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Case study

Failure analysis of Co–Cr hip resurfacing prosthesis during solidification

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ABSTRACT

In this study a failure originated during solidification process into the femoral stem component of Hip Resurfacing prosthesis was investigated. Visual inspection, optical microscopy, scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS) and a commercial software simulation ProCAST were carried out in order to determine the cause and solution of this failure. The results exhibited hot tearing, shrinkage porosity and metal oxide films due to inadequate heat dissipation during solidification process, as a consequence of poor investment casting ceramic mold configuration. Also in this paper was improved the casting design solving this kind of defects.

1. Introduction

Hip resurfacing (HR) Co–Cr prosthesis is usually manufactured by investment casting process. This kind of devices are subject about one million cyclic loads per year due to the gait cycle of a patient. On the other hand, casting manufacturing defects like microcracks, microstructure heterogeneity, distortion, residual stress and stress concentration by surface irregularities can results in a fatigue failure [1]. By this reason it is necessary to develop an appropriated casting design and control parameters of solidification process. Hot tearing or solidification cracking are defects in casting process and occurs at high temperature during the last stages of solidification in which there is only a small fraction of remaining liquid in the interdendritic region. This effect is caused by the inability of the material to withstand the existing thermal stress–strain in the semi-solid state [2]. Hot tears initiate under stress and strain, when the solid crystals are partially separated by the liquid film, at this stage the overall strength of the hot spot of the casting is very low. The tendency of alloys to hot tearing depends on the temperature range in which the cracks can initiate. It has been assumed, that process of the cracks formation starts at the temperature of grains interlocking [3].

Mechanical loading, tensile or compressive, is caused by restrained thermal contraction. This effect is the consequence of cores, geometry constraints and other factors, which act to resist the movement of the casting surface during solidification [4–7]. For example, complex casting geometries may result in constraints that can place regions of the casting in tension that can occur in hot tearing [8].

The aim of this study was to establish the causes of failure in HR prosthesis before implantation in patients. For this purpose microstructure examination and a finite element method (FEM) were undertaken to simulate the prosthetic implant casting and solidification process.

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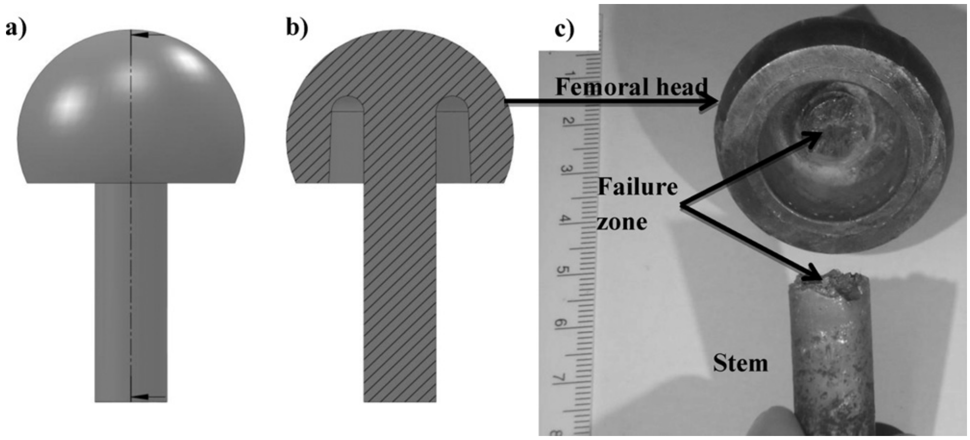

Fig. 1. Femoral prosthesis: (a) schematic prosthesis component, (b) schematic half section, and (c) view of the hip prosthesis showing the failure zone.

2. Experimental

2.1. Characterization

A HR femoral component failed during the manufacturing machining process was analyzed. Fig. 1a and b shows a schematic femoral prosthetic component with 40 mm of head diameter and 50 mm of stem length. In order to characterize the failure in the femoral component, visual inspections, scanning electronic microscope (SEM) and energy disperse spectroscopy (EDS) were used to explore in high magnifications the morphology and identify elements involved in the beginning of the failure. The materials of the components are made of typical cobalt-chromium-molybdenum alloy according to the chemical composition ASTM F75-07 [9] shown in Table 1.

2.2. Casting simulation

Commercial software: ProCAST V.2008 was used to simulate the behavior of fluid flow during mold filling and solidification of the ASTM F75-07 alloy using the same casting parameters: 6 mm at thickness of ceramic shell molds was modeled according to the current process. The molten alloy was pouring into the mold cavity preheated at 950 °C with a filling time of 2.4 s with an inlet of 1.0 kg/s at a molten alloy temperature of 1500 °C according to the requirement manufacturing process. The parameters used for the ceramic shell mold was 500 W m^2/K as a heat transfer condition between ceramic mold and the alloy and 20 W m^2/K as a heat transfer condition between ceramic mold and the ambient temperature.

3. Results and discussion

3.1. Visual inspection

The femoral component stem showed an extended failure located between the femoral head and the beginning of the stem at the change geometry direction as shown in Fig. 1c. It is possible to observe half section of the femoral component

Table 1
Elemental composition of the CoCrMo test samples and ASTM F75-07: Standard Specification for Cobalt-28 Chromium-6 Molybdenum Alloy Castings and Casting Alloy for Surgical Implants.

Element	Test sample (wt%)	ASTM F75-07 required (wt%)
Co	Balance	Balance
Cr	28.3–28.9	27–30
Mo	5.9–6.4	5–7
Ni	0.19–0.33	<0.5
Fe	0.13–0.26	<0.75
C	0.21–0.23	<0.35
Si	<0.4	<1
Mn	<0.6	<1
W	<0.05	<0.2
P	<0.016	<0.02
S	<0.008	<0.01
N	<0.12	<0.25
Al	<0.06	<0.1
Ti	<0.007	<0.1
B	<0.003	<0.01

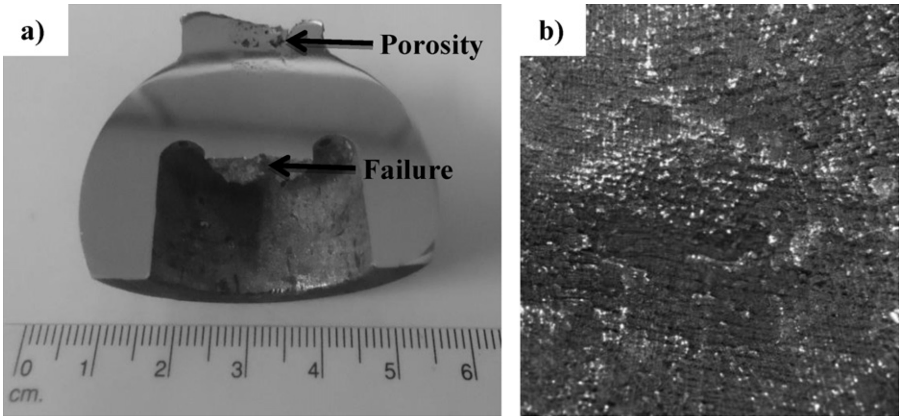

Fig. 2. Femoral component showing: (a) the failure and porosity defects and (b) failure component zone.

showing the failure zone (see Fig. 2a). In addition, shrinkage porosity defects are visible into the femoral head. In Fig. 2b is shown the crack surface with presence of oxides.

3.2. Microscopy analysis and simulations

In Fig. 3a and b are shown the SEM images at high magnification of the hot tearing failure zone with dendritic surface morphology. It is possible to observe the last solidified dendrites layer and the interdendritic crack. This effect may be explained due to the interdendritic tear occurred during the last stage of solidification. In Fig. 3c shows the typical secondary phases ($M_{23}C_6$ carbide) embedded in the cobalt-base alpha matrix (fcc) [10,11]. It is possible to observe the presence of

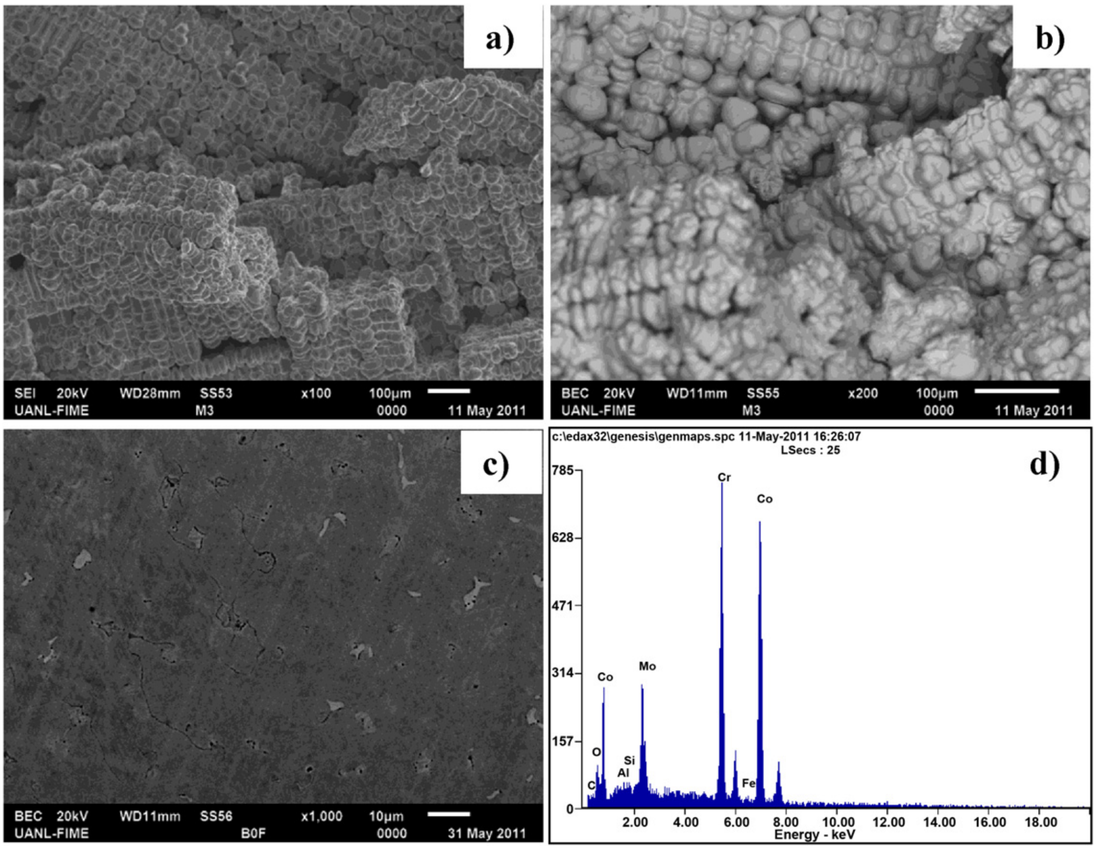

Fig. 3. The image shows: (a and b) SEM micrographs at 100× and 200× for hot tearing, (c) Co–Cr microstructure at 1000×, and (d) EDS analysis defects.

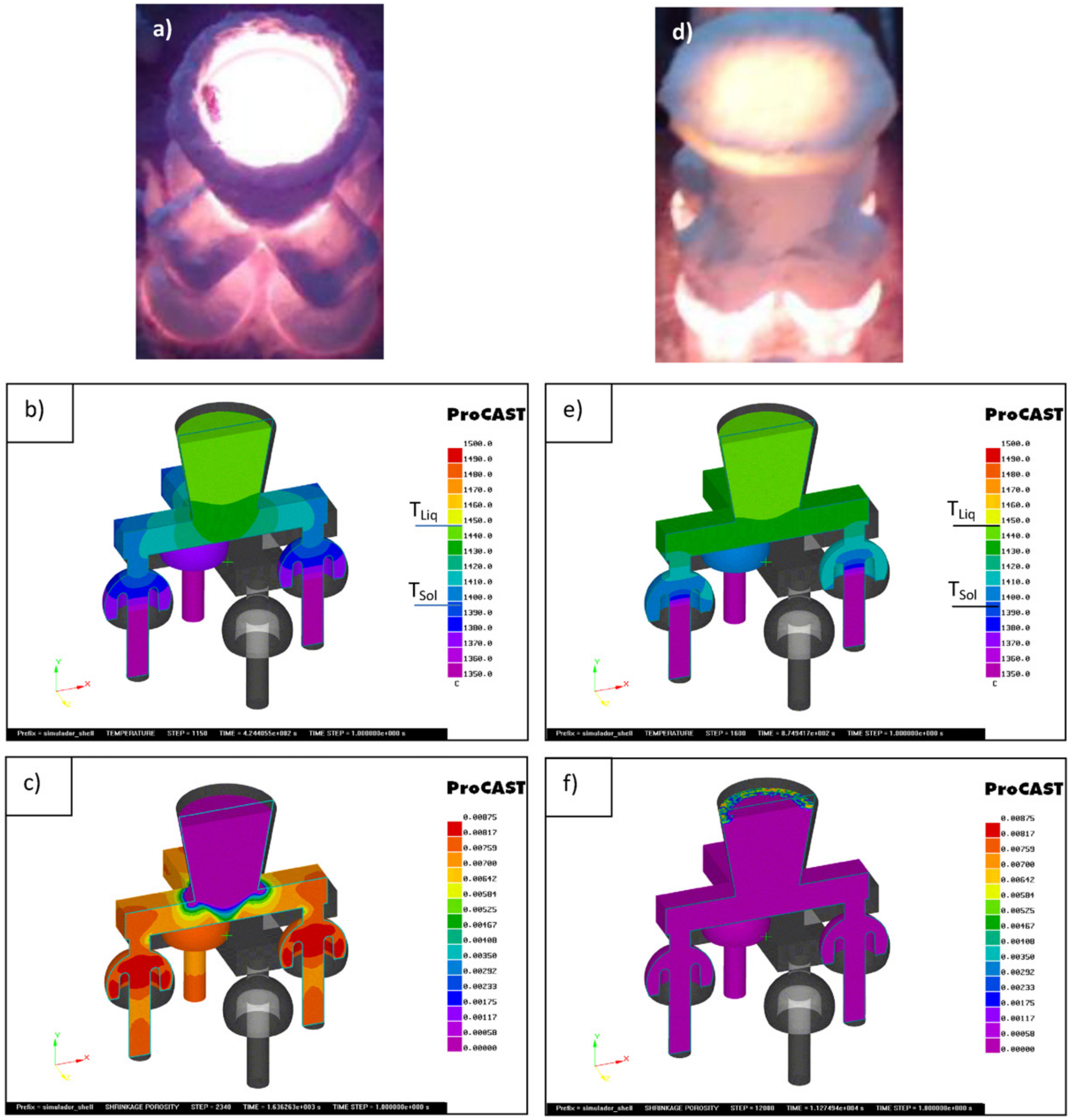

Fig. 4. Simulations of solidification process for both normal and insulated conditions. (a) Picture of casting solidification, (b) solidification temperature, (c) shrinkage porosity for normal casting heat transfer condition and (d) picture of insulated casting solidification, (e) solidification temperature, and (f) shrinkage porosity for insulated condition.

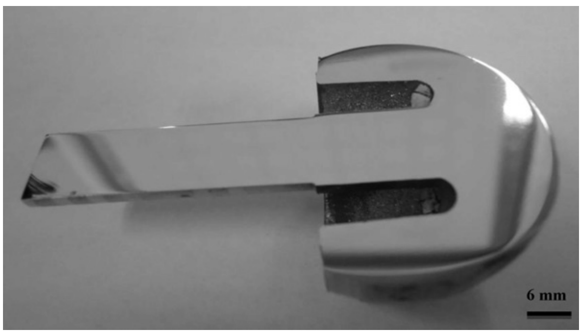

Fig. 5. Femoral prosthesis without defects.

microporosity of the failure zone. The EDS spectrum in Fig. 3d shows the composition of characteristic ASTM F75-07 alloy with presence of oxygen which lead a layer oxide shown in Fig. 2b.

The hot tearing defect was confirmed by the ProCAST simulations. In Fig. 4a is shown the casting solidification process where is possible to observe how the heat irradiation is homogenous at all parts of the ceramic mold. In Fig. 4b is shown the solidification temperature where the liquid temperature T_{liq} is 1449 °C and the solidus temperature T_{Sol} is 1397 °C. It is possible to observe how solidification occurred at 424 s this did not permit to feed enough the hot spot located on the stem change direction. It was confirmed when was analyzed the shrinkage porosity prediction in Fig. 4c where is possible to observe that in this location was accumulated heat resulting in thermal contraction and as a consequence hot tearing coinciding with the examination made in visual inspection, see Fig. 2a.

With the purpose to eliminate these defects, it was undertaken additional experimentation setting an adiabatic insulation on the feeder, runners and gates as is shown in Fig. 4d, where is possible to observe how the heat irradiation is higher on the HR prosthesis regarding to the insulated upper part of the ceramic mold. It suggests a directional solidification which was validated by ProCAST simulations. In Fig. 4e is possible to observe a better temperature distribution of the feeder system being more efficient, this was confirmed in shrinkage porosity prediction image presented in Fig. 4f where porosity defects were present only on the pouring cup. This simulation was validated analyzing the transversal section of the femoral component where none defects were seen, see Fig. 5.

4. Conclusions

It is concluded from this study the effect for ceramic shell mold parameters as causes of implant failure:

1. The failure was presented into the femoral stem as hot tearing and shrinkage porosity caused by casting parameters and solidification process.
2. The proposed sequence of failure is: due to the heat transfer cooling condition, the stem in semi-solid state was the last part of the solidification resulting in an oxide film, shrinkage porosity and stress induced by thermal contraction.
3. In order to prevent femoral component failure, process conditions must be controlled being in this case a control of the heat transfer condition of the ceramic shell mold.

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