EFFECT OF POROSITY ON MECHANICAL PROPERTIES OF DIE CAST ALUMINUM ENGINE BLOCK

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ABSTRACT

Casting imperfections, especially porosity in Aluminum alloy engine block plays a major role in determining the mechanical properties. An experimental study was carried out to investigate porosity in samples taken from different locations of the engine block, i.e. thick and thin sections. The samples were extracted from thick and thin sections of the engine block, having section thicknesses of 20 mm and 5 mm, respectively. Mechanical testing of these samples was carried out to show effect of section thickness and its associated porosity on ductility and ultimate strength. The three-dimensional porosity of an AA 384.1 engine block was analyzed through computed tomography (CT) scan. Samples from thick and thin sections within the engine block were analyzed to investigate the effect of different cooling rates. Volumetric porosity for thin sections was within the range of 0.0875% to 0.15% while that for the thick sections it was 0.24% to 0.35%. Mechanical properties of the samples with thin sections were compared to that of thick sections. It was found that thin sections have higher ultimate tensile strength (UTS) and ductility as compare to thick sections. Consequently, thin sections show lesser volumetric porosity as compare to thick sections. The results show that the samples taken from a portion near the mould wall or cooling core have fine grain size, lesser porosity and hence higher ductility. While the samples taken from the portions away from mould wall or cooling core has higher porosity and lower ductility. The overall volumetric porosity for thin sections is lower than thicker sections.

KEYWORDS: *Porosity, Engine block, Computer Tomography*

INTRODUCTION

In today's modern era, weight reduction is main concern for engineering design. Aluminum engine blocks are replacing Cast Iron due to their lower weight and high thermal conductivity. At present, globally more aluminum is produced than all other non-ferrous metals collectively (Akhter and Anrberg, 2009). Casting is generally more economical for producing approximate final shaped components for casting alloys. Permanent mould casting is being widely used in auto industry for manufacturing of engine blocks. Any defect present in the casting process can be carried over to the final product. These defects need to be controlled or minimized in components that require mechanical performance, viz. fatigue resistance, percent elongation and yield strength. Porosity is the most common and consistent problem of casting consumers. Porosity is one of the major defects encountered in die cast products and render high percentage of rejected parts than any other casting defect (Akhter *et al.*, 2009; AlMufadi and Irfan, 2014). Al-Si based alloys like A 356/ A 357 are widely used for production of engine blocks due to their high strength over weight ratio. Mechanical properties of these alloys are dependent on microstructure, which in turn depend on local solidification conditions. Casting of metals is likely to introduce casting defects like porosity (gas or shrinkage) and inclusion, that substantially reduces mechanical properties like fatigue strength of these alloys (Anton du Plessis, 2016). Cooling rate is important parameter that effects the formation of micro porosity. Higher cooling rate increases grain density, reduces dendrite arm spacing and an average pore size. Lower cooling rate increases time for gas precipitation from the melt and results in higher porosity (Boeira *et al.*, 2009; Anyalebechi, 2011). Hydrogen is the only gas that is considerably soluble in aluminum (Caceres *et al.*, 2005; Boromei *et al.*, 2010). Hydrogen can precipitate from moisture already entrapped in the die, decomposition of water vapor from the atmosphere, combustion of fossil fuels, die lubricants, fluxes and dirty tools (Conley *et al.*, 2000; Campbell, 2005). Rapid cooling rate can effectively decrease the number and size of pores (Dobrzanski *et al.*, 2008; Grosselle *et al.,* 2009; Hu, 2016). Thermal gradient, solidus velocity and riser system play an important role in mechanical properties of the casting.

Different researchers have worked on analyzing and

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quantifying the porosity, viz., Shabestari et al. (2004) performed an experimental study to find the effect of copper and solidification conditions on the microstructure and mechanical properties of Al-Si-Mg alloys. Four different molds were used to study the effect of cooling rates. It was reported that higher cooling rates decrease dendrite and eutectic cell which consequently reduces porosity. Ultimate tensile strength and elongation increase with an increase in cooling rate of the casting because of smaller porosity. Caceres et al. (2005) conducted an experimental study to develop correlation between section thickness, micro hardness and yield strength. It was found that thinner and thicker cross-section specimens had different porosity patterns. Lee (2007) used an experimental approach and constitutive prediction to study the effect of microporosity on tensile properties of A 356 aluminum alloy. He reported that ultimate tensile strength and elongation show linear and inverse parabolic decrease, respectively, as the micro porosity increases. Thin sections have better mechanical properties due to lesser porosity (Lee, 2007; Leo *et al.*, 2009). Recent work by Fiorese et al. entails an extensive classification of defects and imperfections in aluminum alloys (Manas and Makhlouf, 2011). Shrinkage porosity seems to have more detrimental effect as compare to gas porosity. Fracture initiates easily due to the shrinkage porosity because of its sharper root radius. Clustering of pores provides easy linkage between neighboring pores that deteriorates mechanical properties. H.D. Zhao et al. (2009) carried out an experimental and numerical analysis of gas entrapment defects in plate ADC12 die castings. Fraction and maximum pore size were analyzed quantitatively and hence its effect on mechanical properties was examined. Yield strength and ductility decrease as the fraction porosity and maximum pore size increase (Salazar and McNutt, 2013). Boeira et al. (2009) found that minimizing the solute content of alloy and increasing metal/mold heat transfer coefficient result in lowering porosity levels at areas closer to the casting surface (Shabestari and Moemeni, 2004). Similarly, Akhter et al. (2009) carried out a comparative study on porosity and pore morphology in a directionally solidified casting A 356 alloy (Sigworth, 2011). It was found that porosity increases with the increase in distance from the chill, as shown in Figure 1. Irfan et al. (2012) carried out an experimental investigation to find the effect of porosity reduction on the mechanical properties of die cast engine blocks. It was found that higher cooling rates reduce percentage porosity, which consequently increases the UTS and ductility of the castings.

As two-dimensional porosity, analysis depends on the cross-sectional area from which a sample is extracted. The random sampling area never represents a true porosity in the specimen. An introduction of three-dimensional computed tomography (3D CT) scanning technique has paved a way for investigating the internal details of an object non-destructively. In contrast to the two-dimensional porosity analysis, a study of three-dimensional porosity is more comprehensive in relating mechanical properties to porosity as it takes into account the whole volume of the object (Wang *et al.*, 2009). AlMufadi and Irfan (2014) carried out an experimental investigation on AL-Si alloy to find the effect of cooling rate on volumetric porosity of permanent mould castings (Ye, 2003). Porosity of tensile specimens casted at different cooling rates was analyzed using computed tomography scanning. Higher percentage of volumetric porosity was found in specimens casted at lower cooling rates compared to specimen casted at higher cooling rates. Consequently, better mechanical properties viz UTS and ductility were observed for specimens casted at higher cooling rates. Upto the date no work is found on the analysis of volumetric porosity for thick and thin sections of an engine block, this encourages the researchers to carry out volumetric porosity analysis of and its effect on the mechanical properties of this most vital component of an engine.

The current research will further highlight the usefulness of three-dimensional computed tomography (3D CT) scanning technique in casting field for measuring three-dimensional porosity.

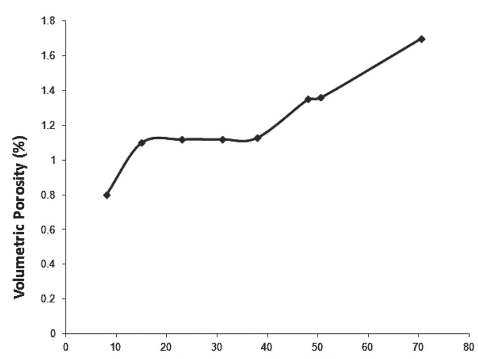


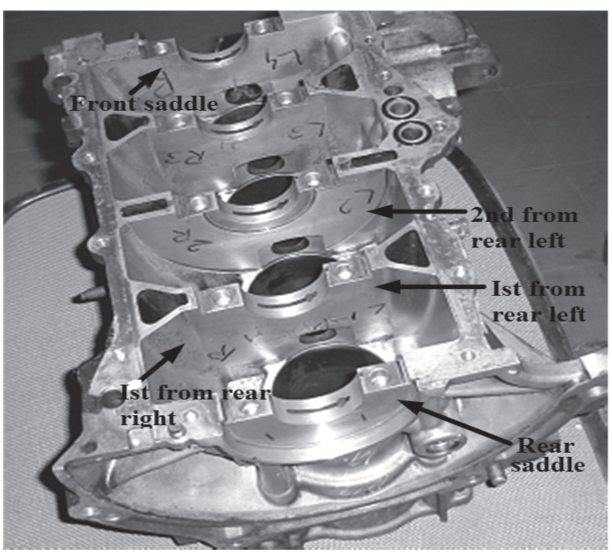
Fig 1. Relation between distance from the chill and volumetric porosity of as cast Al-Cu alloys

EXPERIMENTAL WORK AND MATERIAL

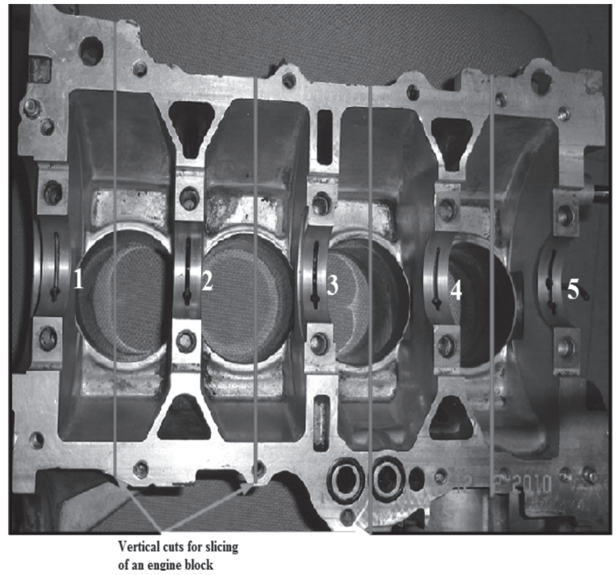
Experiments were performed for the quantitative analysis of the amount and size of volumetric porosity for thick and thin sections of a HPDC aluminum engine block was performed. Mechanical tests were carried out to find the effect of the difference in volumetric porosity on the mechanical properties of these sections.

An aluminum four-cylinder inline engine block was labeled and sectioned as shown in Figure 2. The engine block was manufactured through HPDC using an injector pressure between 10 and 175 Mega Pascals (1,500 and 25,400 psi) (Zhao *et al.*, 2009). The saddles (thick sections) of an engine block were first labeled according to their position relative to the front or rear end of the block (Figure 2 a). The saddle next to the rear is labeled as R1 and L1, where 1 stand for saddle first from rear, L and R stand for left and right sides of the saddle respectively. The left and right sides demarcation is necessary to label the respective cooling channels located on both ends of the saddles. The engine block was sliced vertically into five parts using hacksaw for extraction of saddle and cooling channels (Fig. 2b).

The saddle was extracted along the cooling channel from the engine block. Further machining was performed on

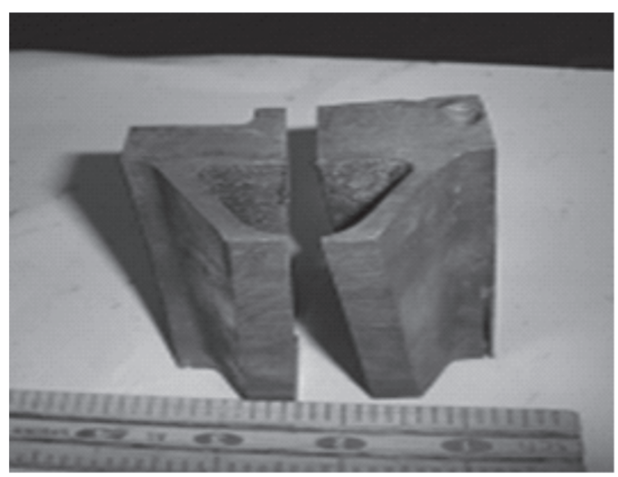


(a) Labeling of the die cast Al engine block

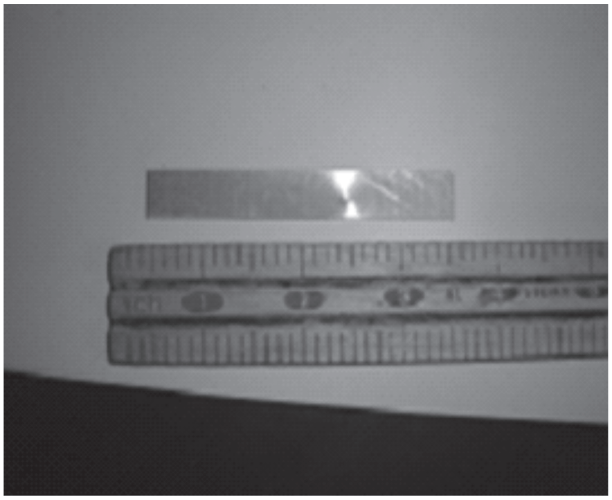


(b) Slicing of an engine block for extraction of saddles and cooling channels.

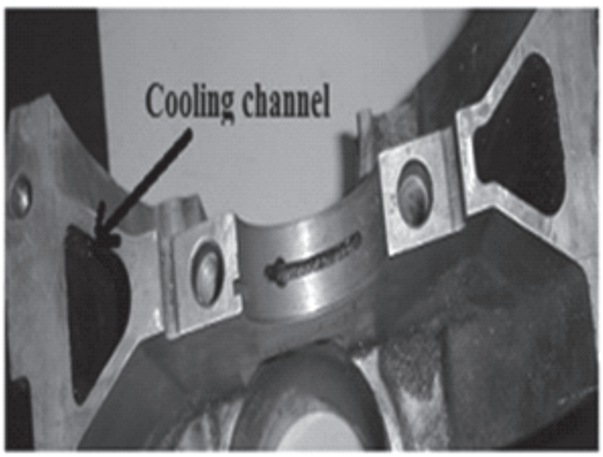
Milling machine for the extraction of saddles and cooling channels. The remaining portion of an engine block left behind was labeled as scrap. Samples were extracted for the volumetric porosity analysis and tensile tests from saddles and cooling channels (Fig. 3). Samples of thin and thick sections were extracted from cooling channel and saddle, respectively as shown in Fig. 4. Tensile samples were prepared according to the ASTM E8M standard as shown in Fig. 5. Mechanical testing of the samples was carried out on SENTECH universal testing machine (Max. capacity 300 KN). All the samples were tested according to E 8M -01, using a strain rate of 0.0015 s -1 (3mm/min).



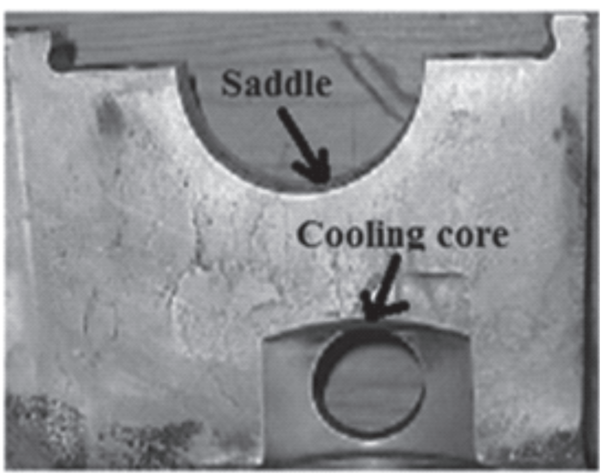
(a) Slicing the cooling channel.



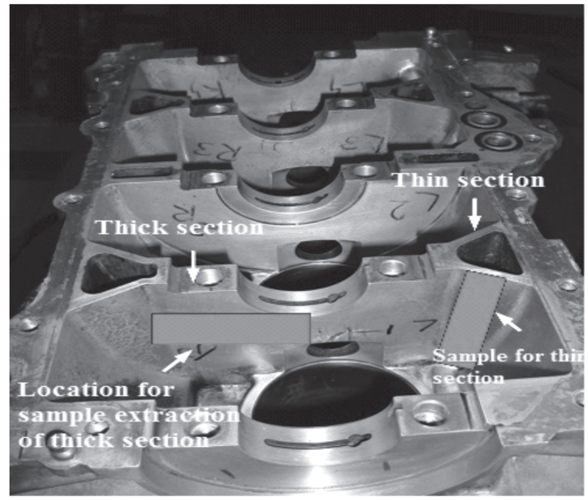
(b) Rectangular strip extracted from cooling channel



(a) Cooling channel



(b) Saddle.



(c) Location of sample extraction.

Fig 4: Sample extraction from thin and thick sections.

MATERIAL

Spectroscopic analysis of the extracted samples was carried out using Spectomax metal analyzer. Material composition of the alloy is given in Table 1. The composition closely matches with that of AA384.1.

Table 1. Composition of Al alloy (percentage by weight)

Al	82.696
Si	12.5
Fe	0.857
Cu	2.58
Mn	0.244
Mg	0.251
Ni	0.077
Zn	0.77
Sn	0.025

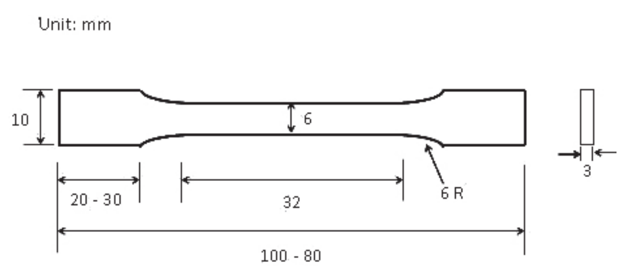


Fig 5. Standard Tensile Specimen

RESULTS AND DISCUSSION

Tensile test

Tensile tests were carried out for a total of 12 specimens. Six samples each were extracted from thick and thin sections, respectively. Figure 6 shows some of the tensile stress strain curves for the tested samples.

Table 2 shows results of tensile tests relating to UTS and ductility for thick and thin sections. Column 3 of Table 2 shows the ultimate tensile strength of the specimens. The variation among the strengths of thin and thick sections are attributed to the higher cooling rates in thin sections. Column 4 of Table 2 shows percent strain to failure for specimens of thick and thin sections. The percent strains to fracture of thin sections are higher as compared to thick sections. This again is attributed to the higher cooling rates in thin sections due to their lower moduli (V/A) [volume/surface area].

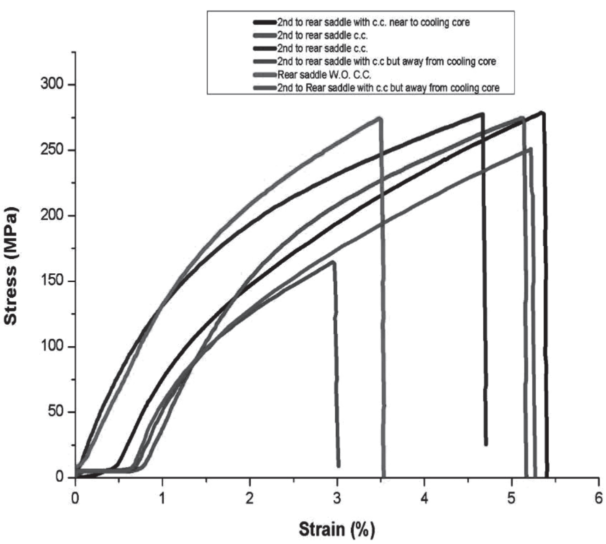


Figure 6. Stress Strain

Figure 7 shows mean stress and percent strain for the thick and thin sections. It can be seen that mean strength and ductility for thin sections are comparatively higher than the thicker sections. Also it can be seen that the reduction in porosity effects the ductility more than the yield strength.

Analysis of Three-dimensional porosity in the fractured tensile samples was carried out using micro-CT scanner at Stellenbosch University CT facility South

Table 2: Experimental results for thick and thin sections

Sample #	Section thickness	UTS (MPa)	Strain to fracture (%)
1B	Thin	273.47	5.1284
2B	Thin	278	4.668
3B	Thin	263.19	6.528
3A	Thick	263.46	3.467
2A	Thick	164.33	2.957
1A	Thick	249.161	5.114
2S1	Thin	254.74	4.917
1S1	Thick	211.105	2.35
1C1	Thin	281.41	5.367
1C2	Thin	234	7.9
S1	Thick	195.33	2.112
2C1	Thin	278.75	5.338

Table 3: Comparison of volumetric porosity and pore size for thick and thin sections

Sample #	Percentage volumetric porosity (%)	Max. pore size (mm) in samples
2S1 (Thin)	0.35	0.115
2C1 (Thin)	0.150	0.239
S1 (Thick)	0.65	0.65
1S1 (Thick)	0.19	0.337

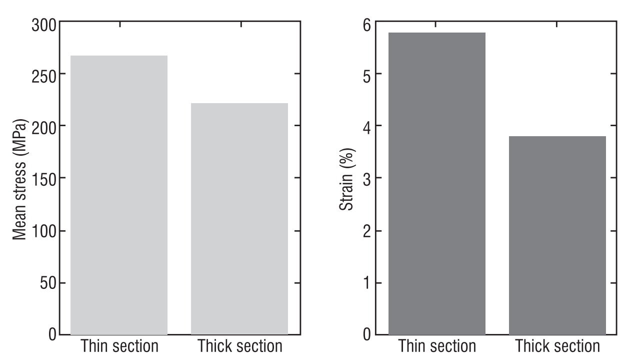
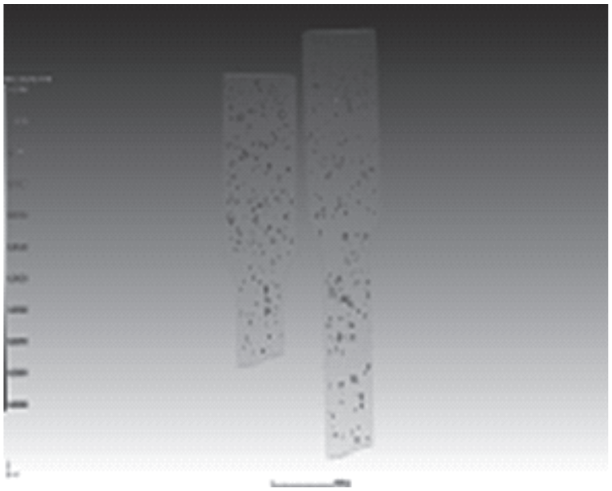
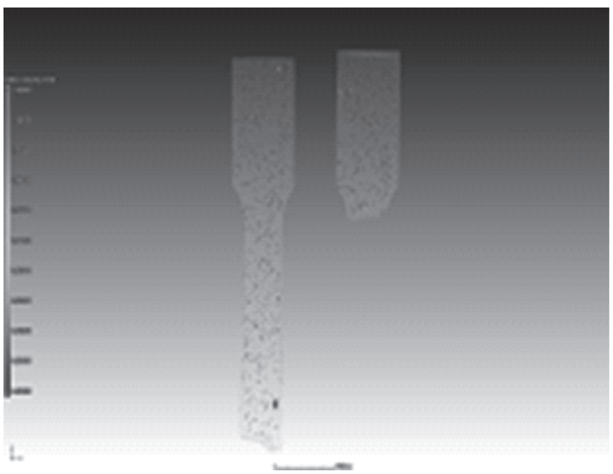


Figure 7: Comparison of mechanical properties for thick and thin sections

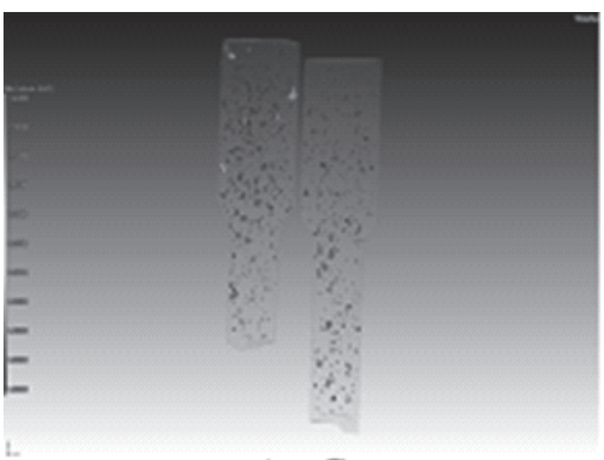
Africa. Micro CT scans were done at 150 kV voltage and 100 uA (microAmperes) current setting for X-ray generation. Beam filtration was used to minimize beam hardening. The voxel size of the scan was 30 micrometers. Each image in a stepwise rotation of 360 degrees was acquired with 500ms. The percentage volumetric porosity and maximum pore sizes found in thick and thin samples are given in Table3. It can be seen that



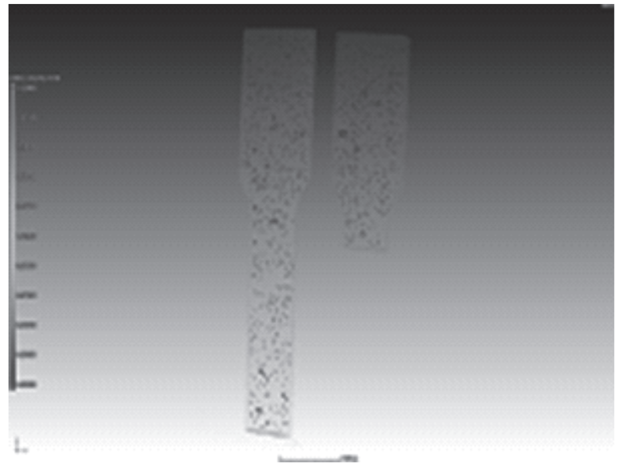
(a) Sample 1S1 (Thick section)



(b) Sample 2S1 (Thin section)



(c) Sample S1 (Thick section)



(d) Sample C1 (Thin section)

Figure 8: CT scan of samples 2S1, S1, 1S1, 2C1

percentage volumetric porosity and maximum pore size are higher for thick section sample viz., S1, 1S1, as compared to thin section samples 2S1 and 2C1. It is evident that the percentage volumetric porosity is higher for thicker sections along with lower strength and ductility (Table 2). Further, it can be noted from Tables 2 and 3 that the strength and ductility of the specimens depend on the percentage volumetric porosity and not on the individual pore size.

Figure 8 shows CT scan images of the analyzed samples. The maximum pore sizes in samples are highlighted with red color and the smaller pore sizes are highlighted with green and blue colors. It can be seen that the percentage volumetric porosity and maximum pore sizes are higher in thick sections as compared to thin sections. The reason is that thicker sections have lower cooling rates and will take longer solidification. Hence, unlike thinner casting sections, larger pores can be seen in thicker sections, because the pores in thicker sections will have sufficient time to grow before the completion of solidification

CONCLUSIONS

Mechanical tests were conducted on samples extracted from an aluminum engine block. Three dimensional analyses were carried out on fractured samples. Samples extracted from thicker sections within the engine block have inferior mechanical properties as compared to thinner sections. The overall strength is greater in case of thin sections but ductility seems to be affected more with section thickness. The overall volumetric porosity ranges from 0.0875% - 0.15% for thinner sections, where as it is in the range of 0.24% - 0.35% for thicker sections (Table 3). The overall maximum pore size is larger in thicker section as compared to thinner sections but there can be a larger individual pore size for thinner sections. Percentage volumetric porosity seems to have a significant effect on UTS and ductility and it does not depend on one individual pore.

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