importance on the blister formation is quite clear and it has been discussed in different literature works [3-5], their interaction cannot be easily quantitatively described. Thus, a FE model to investigate combined effects of the above factors has been developed and has been run in various combinations of geometrical/process parameters to investigate their correlations. The present contribution summarizes the model and illustrates the conditions leading to early blister formation. Model predictions are compared to experimental tests carried out on cast parts made of ENAC AlSi11Cu2(Fe) alloy.

FE MODEL OF SURFACE REGION OF CAST PARTS

A FE model was developed to investigate the local stress and strain state of a die-cast part proximal to the subsurface pressurized pore [3]. The pore was assumed ellipsoidal with rotational axis normal to the cast surface and the problem was approached by a 2D axisymmetric model developed in Abaqus with fully coupled thermal-stress analysis. The geometrical and loading parameters, as well as the element size, were given in parametric form. Pore geometry was given in terms of C/A ratio (varied between 0.06-2, C representing half of the pore size along its axis), its size in terms of radius A (1.5-15 μm), its position in terms of ligament thickness H (0.4-152 μm). The mechanical behaviour of Al-based cast alloys was assumed to be

isotropic and elastic-plastically either at room or at high temperatures, neglecting in the latter case any creep effects. The mechanical behaviour of Al the alloy was differentiated by true stress vs. true plastic strain correlation, which was described by the power law relationship, with temperature-dependent power-law parameters derived from experimental data analysis. The modelled portion of cast part was subjected to a thermo-mechanical cycle. The temperature was cycled from 24°C to a maximum heat treatment temperature T_h and decreased to 24°C. Correspondingly, the inner pressure was increased from an initial value of p_o to p_h and decreased to its initial value p_o. The temperature-dependence of pressure was obtained by the assumption of perfect gases and of constant pore volume. Similarly, the pressure at 24°C was related to that at alloy solidus temperature (p_s), at which the pore was assumed to form. p_s was assumed to be close to that applied during the intensification stage of the process and used as reference pressure.
The model results for ENAC Al-Si9Cu3(Fe) alloy are presented in Fig. 1a for the case of a relativly small and sligthly flattened pore (A=15μm), which ligament thickness was 24μm, with a relatively low reference pressure (30MPa). Plastic deformation developed at temperature of about 400°C and at 420°C is reached 0.1mm/mm in the most critical regions, while plastic deformation localized within a 3D ring extending from the pore surface farthest from its axis towards the outer surface. Additional 10°C to the heat treatment temperature were sufficient to significantly increase the region of plastic deformation and the vertical displacement of the free surface just above the pore (Y_{surf}) corresponding to defect development. At 440°C (Fig.1a) the strain accumulated exceeded 0.2mm/mm in large parts of the ligament. For cast Al alloys these strain levels correspond to excessive material damage and are not taken into account by the model. In the case of ligament cracking, the inner pressure could decrease to the atmospheric one and blister could implode, leaving surface defects of different geometry. Y_{surf} was used to summarize the surface situation at the end of a heat treatment cycle and to identify the blister formation, corresponding to Y_{surf} greater than 5 μm. Since Y_{surf} rapidly increased with temperature, a critical temperature for blister formation was identified. The geometry and plastic strain distribution of a laminar-shaped pore are here shown in Fig. 1b and 1c. The reference inner pressure, pore volume and ligament thickness of this pore are the same of the rounded pore of Fig. 1a and C/A was decreased to 0.06. For this defect geometry blisters can be observed at temperatures as low as 390°C, indicating a greater tendency to blister formation for flattened subsurface defects. This pore geometry led to a heavily localized plastic strain field and blister opening is expected in a more localized angular ring surrounding the defect within the ligament. Further, the ligament thickness at maximum surface displacement can be approximately considered unaltered with respect to the initial one. Finally, the observation that the material facing the inner half-part of the pore is not plastically strained, suggests that the initial shape of initially oblate elliptical pores can be deduced by the shape of the deformed pore after blister formation.

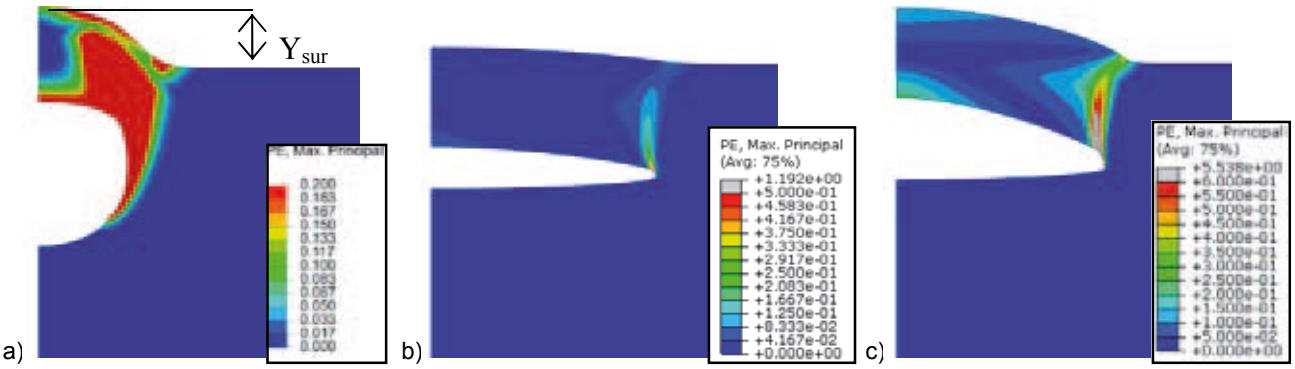

Fig. 1 a) Geometry and plastic equivalent strains at 440°C in the modelled region containing a pore with C/A=0.53, A= 15 μm, H= 24 μm, p_s = 30 MPa; b and c) geometry and plastic equivalent strains in the case of a pore with C/A=0.06, H=2.4 μm, volume 7.5 μm^3, p_s = 30 MPa at 360°C (b) and 370°C (c). In b) and c) grey colour corresponds to plastic strains exceeding 0.5 and 0.6 mm/mm, respectively.

Other sets of FE model runs, with different pore shape, ligament thickness and reference pressure were done, observing in many cases the existence of a critical value of these parameters, at which blister evolved for small parameter increments. Examples are given in Fig. 2, which results refer to the pore geometry characterized by *C/A*=0.53 as in Fig. 1a. Fig. 2a shows that, at a given temperature, a critical *C/A* exists

below which blister form at given ligament thickness. The observation that in the above model *C* can be assumed as a scale factor either for geometry (referred to by means of *A/C*) and position (referred by means of *H/C*) helps in grouping modelling results. Fig. 2b illustrate the temperature above which blister forms for a given pore geometry and reference pressure (in the present case 30 MPa) at different *H/C* ratios.

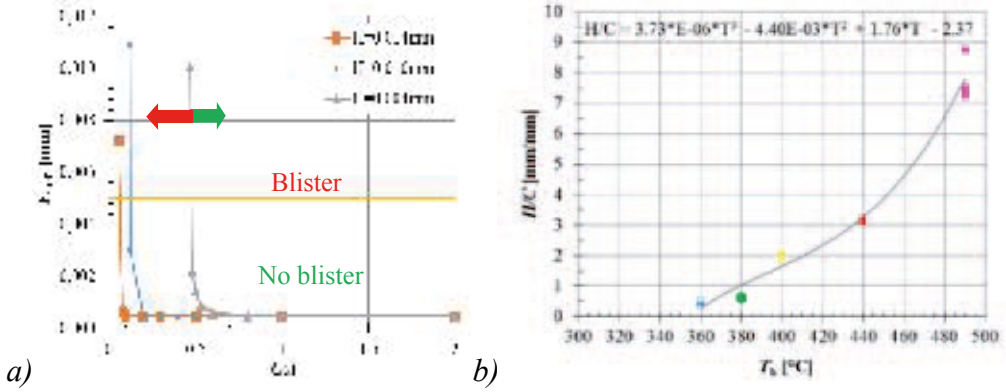

Fig. 2. a) Identification of critical *C/A* values for blister formation varying ligament thickness for oblate pores of the same volume (7.5 μm^3) and p_s=30 MPa; b) Temperature-dependence of the critical *H/C* values (for *C/A*=0.53).

EXPERIMENTAL VALIDATION

Experimental validation was carried out on some HPDC cast parts of ENAC AlSi11Cu2(Fe) alloy, a material which mechanical behaviour is close to that of the alloy used for FE simulations. The cast parts were produced with p_s slightly higher than 30 MPa. A set of cast parts was heat treated for 20 min at different temperatures and the onset of the blisters was checked visually. The results of experiments showed the onset of the first, isolated blisters at temperatures of 350-370°C. Microtomography observations were performed on selected samples on a roughly cylindrical region, of about 3 mm thickness, using a X25 equipment by NSI (North Star Imaging). Scans were performed at X-ray source voltage of 67 kV and a current of 55 μA . The set focal spot size was 3.7 mm. Under these conditions, the unsharpness geometry is 0.34 pixels. The continuous scan parameters are set as 1440 projections and a frame average of 3. Current spatial calibration was performed at the end of each test. The obtained data have been analysed by efX-ct software by NSI. Metallographic observations were then carried out on sections including defects of interest. A second set of experiments was carried out to monitor evolutions of blisters in the same material volume. In this case a single sample machined from a cast part of the same batch, 10 mm wide and 20 mm long and about 3mm thick was cyclically heat treated at temperatures from 300 to 540°C, with hold times of 20 min at each temperature. After each cycle, microtomography and visual observations were carried out on its volume. Metallographic observations were carried out at the end of the heat treatment cycles.

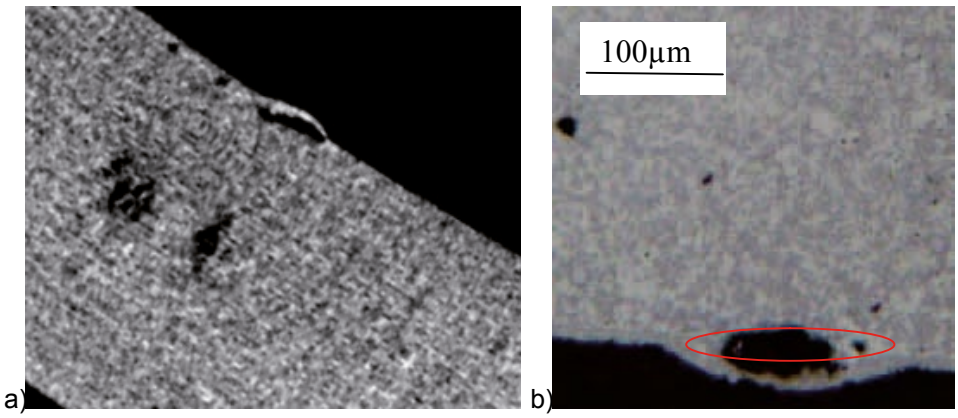

Fig. 3. Subsurface lamina-type discontinuity plastically deformed during heat treatment at 360°C and giving rise to a blister. a) microtomographic image, b) light optical micrograph.

The first set of microtomography observations revealed the formation of blisters at low temperatures, correlated to lamina-type, flat discontinuities, see Fig 3a. A metallographic section of the same blister is given in Fig. 3b. The ligament thickness of all the defects observed was of about 15 μm, corresponding to the

thickness of the thin 'skin' of refined microstructure, often observed in HTDC parts. The two rounded pores in Fig. 3a did not give rise to blister at 370°C. According to simulations results focusing on rounded pores, given in Fig. 1. and 2, at 370°C the critical H_{cr}/C is 0.75 (and, correspondingly, the critical H_{cr}/A is 0.37) and thus blisters can only form from pores with A > 80μm. This is not the case of the rounded pores in Fig. 3a).
On the contrary, for the same reference pressure and temperature Fig. 2a suggests a critical C/A of about 0.15 for H of 10 μm, that in terms of the geometric ratio H/C means 1.26. The red-colour elliptical contour in Fig. 3b suggesting the possible initial pore diametric section in a plane parallel to the one of the metallographic section, corresponds to C/A of 0.15, with C = 12.5μm. In this case model predicts a critical ligament thickness for blister formation of 1.26*12.5μm =15.75μm, comparable to that seen in Fig. 3b.
Focusing the attention on the results of the second set of experiments, the first blister is developed on the surface of the sampled cyclically heated during holding at 350°C (Fig. 4a). On the surface it appeared as rounded, with an inner protrusion and an outer depressed ring. The morphology was compatible to that previously commented for blister developed from a wide lamina-type defect (either single or resulting from coalescence of close defect) with a very thin ligament thickness that cracked at high temperature and collapsed during cooling. The mechanism was confirmed by the fact that no evolution of the same defect was observed after heat treatments at higher temperatures (Fig. 4b). Microtomographic analyses revealed an irregular outer surface in the transverse section plane diametric for the defect (Fig. 4c). Microtomographic analyses were not able to resolve any ligament, reasonably due to resolution limits of the equipment. On the other hand, a confirmation of the defect features by metallographic section was not possible at these stages of cyclic heating. Fig. 4d reveals the massive blister formation occurred in the same specimen at 540°C, involving mostly rounded-shape defects at relatively high depths, often coalescing into large discontinuities. Their geometrical analysis and comparison with FE model predictions will be addressed in a future work.

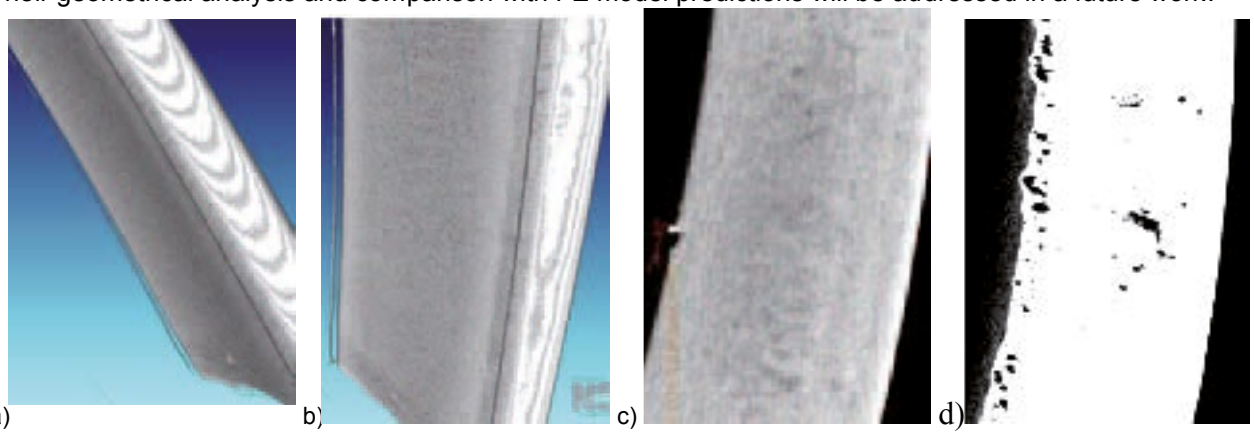

Fig. 4 Blister observed on the surface of the specimen with cyclic heat treatment up to 350°C a) and 375°C b). Tomographic section of the same specimen heat treated up to 350°C c) and 540°C d).

CONCLUSIONS

The developed FE model led to the identification of critical conditions for blister formation during heat treatments on an Al-Si-Cu casting alloy at temperatures in the range 350-400°C. Strain field maps revealed plastic strain localization in the lateral part of the ligament, so that blisters can form more easily from lamina-shaped discontinuities. Microtomography and metallographic observations analyses carried out on samples from HPDC parts made of EN AC AlSi22Cu2(Fe) heat treated alloy were consistent with model predictions. Microtomography revealed to be an helpful tool to investigate the distribution and evolution of inner discontinuities during component processing, such as in the case of heat treatment.

REFERENCES

[1] E. Gariboldi, F. Bonollo, P. Parona. Handbook of Defects in High Pressure Diecastings. AIM, Milano (2011) p. 77-79.
[2] R. Lumley, R. Odonnell, D. Gunasegaram, M. Givord. Metall. Mater. Trans. 38A (2007) p. 2564.
[3] O. Ozhoga-Maslovskaja, E. Gariboldi, J. Nicolas Lemke, Materi. & design 92 (2016) P. 151.
[4] M. Dargusch, G. Dour, N. Schauer, C. Dinnis, G. Savage. J Mater Proc Techn. 180 (2006) p. 37.
[5] X. Niu, B. Hu, I. Pinwill, H. Li. J Mater Proc Techn 105 (2000) p.119.