Towards a Rapid determination of the Fatigue Strength of a Hip Prosthesis: Influence of the manufacturing process and use of finite element analysis

INTRODUCTION
For several years, some authors have worked on the rapid estimation of the High-Cycle Fatigue (HCF) properties of metallic materials based upon temperature measurements under cyclic loadings. This method is so-called “self-heating tests” [1-3]. More recently, the development of a two-scale probabilistic model has shown that self-heating tests permit to identify, not only, the mean fatigue limit, but also the scatter of classical fatigue results [4-6]. The fatigue testing of a new hip prosthesis must be performed as part of the design approval. It is well known that traditional fatigue test campaigns (e.g. staircase method) require large sample sizes and testing time to accommodate the scatter associated with component fatigue test results [7].

In a previous work, our research group has shown that less than 2 hours were sufficient to run and to plot the self-heating mean fatigue limit of raw material Ti6Al4V specimen used to forge hip prosthesis. The results were compared against classic staircase fatigue testing results [8]. In this study we extended the evaluation of the self-heating testing on a specimen from a forged Ti6Al4V hip prosthesis. The objective was to check if the approach could account for the influence of the manufacturing process (hardening) on the mean fatigue strength of a forged specimen compared to previous results measured on raw material Ti6Al4V specimen. In parallel, we started developing a methodology using finite element analysis to simulate the complete forging process of a stainless steel hip prosthesis: The calculated level and distribution of hardening after the manufacturing process in specific region of interest will allow identification of the scatter of fatigue results associated with the self-heating curves. Once validated, this approach will also be used to design fatigue testing specimen having equivalent material state to a forged hip prosthesis.

METHOD
Rotating bending fatigue testing machine was used to measure self-heating mean fatigue strength of a specimen machined from a forged Ti6Al4V hip prosthesis (Fig.1). An IR Camera measured the specimen stabilized temperature for different block loads (Fig.2). Mean fatigue strength of the forged specimen was normalized and compared to previous self-heating mean fatigue strength measured on raw material Ti6Al4V specimen (660 MPa) [8] (Fig.3).

We sequentially simulated all steps of the manufacturing process of a forged stainless steel hip prosthesis (heating, rolling, cambering and forging) using the FEA Software package “FORGE 2008”. We started validating the FEA results by comparing geometry of simulated and real parts at different steps of the manufacturing process. Based on the calculated material hardening distribution of the forged implant in specific region of interest, we used the FEA approach to design the manufacturing process of a forged fatigue testing specimen that will have equivalent hardening to a forged hip prosthesis.

RESULTS
The self-heating testing approach confirmed the beneficial influence of the forging process on the mean fatigue strength of a specimen from a forged Ti6Al4V hip prosthesis (+17% compared to the Ti6Al4V raw material). (Fig.3)

We started validating the FEA results of a stainless steel hip forging process by comparing real and simulated geometries at different steps of the process: After the rolling step there was less than 2% difference between the simulated and the real length of the bar.

We calculated the final material state of a forged hip prosthesis (Fig.4) and based on those results we used the FEA approach to design a manufacturing process of a forged fatigue testing specimen that will have equivalent material state to a forged hip prosthesis (Fig.5).

DISCUSSION
The self-heating testing approach confirmed the beneficial influence of the forging process on the measured mean fatigue strength of a specimen from a forged Ti6Al4V hip prosthesis. FEA simulation of the forging process allowed quantification of the material state (hardening) at the end of the process. The FEA approach was also used to design the manufacturing process of a forged fatigue testing specimen that will have equivalent hardening to a forged hip prosthesis. However, the validation of the FEA results is not completely achieved: A comparison between the predictions of the model and the measurements of hardening in specific region of interest still needs to be completed.

Although we are currently validating the self-heating fatigue testing method on raw material specimen and forged specimen, the final objective will be to routinely measure the fatigue strength performance of products directly on production hip prosthesis.

REFERENCES