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Optimization for Residual Stresses in a Cast Part

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ABSTRACT

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 greater research has 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 were 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 were 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 were used to verify the finite element analysis findings.

***Keywords*— Casting, Finite Element Analysis, optimization, residual stresses, crack compliance method.**

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I. 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 et. Al [1]. 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 industry of casted parts. This work presents a comparison of residual stress development between parts that has and 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 is exceeds the material value. Their influence depends on their magnitude, sign and extent relative to the controlling geometry. It will also be associated with a particular mode of failure. Interpretation and optimisation of residual stresses in terms of manufacturing history and service performance would mean better materials fabrication, processing and usage.In this work a shifter is taken the component of interest as it is a precision cast part. It is used in four wheeler transmission systems. This part is seen to develop cracks during its service which has been credited to fatigue. Since residual stresses cause these crack formations under fatigue, the component was studied and analysed for residual stresses.The objective of this work was 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 shape of the shifter so that lesser residual stresses developed during casting without affecting the functional integrity of the component.

I. Literature Survey

This work deals extensively with the simulation of residual stresses. Therefore a lot of literature has been studied to model the optimum finite element problem. Liu et al. [3] have studied 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 FE model to simulate the die casting process. The simulation models 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 stress in foundry casting by FEM. Vijayaram et al. [6] 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 Vaneunder 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 stress based on finite difference method using a three-dimensional code that 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 phenomena 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.

II. Methodology

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

The block model was first put through the simulation to get the optimum mesh pattern and element size. Then, the same conditions were applied to the shifter. Depending on the stress field, the next step involved determining the optimum geometry for the shifter which will result in lesser residual stresses while maintaining the functional integrity of the shifter. To validate the results, the modified shifter was tested experimentally using crack compliance method. This method gave strain values which had to be converted to stress.

III. Finite Element Modeling and Analysis

The complete finite element model was created and meshed in ANSYS 12.0. To get the most accurate mesh pattern and the optimum element size, a simple cast block was first taken as an example. The element type selected for residual stress analysis was SOLID 227 as it is a coupled field element with ten nodes, each node having five degrees of freedom. It is a quadratic element type with a pyramid shape and supports both structural as well as thermal loads. The geometrical and material properties for the shifter cast and mold are given in Table 1. After three iterations, the element size for the cast and mold were selected as 2.3 mm and 4 mm respectively. The material for the shifter and the sample block was taken as cast steel. In both the original and the sample block, mold is taken as a simple cube surrounding the cast part larger in size, with appropriate cavity provided for casting. Half symmetry boundary conditions were used in the analysis to reduce time and memory required for computation. Figure 1 shows the fully meshed shifter and Figure 2 shows the shifter and cast assembly utilizing the half symmetry. Figure 3 shows the meshed shifter cast and mold considering half symmetry boundary conditions.

The analysis procedure was divided into three steps as follows:-

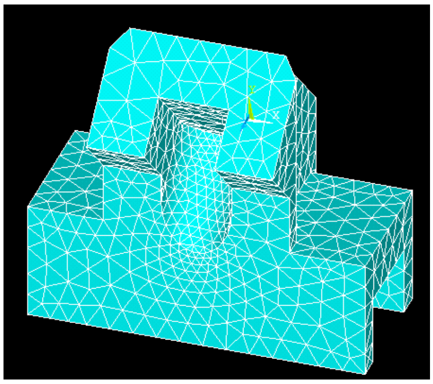

Fig.1 Shifter (cast) mesh .

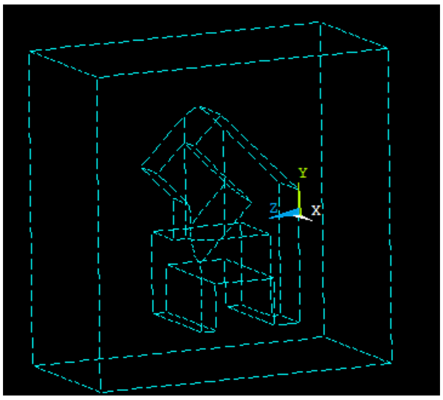

Fig.2 Shifter cast and mold assembly with half symmetry.

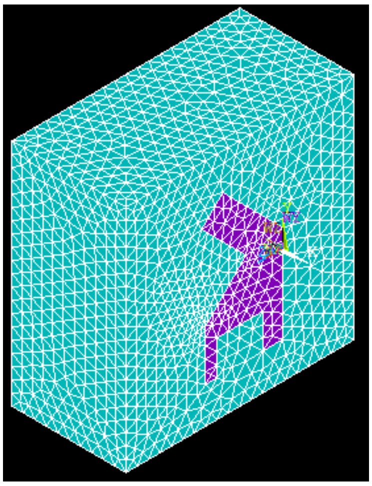

Fig.3 Meshed half geometry.

A. Before Shake Out (thermal analysis)

This phase analyzed the heat flow that takes place when the molten metal (at temperature 1400˚C) is poured into the sand mold at room temperature (25˚C). Due to the high temperature gradient, heat transfer occurs by all the three modes, i.e. conduction, convection and radiation. Conduction takes place between the external surface of the casting and the inner surface of the mold cavity. Convection and radiation takes place between the external surface of the mold and the ambient. Thus three types of loads were given and the symmetry face was given insulated boundary conditions as shown below in Figure 4. This resulted in a transient thermal analysis which was simulated for 8 hours of mold filling and cooling time. Time step size was taken as 10 seconds which meant time incremented in steps of 10 seconds. The thermal result file obtained from this phase was saved as ‘before.rth’ and was used later.

TABLE I
GEOMETRICAL AND MATERIAL PROPERTIES FOR SAMPLE BLOCK

S. No.	For sample cast and mold	
	Property	**Value**
1	Cast volume	102.65 cm^3
2	Mold volume	1000 cm^3
3	Cast conductivity (sand)	1.1 W/mK
4	Cast specific heat (sand)	1074 J/kgK
5	Cast density (sand)	1500 kg/m^3

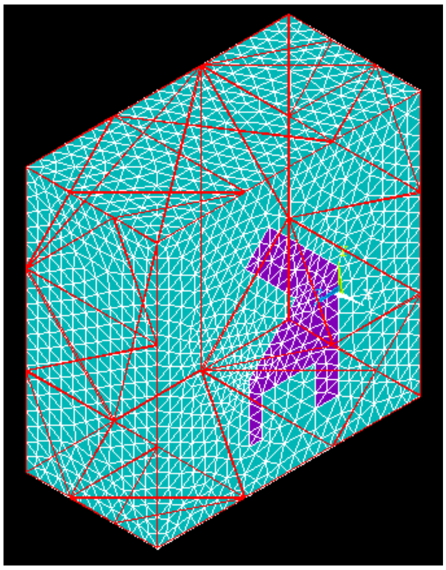

Fig.4 Convective boundary conditions for before shake out.

B. After Shake Out (thermal analysis)

In this phase, the mold was removed and the cast was allowed to cool by itself in atmosphere. Thus the heat transfer takes place only by convection and radiation between the surface of the cast and the ambient temperature. The current temperature distribution was governed by the previous step and thus the before.rth file was read as temperature field input. In this case temperature dependent film transfer coefficients were used and the hot cast was kept for cooling in atmospheric condition for 12 hours. Same time step size was used. Again the thermal result file was saved as after.rth and would be used as input in structural analysis.

C. Structural Analysis

This was the final step of the procedure and composed of finding stresses developed due to the two temperature gradients obtained in the two previous steps. In this step structural boundary conditions were given to the cast part as it had to be fixed in space. The cast block was constrained in such a way that no rigid body motions were possible. Then the translations and the rotations along the X, Y and Z axes were constrained. However, provisions were made so that the cast is free to shrink. To do so, three nodes were fixed. These constraints are applied as shown in the Figure 5 below.

The resultant temperature distribution after the two thermal analyses was plotted as shown in Figure 6. Here the temperature range varies from 25.02˚C to 32.432˚C. This is the condition 20 hours after filling the mold, i.e. after shakeout. The final result of the structural analyses was taken as the von mises stress plot which is same as the residual stress in this case. Thus we can see that the maximum residual stresses were obtained where the heat transfer is difficult. The results were plotted as shown in Figure 7.

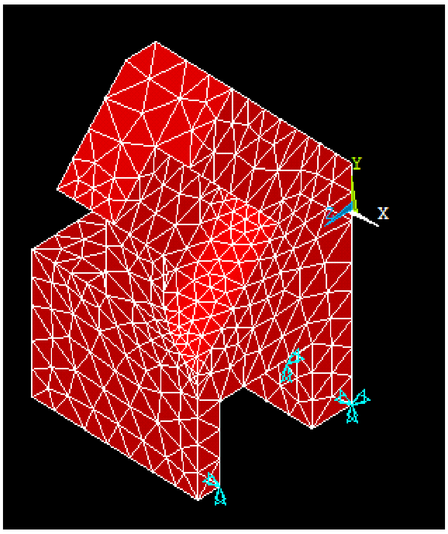

Fig.5 Structural boundary conditions.

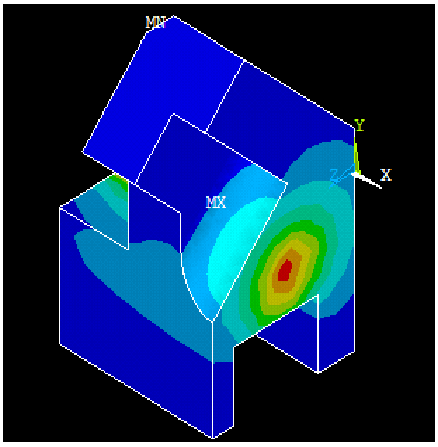

Fig.6 Temperature distribution for shifter 20 hours after filling the mold.

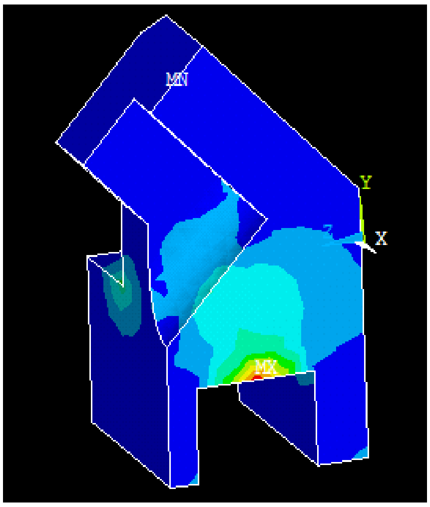

Fig.7 Von Mises stress plot i.e. residual stresses developed due to heat transfer. Maximum value 7.015 E+9 N/mm^2

IV. Optimization for Minimum Residual Stress

The main objective of this paper was to identify the areas of maximum residual stresses as crack formation starts at these areas. Once these areas were identified correctly in the previous steps, shape optimization [11]-[14] was done so as to get a geometry where the residual stresses were least and also evenly distributed. Several iterations were done so as to get the optimum geometry while keeping the functionality and formability of the component intact. The iterations were stopped once further modifications resulted in complicated geometries which in turn indicated difficulties during casting or increase in production costs. The modified part was as shown below in Figure 8. This modified geometry was put through the same analysis for residual stress as was done before. Figure 9 shows the modified mesh and the resultant von mises stress plot were as shown in Figure 10.

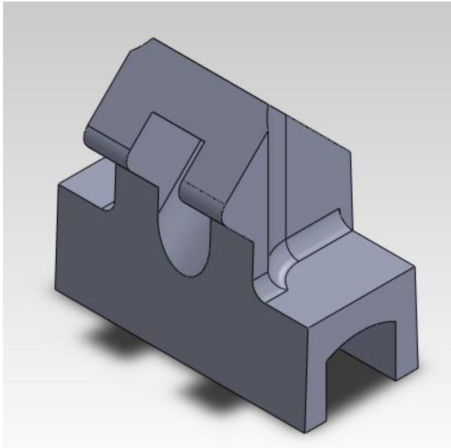
Fig.8 Modified shape of shifter.

As it is clear from Figure 7 and Figure 10, the residual stresses in the modified shape are not only lesser but also more evenly distributed. The shape change was done keeping in mind the functional requirements of the component. The changes included addition of fillets and drafts to the master component among other changes.

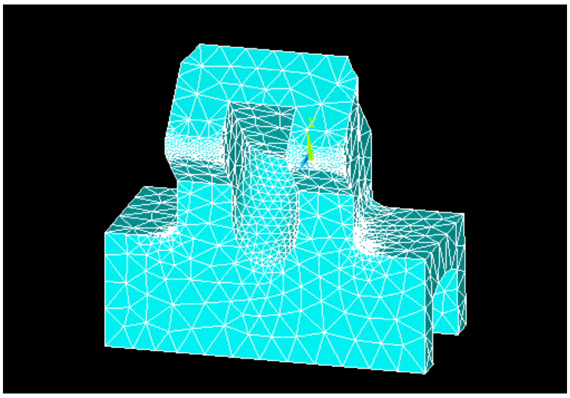
Fig.9 Modified Shifter mesh .

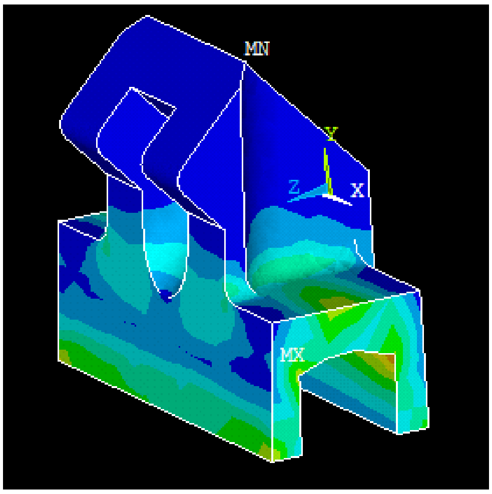

Fig.10 Von Mises stress plot i.e. residual stresses developed due to heat transfer in the modified geometry. Maximum value 6.352E+9 N/mm^2

V. EXPERIMENTAL VALIDATION

The above work was validated by using crack compliance method, also known as incremental slitting method. It is fracture mechanics based approach. A detailed literature survey was done before selecting this method as various other residual stress measurement techniques are available. This method involves the determination of a residual stress by successive extension of a slot and measurement of the resulting strains or displacements [15]-[16]. It is a destructive technique but has increased spatial resolution for residual stresses and increased sensitivity to low stresses. The basic principle behind this technique is that the slit will be cut incrementally with depth (x-direction) and simultaneously the residual stresses will release on the plane normal to the slit (y-z). Strain gauges mounted on this plane will measure the strain change caused by this stress release after every increment [15].

A. Methodology

In this method, a slot or cut is first made into the component using EDM wire cutting technique. It is known that every manufacturing process will induce some residual stresses in the component. Since the magnitude of residual stresses was important in this procedure, any contamination due to milling or slitting operations would have resulted in faulty readings. But in case of EDM wire cutting, material is removed by spark erosion resulting in almost zero change in residual stress. Therefore it was selected for introducing the slot.

The first step involved preparing the shifter surface for sticking the strain gauges. This surface was normal to the direction of cut. The surface was hand ground slowly using sand paper so that no additional stresses were introduced. Then it was cleaned using acetone to remove any oil or burrs. Strain gauges were stuck using instant glue. They were placed along y and z directions. Strain gauge electrical connections were made from NI 9219 4-Channel, 24-Bit, universal analog input module using tape wires. Yellow and green wires connected the strain gauge along y-direction and blue and purple connected to the strain gauge along z direction. Proper water proofing was done using silicon glue. The NI 9219 module was connected to NI cDAQ-9171 chassis. The chassis and the laptop were connected with USB cable. These electrical connections ensure that strain measurements happen continuously and are recorded simultaneously. These connections were as shown in Figure 11 and 12. The programming for the strain measurement using NI 9219 was done for the two strain gauges using NI LabVIEW 2013. Quater bridge configurations were considered for each case separately. Destinations for saving files, output graph modes and scale factors were also set. The connections were checked using a fake run.

The setup was then mounted on the wire EDM machine as shown in Figure 13. The programmer then clamped the component for cutting and positioned it so that the cutting wire was 0.1 mm away from the cutting surface.

Fig.11 Strain gauges along y and z directions. Wire connections are soldered and waterproofed.

Fig.12 Wire connections to NI 9219 module.

Fig.13 Complete experimental setup

It was made sure that the gauges were on the free end away from the clamping and that the cut was to be made along the x-direction. The EDM wire cutting machine was operated at low power and speed (0.5mm/second) with a brass wire while temperature-controlled de-ionized water kept flowing continuously, so that no noticeable thermal stresses were induced during the process. The brass wire was loaded on a spool so that the cutting length kept changing. This was done so as to keep the wire from breaking. After all the machine settings were done, the NI LabVIEW 2013 program was started and the operator started the water flow. At this point, the strain gauges were calibrated.

The operator then started the current flow. For 0.1mm the clamping table moved without cut and then it started cutting the shifter component verified by localised sparks as shown in Figure14. Figure 15 shows the screen shot of readings along z direction after 0.2mm cut has been achieved. At this point the stresses on the surface yz have been released which resulted in expanding of the surface in the plane. This is called surface compliance due to the crack generated and hence the name. This expanding of the surface in y and z directions is measured by the two strain gauges along them. The slit is basically required just to cut the surface but was progressed upto 4 mm to verify any further changes in strain field. Figure 16 shows the final component after cutting.

Fig.14 Shifter under cutting process

Fig.15 Screen shot showing the stress and strain readings at 0.2mm cut.

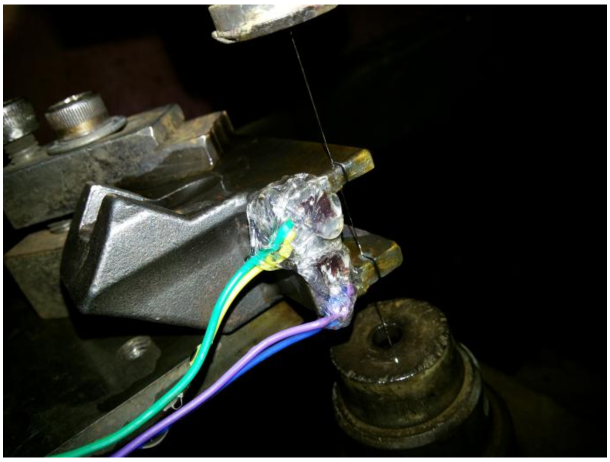

Fig.16 Finished component after cut.

VI. Results and Discussion

The von mises plot from numerical analysis gives the maximum value of residual stresses in the original shifter as 7.015 E+9 N/mm^2 and that of the modified geometry is 6.352 E+9 N/mm^2. Now the test results give values of stresses in y and z directions. These are to be converted into von mises stress by using the following formula:-

$$s = (s_z^2 + s_y^2)^{1/2}$$

The values of S_z and s_y are 6.839E+9 N/mm^2 and 1.058E+6 N/mm^2, respectively. Thus using the above equations, we get the value of von mises stress as 6.839E+9 N/mm^2. As seen from these values, the numerical results and the experimental results agree with each other for the maximum residual stresses induced in the shifter. The difference in the values may be credited to the non linearity of the actual casting process.

VII. Conclusions

The finite element analysis showed the areas of maximum residual stresses. Shape optimization was done successfully and the results showed decrease in the values of residual stresses. The experimental testing gave the values of residual stresses closer to the numerical analysis results. Thus the optimization done in the shifter to reduce the residual stresses obtained during casting was a success.

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