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MECHANICAL RESISTANCE AS A FUNCTION OF LOCAL PROPERTIES

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ABSTRACT

The present study makes an estimation of an automotive engine piston mechanical properties and fatigue life based on some characteristics of metallurgical microstructure. Because it is intended to assess the properties in specific locations of the component it is made a local microstructure approach. The critical points of the engine piston were metallurgical analyzed (amount of phases and SDAS) and these were related to ultimate tensile strength and fatigue life.

The conclusion of the work is that in an engine piston the mechanical and fatigue properties are very dependent of local metallurgical properties (amount of the eutectic phase). As a consequence the component may fail in an unexpected area that may change the local assessment expected results.

KEYWORDS: Metallurgical properties, Mechanical properties, Fatigue life.

1. Introduction

Assessment of components failure is strongly dependent on failure localization. The component point where failure occurs strongly depends on local properties. And these local properties are also influenced by the processing technique. In the specific case of an engine piston local properties are influenced by the casting technique. Mechanical properties (tensile strength, tensile strain, Young modulus, etc) as well as fatigue properties (fatigue life) are very dependent on casting method. The most direct effects of casting techniques are on the metallurgical microstructure that bounds the mechanical properties. One of the important variables affected by the casting technique is the cooling rate and the cooling rate strongly restricts the microstructure. As it is known the values of the SDAS (secondary dendrite arm spacing) as well as other constituent dimensions are correlated with mechanical properties as, for example, the ultimate tensile strength. Usually, in design, it is not taken into consideration that in different parts of one cast component there are different values of constituent dimensions (SDAS, amount of constituents, etc). These differences in metallurgical properties are conducting also to different mechanical and fatigue properties in the same single component material.

The automotive engine pistons are usually cast in near eutectic aluminium-silicon alloys. The structure and properties of cast aluminium silicon eutectic alloys are very dependent on the cooling rate, composition, modification, heat treatment operations, etc [3,5,6]. That's why to estimate the mechanical properties and fatigue life of the cast piston is not enough to know the material characteristics and properties. It is also necessary to know all the factors that are influencing the characteristics of the final casting part: type of casting, temperatures (melt and mould), cooling rate, refiners etc. [4,9,11], and to know it in the different parts of the component because they strongly change along the same component. A way to predict both mechanical properties as well as the fatigue life of the material component is based on some metallurgical characteristics of the obtained casting.

A number of papers have been published showing several relations that estimate the tensile strength with other different microstructure characteristics. For example, Bernsztejn proposed a relation to calculate the average strength as a linear function of the volume fraction of silicon [1]:

$$\sigma = \sigma_\alpha \cdot V_V^\alpha + \sigma_{Si} \cdot V_V^{Si} = \sigma_\alpha + V_V^{Si}\left(\sigma_{Si} - \sigma_\alpha\right) \quad (1)$$

where σ_α and σ_{Si} are rupture strengths in the volume unit.

This formula neglects the influence of the morphology, the average size, and the distribution of brittle particles, that is, silicon precipitates and also the volume fraction of constituents which can differentiate the properties of materials of similar value of the silicon volume fraction to an important degree.

A correlation between tensile strength (σ) and silicon particle size for aluminium-silicon alloy containing 17-27% Si, was presented by Mandal et al.[7]:

$$\sigma = 252{,}8 - 3{,}73 \cdot particle\,size \quad (2)$$

Another relationship between tensile strength and secondary dendrite arm spacing and the size of silicon lamellas in interdendritic eutectic regions, was proposed (ASM Int. 2004):

$$\sigma = k + k_2 \cdot \gamma^{-\frac{1}{2}} + k_3 \cdot \lambda^{-\frac{1}{2}} \quad (3)$$

where: σ is the tensile strength, k, k_2 and k_3 are empirical constants, γ is the size of silicon lamellas in interdendritic eutectic regions and λ is the secondary dendrite arm spacing.

Secondary dendrite arm spacing is also in attention of researcher and generates several models to estimate tensile strength [10]:

$$UTS = -1{,}4399 \cdot SDAS + 340\ [\text{MPa}] \quad (4)$$

where: UTS is ultimate tensile strength and SDAS is secondary dendrite arm spacing.

In order to optimize the design of the cast components based on local properties it is necessary to know the local metallurgical properties which determine the mechanical properties that may help to estimate the failure of the component.

2. Experimental method

A commercial engine piston obtained by gravity casting on permanent mould was studied. The engine piston was provided for this study by Rito, Lda company from Portugal. The material used to cast the piston was a near eutectic aluminium-silicon alloy. The piston was sectioned, polished and optical analysed in order to quantify the volume fraction of phases and measuring the secondary dendrites arm spacing (SDAS). The quantification of phases (eutectic, α-Al dendrites, intermetalics) was done optically and using statistical methods. The SDAS was quantified by identifying and measuring small groups of well-defined secondary dendrite arms on the screen of the image analyzer. The value of SDAS was then determined using SDAS=d/nM, where d is the length of the line drawn from edge to edge of measured arms, M is the magnification, and n is the number of dendrite arms. The volume fractions of the constituents were quantified by image analysis. (Fig.1)

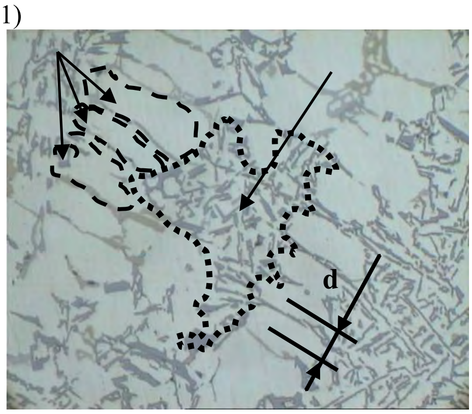

Fig.1. Microstructure analysis.

The regions of the piston that were studied are: 1. Top position, 2. Piston ring position, 3. Top pin position, 4. Down pin position, 5. Skirt position. (See fig. 2).

To verify the results obtained by analytical formulas was done an FEM analysis with Cosmos software to the piston and from the elastic stresses plot were extracted the values of stresses on the selected regions.

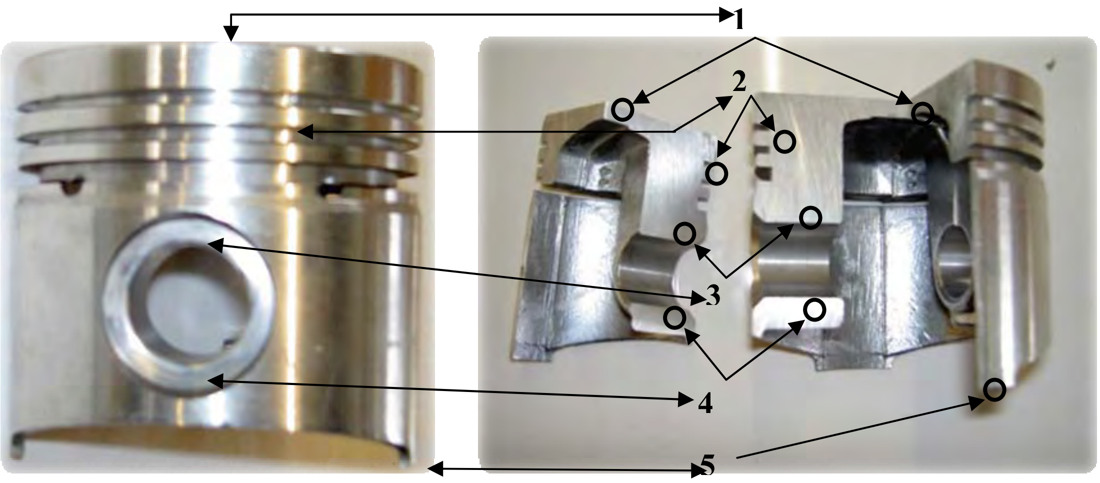

Fig. 2. *Position of regions studied.*

3. Results

The secondary dendrites arm spacing measured values are presented in fig. 3. The SDAS shows an increasing of about 90% from skirt position-24µm to top position-47µm.

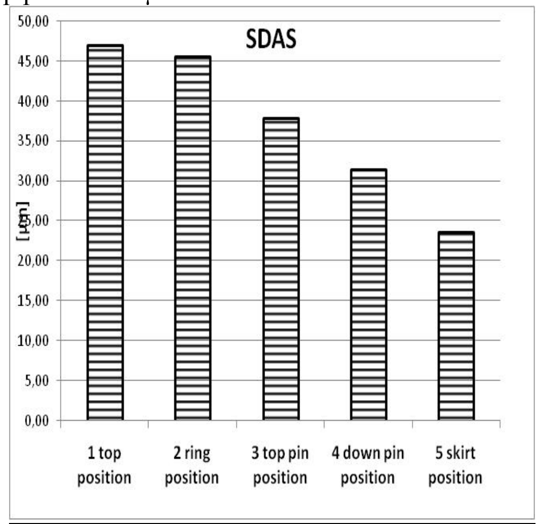

Fig. 3. *Secondary dendrites arm spacing (SDAS).*

From volume fraction quantification of constituent phases (Fig. 4) is noticed that the volume fraction of eutectic phase is increasing from position 1 (top position) to position 5 (skirt position) which is in opposite relation with the α-Al dendrites phase.

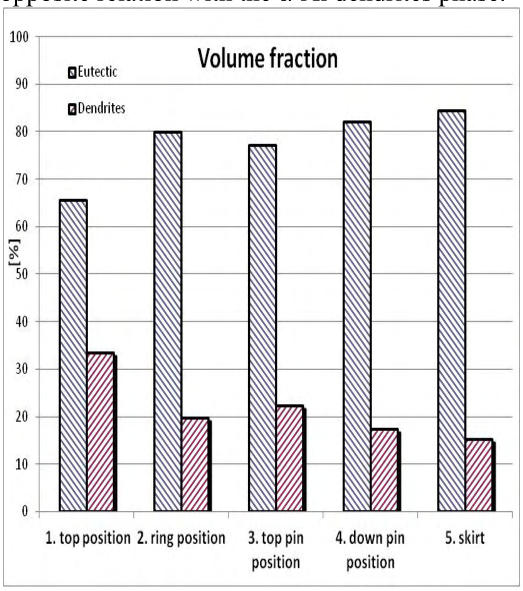

Fig. 4. *Volume fraction of eutectic and α–Al dendrite phase.*

Analysing together volume fraction of the eutectic phase with the SDAS results it is interesting to highlight the fact that exists a relation between them: the region with higher values of the SDAS has small amount of eutectic phase and reverse the region with smaller values of the SDAS has low values of the eutectic phase.

4. Discussion

Mechanical and mechanical fatigue failures occur in critical localizations. Critical localizations are not those where stresses are higher then in the rest of component but where the ratio of local stress vs. ultimate tensile local strength is higher. Thus, estimative prediction of the cast aluminium component properties should be made based on local material mechanical properties which makes possible calculate the ratio of stress vs. UTS. Local mechanical and fatigue properties may be obtained by local metallurgical features.

In all the casting moulds different variables such as component wall thickness, mould thickness, etc causes different cooling rates in different places of the cast component.

The decreasing tendency of SDAS could be explained by the differences of cooling rates in different places of the mould. As is already known from literature [3, 8], the secondary dendrites arm spacing, for a given alloy, is influenced mainly by the cooling rates.

Empirical equations were used to estimate the values of the ultimate tensile strength in all the specific regions described above. From several equations that exist in literature that correlate the ultimate tensile strength and the secondary dendrites arm spacing, the one developed by Takahashy and all [10] was adapted for the present studied alloy. The results of the microstructure and predicted UTS are presented in table 1.

Table 1. *UTS calculated using Eq.4*

Position	SDAS [µm]	UTS [MPa]
1. top position	46,98	202,36
2.ring position	45,60	204,35
3.top pin position	37,94	215,38
4.down pin position	31,47	224,69
5. skirt position	23,64	235,97

It can be seen that there is a change in SDAS of about 100%, as occurs between positions 5 and 1, and that it is equivalent to significant changes in UTS, e.g. the stress level changes from about 236 to 202 MPa (about 17%).

A previous study [2] was done by the authors of this paper to develop a relation of volume fraction with the ultimate tensile strength because in some alloys the SDAS are not easy to measure due to the fact that they are not well defined. The majority of the existing relations are able to calculate an estimative value of the ultimate tensile strength from the measured value of secondary dendrite arm spacing and only some of them were developed to correlate the amount of the eutectic phase with the UTS. This study also does a verification of the two formulas: one based on volume fraction of eutectic and the other one based on SDAS.

The previous developed equation that correlates the ultimate tensile strength with the volume fraction of the eutectic phase is: [2]

$$UTS = 100 + 1{,}55 \cdot V_{fr.eutectic} \text{ [MPa]} \qquad (5)$$

The values of the expected ultimate tensile strength obtained by equation 5 are shown on table 2.

Table 2. *UTS calculated using Eq.5*

Position	Vol.F.eut. [%]	UTS [MPa]
1. top position	65,67	201,79
2. ring position	79,96	223,94
3. top pin position	77,21	219,67
4.down pin pos.	82,11	227,26
5. skirt position	84,50	230,98

Two important notes from these results are: there is a difference in local UTS of about 15% on different locations of the same component; there is a very good approximation with the ones obtained by equation 4 (Table1).

These differences are big enough so that they should be taken in consideration in designing the component. As a fact they may strongly affect not only the local mechanical properties but also the fatigue properties. In a previous paper [2] it is shown that a difference in about 25% on UTS, in a similar near eutectic alloy, is equivalent to a change in the fatigue limit of about 50%, which means a difference in fatigue life of about two orders of magnitude. Thus a 15% difference in UTS as the one obtained in the present study may be equivalent to at least one order of magnitude difference in fatigue life, which is quite relevant in fatigue life predictions. In order to verify how these changes may affect a specific component design, an analysis of stresses obtained by FEM and real local stresses (estimated based on metallurgical eutectic volume fraction) on a piston was performed.

Example of component design

As observed in fig. 6, due to the pressure at the piston head (Fig.5), there are mainly two important critical areas: top piston pin holes and the piston head. The values of stresses, obtained by FEM in each verified position (see fig. 2) are presented in table 3. It is worth to note that on design it is used a limiting value (for example Ultimate Tensile Strength) for the material, e.g, for the whole component. If the stress value is plotted against the UTS it is obtained the predicted ratio stress/UTS (table 3). A single input value (global material) of the ultimate tensile strength is used and is equal for the whole component.

Table 3. *Predicted and Real Stress/UTS ratios.*

Position	Ultimate tensile strength [%] Eq.4	Stress [MPa] FEM	Predicted Stress/UTS ratio FEM	Real Stress/UTS ratio	Real and Predicted ratios differences
1. top	202,36	56,00	23,7	27,7%	3,9%
2. ring	204,35	78,40	33,2	38,4%	5,1%
3. top pin	215,38	96,00	40,7	44,6%	3,9%
4.down pin	224,69	44,00	18,6	19,6%	0,9%
5. skirt	235,97	21,20	9,0	9,0%	0,0%

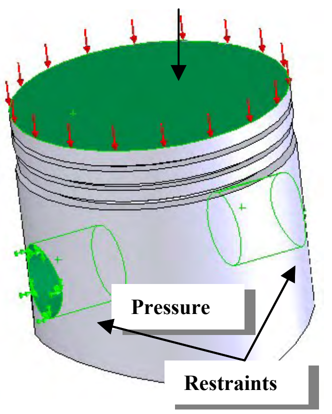

Fig. 5. *Pressure and restraints applied surfaces.*

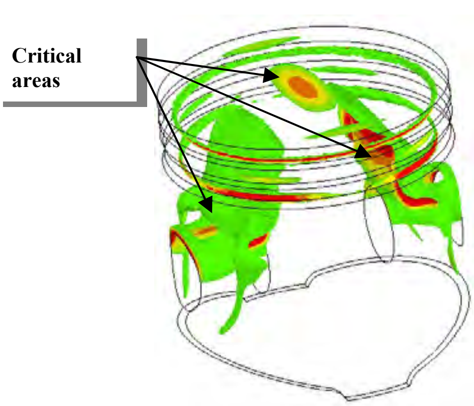

Fig. 6. *Stress distribution critical zones.*

However if the values of the stress (obtained by FEM) are plotted against the real ultimate tensile stress values (as obtained by the metallurgical features in different parts of the component), a new ratio is obtained (real stress/UTS ratio) (see table 3). The differences between these two ratios, the predicted and the real ones are plotted in the last column in table 3. It can be seen that there are some differences on material local resistance with a maximum difference of about 5%. It is worth to note that these differences may have a significant influence mainly on fatigue predictions and that they also may cause a shift of the critical points changing the expected failure locations and making it more difficult to obtain reliable failure assessments.

4. Conclusion

This study wants to verify if, in the case of cast components, the value of ultimate tensile strength could be different in different locations of the component. The main conclusions of the study are:

- Substantial changes of mechanical and fatigue properties may occur in different locations of the component;
- Those differences can be easily predicted by using different metallurgical features such as SDAS or phase volume fractions;
- The differences observed may have an impact on mechanical and fatigue design of the component;

Finally it should be emphasized that damage assessment can be influenced or distorted by a wrong failure location prediction.

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