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Modeling of the Effect of a Defect on HCF Life of a Magnesium AZ91 Specimen Subjected to Transverse Load

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Abstract

Material defects formed while manufacturing, fabricating and material handling are crucial in deciding the fatigue life of machine member. Research reports the modelings of effect of a defect upon the high cycle fatigue (HCF) behavior of materials are sparse. This paper attempts to model the effect of a defect over the HCF life of cast magnesium AZ91alloy by introducing defects of two different volumes, at three different locations (top, middle and bottom of the specimen in critical zone) in AZ91 specimen, which is subjected to transverse load. Transverse load HCF test results obtained using ASTM standard D671 specimens machined from low pressure cast and gravity cast magnesium AZ91 were used for the modeling. The results reveals that defect in the critically stressed part of the specimen drastically reduce fatigue life of specimen even for an insignificant increment of load.

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Keywords: Magnesium alloy; gravity casting; defects; high cycle fatigue; finite element modeling

1. Introduction

Many machine parts operate well initially and they fail in service due to fatigue failure caused by repeated cyclic loading. Characterizing the capability of a material to survive during its life time is the aim of fatigue analysis. The time history of stress or strain and the exact location where a crack is going to start are the critical factors. This is precisely why finite element analysis (FEA) is important in this discipline. Using FEA and finite element modeling (FEM), an analyst can choose any location within a model and concentrate attention on it, using the intrinsic ability of the technique to bring in dynamic effects. For this reason, the FEM has become a reliable tool for the numerical solution for wide range of problems and its results are important in calculating and verifying safe part lifetimes [1].

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Finite element modeling is employed for a variety of different purposes and modeling requirements depending on the intended use of each component. For fatigue analysis, the results are very sensitive to the accuracy of the calculated stresses and strains in localized regions of a component [2]. To achieve acceptable levels of accuracy, the following are essential requirements

The component must be represented accurately, both in terms of its physical behavior and material characteristics.

- Externally applied loads and constraints must also be represented accurately.
- It is important that elements are chosen to generate accurate grid point stresses and strains, as fatigue cracking usually starts at free surfaces and edges.
- Ideally, the mesh should be refined to a point where further refinement produces little change.

Inhomogeneities due to porosity are currently not considered in the design of structural components made from castings. Instead, ad hoc safety factors are used to address a designer's uncertainty in how the casting will perform in service. These safety factors are based on the assumption that castings perform unpredictably, if not poorly. Applying such safety factors to the entire cast material might do little for the robustness of the design other than increase the casting weight. Many components designers become frustrated by castings designed with very large safety factors that fail in service; they are hesitant to use castings. Such frustrations could be avoided if the quality of the cast material throughout the casting could be known ahead of time and incorporated into the design [3]. Though there were many investigations carried out on asserting the fatigue behavior of a material, literature showing the finite element modeling indicating the ill effect of a defect over the fatigue life of a specimen is less explained. Hence, an attempt is made to create a model and analyze the fatigue life of a specimen with defect and this sub model created will be useful to recognize all the ill effects of porosity on the fatigue behavior of a material. For ease of use in standard design practice, commonly used commercial software ANSYS is employed in the present stress and fatigue life simulations. The porosity field is imported into finite element analysis (FEA) software to determine the complex stress field resulting from the porosity.

2. Materials and investigation

Magnesium AZ 91 is a new age light weight structural material used in Defense, Aviation, Automobile and Communication equipments where reduction of weight is of prime importance. Low pressure cast and Gravity cast AZ 91 alloys were used for the investigation. ASTM D-671 standard specimens were fabricated using the AZ 91 ingots and fatigue investigations were carried out using an electro dynamic shaker system under transverse load. The specimen, investigation and the results were detailed in earlier articles reported by the authors [4, 5]. From the results of the investigations it was noticed that the S-N results scatter due to defects present in the critical sections of the specimen. Hence, the further modeling efforts were carried out to ascertain the effect of defect on the HCF behavior of the alloy.

3. Modeling

Fatigue modeling provides life, damage, and factor of safety information and uses a stress life with several options for handling mean stress and specifying loading conditions. The three components to a fatigue analysis are (a). Fatigue Material Properties, (b). Fatigue analysis and loading options, (c). Review of predicted values.

3.1. Input details

Using CAD interface the geometry of specimen ASTM std D 671 was prepared in three parts namely 1. Bigger rectangle part (Fixed end), 2. Trapezoidal test length part with reduced area and 3. Smaller rectangle part (Moving end). Both part 1 and part 3 (big and small rectangular portions) of the specimen is connected to the part 2 (trapezoidal test length) by curves, due to which the test section area increases gradually. This geometry is attached in plug in mode and simulated in ANSYS.

In this analysis solid 186 elements are used for meshing, which is a higher order 3-D, 20-node structural solid element. It has quadratic displacement behavior and is well suited to modeling irregular meshes. The element is defined by 20 nodes having three degrees of freedom per node: in the nodal x, y, and z directions. The details of elements summary is given in Table 1.

Table 1. Node and element details.

Name	Bounding box (x,y,z) mm	Mass(kg)	Volume (mm^3)	Nodes	Element
Bigger end (fixed end)	41.2, 50.8, 3.91	1.49×10^{-2}	8,123.1	43993	8964
Test length	51.34, 43.99, 3.91	5.63×10^{-3}	3,062.84	17383	3360
Small end (moving end)	10.66, 23.8, 3.91	1.56×10^{-3}	851.39	5075	920

As per the experimental environment, the bigger end of the meshed model is fixed. Load is applied in the moving end of the model, assuming that the load is evenly distributed along the line of application. In par with the experimental loading condition, fully reversed load at constant amplitude is applied to the loading end and Fig 1 illustrates the location of load applied. A fully reversed load in which the load is applied in the form of sinusoidal curve in such manner, the maximum and minimum applied or stress induced is equal in magnitude but opposite in direction and hence the stress ratio ($R = \sigma_{max} / \sigma_{min}$) is -1. The following material properties were fed as input (Table 2).

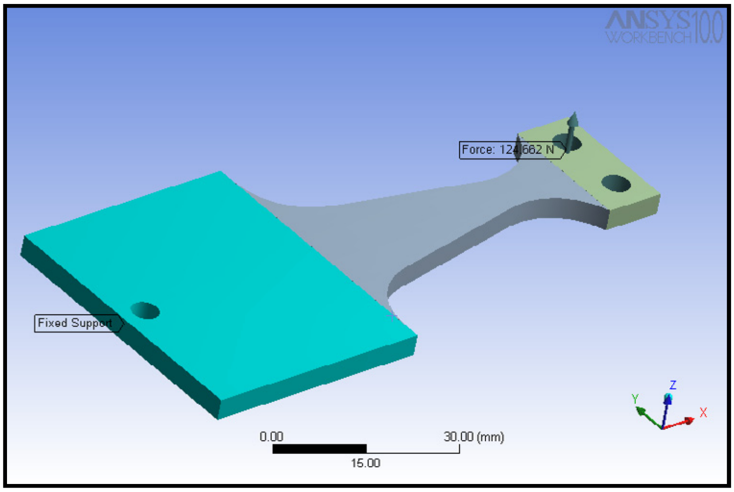

Fig. 1. Loading location.

Table 2. Material properties.

Density	1.84×10^{-6} kg/mm³	Yield Strength	140.0 MPa
Poisson's Ratio	0.35	Ultimate Strength	230.0 MPa
Young's Modulus		45,000.0 MPa	

4. Results and discussion

4.1. Preliminary modeling

Preliminary modeling of HCF results using the investigated results were carried out feeding the above input values and the results well correlates with the investigation results. The Deformation, Equivalent Stress, Predicted Fatigue Life, Factor of Safety and Fatigue Sensitivity values were predicted. S-N plots comparing the experimental and the modeled results were generated for both low pressure cast and gravity cast AZ 91 magnesium alloy (Fig 2) separately.

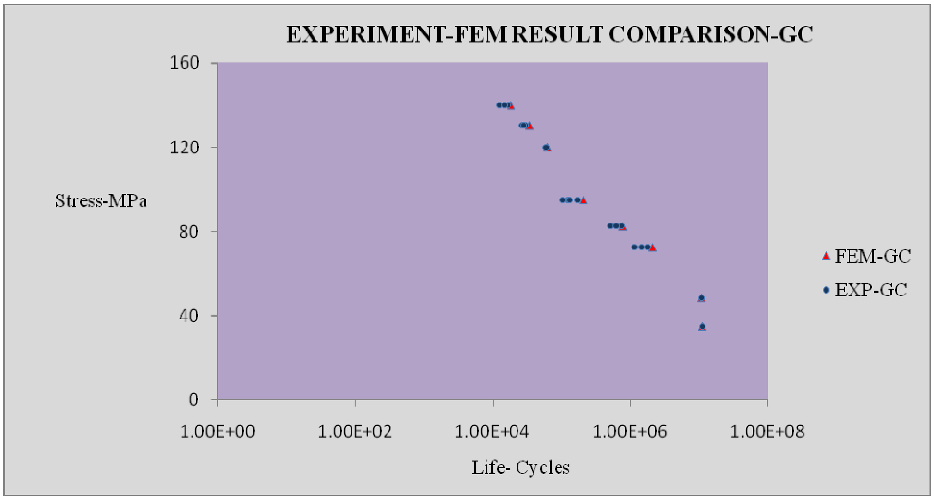

Fig . 2.Comparative S-N Plot of GC experimental and FEM predictions.

4.2. Modeling defect and its effect over fatigue life

It is well known that fatigue life predictions are very sensitive to local stress concentration and this issue is of particular importance in the present study, because the simulations rely on pore fractions defined over a volume that is large compared to the microscopic pore geometry [6]. In the stress simulation, the elastic mechanical properties are made a function of the local porosity volume fraction. As detailed by Hardin and Beckermann [3], the volume fraction of porosity is kept below 1% of the volume of the critically stressed portion of the specimen. Two hollow spherical voids of size 1mm diameter with 0.5 mm deep and another defect of 0.5 mm diameter with 0.5 mm deep were created individually, and which reduces the existing volume by less than 1%. The defects are located in the significant high stressed narrow part of the test section of the specimen (Fig. 3). The S-N property, loading conditions and material properties were kept identical with that of earlier model generated without pores. The property of the defect is kept unity as it is assumed as a hollow space in the specimen. A transverse load is applied to the free end of the specimen restricting movement of the bigger end of the specimen. The volume of the defect and the volume of the critical test length portion are estimated and the results are compared in terms of percentage of volume. Fatigue life, equivalent stress and deformation were considered for the present analysis and the variation in these three parameters for different castings, at different locations (Top, middle and bottom of the specimen) are analyzed and given vide table 3 and 4.

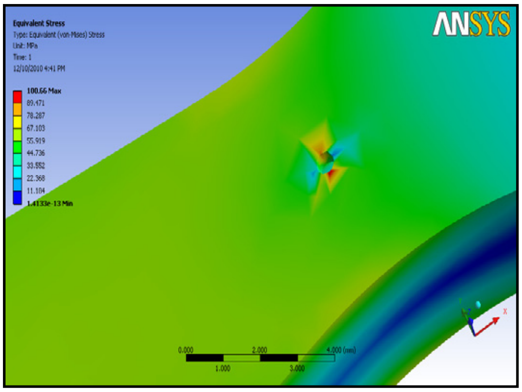

Fig. 3. Location of defect.

Table 3. FEM Predictions – GC Magnesium AZ 91 alloy.

Parameter	*No Porosity*	99.99954 % of Volume			99.99635% of Volume		
		Top	Centre	Bottom	Top	Centre	Bottom
Force N	*45*	45	45	45	45	45	45
Life Cycles	*10200000*	431960	7994300	431960	372530	7449000	372530
Equivalent Stress MPa	*49.998*	85.612	57.380	85.612	86.139	57.232	86.139
Deformation mm	*0.618*	0.69495	0.69491	0.69495	0.69579	0.69478	0.69579

Table 4 FEM Predictions – GC Magnesium AZ 91 Alloy.

Parameter	*No Porosity*	99.99954 % of Volume			99.99635% of Volume		
		Top	Centre	Bottom	Top	Centre	Bottom
Force N	*45*	45	45	45	45	45	45
Life Cycles	*10508650*	2707700	10285000	2707700	2622700	10287000	2622700
Equivalent Stress, MPa	*50.007*	85.612	57.38	85.612	86.139	57.232	86.139
Deformation, mm	*0.618*	0.69495	0.69479	0.69495	0.69579	0.69478	0.69579

Comparing the contour plots it was noticed that deformation results vary in both LPC and GC alloys by application of loads. The deformation increases by 12.45 % when a pore of 0.5 mm dia and deep is located at either surface of the specimen of an LPC specimen, while it drops 12.42 % when the same pore is located at the centre line. As, the pore size is very small compared to the total volume of the test length, the deformation increases marginally when the effect is closer to the surface and further less when it is at the centre. This phenomenon is noticed for both volumes of pores and for both casts (GC and LPC). Existence of a pore of minimum size is seen to have raised the stress value from 50 MPa to 57.38 MPa and 85.61 MPa respectively (14.7% and 71.2%) due to its presence at the centre and at both surfaces and the stress value increases with the volume fraction of the pore. For a reduction of 0.003% volume of the test length due to the existence of higher sized pore, the stress value increase by 40% (approximately) when the defect is on the surface and increases marginally when the same is at the centre (Table 3 & 4) and due to this reason the fatigue life also reduces appreciably as experienced during experiments. Investigating the predicted life contours, the values severely decrease due to the presence of a pore. It was calculated that the volume of model pores created in the present analysis decreases the volume of test length by a fraction less than 1 percent (0.004 % and 0.00365 % respectively) and LPC alloy when the volume of test length decrease by 0.004% due to the existence of a surface pore, the life of the specimen decrease to 25% and for the same pore volume presence at the centre reduce the life to less than 3%. In the earlier discussion on stress, it was noted that the stress value abnormally increases due to the presence of surface pore and consequently the life gets reduced. The imparted load ranged from 45 N to 53 N, which is very much less than the yield strength of the alloy (< 30%), and the pore would create more destructive effects when the load is enhanced. Even for an increase of approximately 7 N load, fatigue life is affected when the defect is located on top or bottom surface of specimen and while the presence of defect at the centre part of the specimen has detrimental effect over fatigue life of a specimen. While comparing the predicted life of a specimen with and without pores of different volume fractions at various locations (top, bottom and at the centre) for a particular load and it was found that the specimen is predicted to have a maximum life when pores are absent. Further the life drastically reduces due to the existence of a surface pore and slightly descends due to a centre pore.

5. Conclusions

The effects of defects of different volume fraction, different locations, for both castings were analysed. The fatigue life, equivalent stress and the deformation behavior were examined. The model forecasts that a defect on the surface of the specimen influences more than at the middle. Low Pressure Cast AZ 91 alloy can handle higher cyclic load compared to that of Gravity Cast alloy

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