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Design optimization of precision casting for residual stress reduction

Appasaheb Adappa Keste, Shravan Haribhau Gawande*, Chandrani Sarkar

Department of Mechanical Engineering, M. E. Society's College of Engineering, S. P. Pune University, Pune, India

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Abstract

Normally all manufacturing and fabrication processes introduce residual stresses in a component. These stresses exist even after all service or external loads have been removed. Residual stresses have been studied elaborately in the past and even in depth research have been done to determine their magnitude and distribution during different manufacturing processes. But very few works have dealt with the study of residual stresses formation during the casting process. Even though these stresses are less in magnitude, they still result in crack formation and subsequent failure in later phases of the component usage. In this work, the residual stresses developed in a shifter during casting process are first determined by finite element analysis using ANSYS® Mechanical APDL, Release 12.0 software. Initially the analysis was done on a simple block to determine the optimum element size and boundary conditions. With these values, the actual shifter component was analyzed. All these simulations are done in an uncoupled thermal and structural environment. The results showed the areas of maximum residual stress. This was followed by the geometrical optimization of the cast part for minimum residual stresses. The resulting shape gave lesser and more evenly distributed residual stresses. Crack compliance method was used to experimentally determine the residual stresses in the modified cast part. The results obtained from the measurements are verified by finite element analysis findings.

Keywords: Casting; Finite element analysis (FEA); Optimization; Residual stresses; Crack compliance method

1. Introduction

Residual stresses are developed during the solidification process due to the temperature gradients between different parts of casting or due to the mechanical constraints imposed by the mold during shrinkage of the cast metal and volumetric change and transformation plasticity associated with the solid state phase transformation according to Chandra [1]. A complex geometry means more internal sections which take longer to cool. Therefore, initially these sections are loaded compressively. This change to tensile loading as it contract within the already cold outer part. This increases the magnitude of tensile residual stresses produced on cooling of the cast.Since the residual stresses can increase or decrease the fatigue life of a component [2], an interest on its consideration during the design process has grown in the foundry industry. This paper presents a comparison of residual stress development between parts that has not undergone topology optimization processes.

The magnitude and distribution of residual stresses in a component or structure is a significant source of uncertainty in mechanical engineering design as it affects subsequent machining, life prediction and assessment of structural reliability. Residual stresses are generated due to almost all manufacturing and fabrication processes and can also arise during service; they will occur under any set of circumstances that leads to differential expansion or contraction between adjacent parts of a body so that the local yield strength exceeds the material value. Their influence depends on the magnitude, sign and extent relative to the controlling geometry. It is also associated with a particular mode of failure. Interpretation and optimization of residual stresses in terms of manufacturing history and service performance would mean better materials fabrication, processing and usage.

This work deals extensively with the simulation of residual stresses. Hence a lot of literature has been studied to model the optimum finite element (FE) problem. Liu et al. [3] have studied

*Corresponding author. Tel.: +91 2026163831; fax: +91 2026163831.
E-mail address: shgawande@gmail.com (S.H. Gawande).

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the development of thermal stresses and predicted the hot tearing and residual stresses in shaped casting. Ragab et al. [4] have used a coupled thermo-mechanical finite element model to simulate the die casting process. The simulation models show the effect of thermal and mechanical interaction between the casting and the die. It also includes the temperature dependent material properties of the casting. Metzget et al. [5] have studied a method to efficiently predict residual stresses in foundry product by FEM. Vijayaram et al. [6] have studied casting solidification simulation process which was used to identify the defective locations in the castings from the generated time–temperature contours. Afazov et al. [7] studied FE prediction of residual stresses of investment casting in a bottom core vane under equiaxed cooling and presented an investment casting simulation of the same to find the residual stresses. Xue et al. [8] did the numerical simulation of casting thermal stresses based on finite difference method using a three-dimensional code which was developed for solving thermal-elastoplastic stress problems during solidification process. Koric et al. [9] applied a three-dimensional transient explicit finite-element method to simulate the coupled and highly-nonlinear thermo-mechanical phenomenon that occurs during steel solidification in continuous casting of thin slabs in a funnel mold. Afazov et al. [10] presented a finite element simulation of an investment casting of a high pressure turbine blade under directional cooling.

In this work a shifter, as shown in Fig. 1, is taken as component of interest as it is a precision cast part. It is a component of four wheeler transmission system. This part seems to develop cracks during its service which has been credited to fatigue. Since residual stresses cause these crack formation under fatigue, the component is studied and analyzed for residual stresses.

The objective of this work is to simulate the formation of residual stresses during casting of a shifter and to identify the areas of maximum impact. The second objective was to modify the shape of the shifter so that lesser residual stresses may be developed during casting without affecting the functional integrity of the component.

2. Methodology

This work started with setting up a numerical problem to determine the residual stresses using a simple block analogous to the shifter. The block is treated as the casting and an enclosing bigger block, with exact cavity is considered as the mold. Since the residual stresses in the castings develop due to temperature gradients and structural constraints, the problem has to be defined, considering both thermal and structural loads. This is done in two phases, namely, before-shake-out and after-shake-out. In before-shake-out phase it is considered that the heat flows during pouring of molten metal into the sand mold at room temperature. In after-shake-out phase, the mold is removed and the cast is allowed to cool by itself at atmospheric conditions. Thus the heat flow between the cast and atmosphere is considered. In addition to the thermal analysis, this phase also considers determining the structural stresses developed due to the two temperature gradients obtained in the above steps.

The block model is first put through the simulation to get the optimum mesh pattern and element size. Then, the same conditions are applied to the shifter. Depending on the stress field, the next step is to determine the optimum geometry of the shifter which will result in lesser residual stresses while maintaining the functional integrity of the shifter. To validate the results, the modified shifter is tested experimentally using crack compliance method. This method gives strain values which have to be converted to stress. The complete methodology can be summarized as shown in Fig. 2.

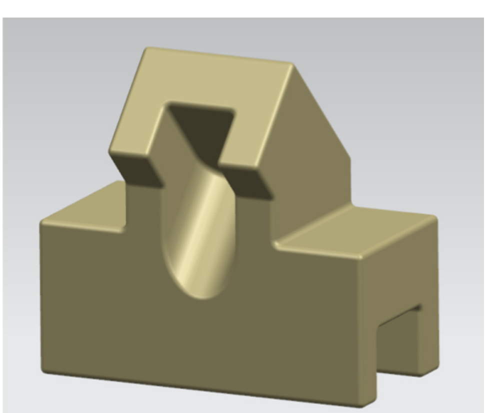

Fig. 1. Shifter (cast part to be studied).

3. Finite element modeling and analysis

The residual stresses are obtained by solving a two stage problem. In first phase, the temperature distribution is determined by cooling the component and in second phase, this prescribed temperature history is used to find the developed residual stresses by an elastoplastic analysis. The governing equations of these two phases are presented below. These equations form the very basis for the finite element analysis. Consider a block analogous to casting (shifter) as shown in Fig. 3. The length of the block is much larger than the width, so that heat transfer occurs through the area A only. Assuming ρ as the block density and isobaric specific heat as cp (since casting process will be at constant pressure), consider a small element of length Δx at a distance x from the origin. An energy balance on this thin element during a small time interval can be expressed as follows.

$$\text{(Rate of heat conduction at } x) - \text{(Rate of change of the energy content of the element at} x + \Delta x) = \begin{pmatrix} \textit{Rate of change of the energy} \\ \textit{content of the element} \end{pmatrix}$$

$$\dot{Q}_x - \dot{Q}_{x+\Delta x} = \frac{\Delta U_{element}}{\Delta t} \quad (1)$$

where, the change of energy content ΔU can be given by:-

$$\Delta U_{element} = U_{t+\Delta t} - U_t$$

$$\Delta U_{element} = m.c_p(T_{t+\Delta t} - T_t)$$

$$\Delta U_{element} = \rho.A.\Delta x.c_p(T_{t+\Delta t} - T_t) \quad (2)$$