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Research Article

The Effect of Different Silica-Based Ceramic Cores on Surface Destruction of a Casting Part

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Abstract— In this paper, the impact of a silica-based ceramic core on the internal defects of a cast component was examined. Specifically, two distinct types of cores were created using coarse and fine zircon powder particles. Subsequently, two nozzles were fabricated through the investment casting process, and their internal surfaces were thoroughly analysed using Borescope and Radiography inspection techniques. Some samples were then taken from the nozzles and assessed using Optical Microscopy (OM) and Scanning Electron Microscopy (SEM). The findings indicated that the casting component hollowed out by the core made from coarse particles exhibited surface destruction. This destruction is likely attributable to the reaction between the core and the metal. In contrast, the component with the core composed of fine zircon particles displayed a very smooth inner metal surface, with no signs of surface damage. Indeed, the finer particles proved to be more stable when interacting with the molten metal.

Keywords— Ceramic core; Zircon; Nozzle; Investment casting.

1. Introduction

Ceramic cores are commonly utilized as structural materials for high-temperature applications, particularly in investment metal casting, where they help create complex internal cooling channels in gas turbine parts. During the investment metal casting process, ceramic cores must endure thermal stress at high temperatures. As a result, they are produced from a blend of refractory materials characterized by varied particle size distributions and the presence of impurities [1].

In effect, the ceramic cores in the investment casting industry are extensively used in hollow shape casting. Proper match between the ceramic core, ceramic mould and metal blade is essential for proper performance of the casting process. Also, a ceramic core must have other specific properties such as dimensional conformity, mechanical strength, thermal shock resistance, thermal stability, gas permeability, chemical inertness against the super alloy, and enough mechanical weakness to prevent the generation of cracks or tears in the casted part. Basically, most of the dimensional conformity is due to zircon ($ZrSiO_4$) that is as an essential component in silica-based ceramic cores, and can improve their high temperature properties. It is also useful in investment casting mould due to its low thermal expansion coefficient (≈4.1× 10^{-6} °C^{-1} at 25–1400°C), low coefficient of heat conductivity (5.1 Wm^{-1}°C^{-1} at 25°C and 3.5 Wm^{-1}°C^{-1} at 1000°C) and high thermal and chemical stability [2].

Generally, in Equiaxed investment casting, ceramic cores are comprised of silica-based material and they are produced by means of hot injection moulding. Silica-based ceramic cores are extensively used due to their good properties such as low coefficient of thermal expansion as well as good leach ability from the interior of the thin-walled nozzles. Usually, for the leaching process a KOH solution is utilized at its boiling point. Chemical composition of the Silica-base ceramic is composed of the refractory materials including SiO_2, $ZrSiO_4$ and Al_2O_3 [3].

The main component in the silica-based ceramic materials is fused silica. Fused silica may partially crystallize in the temperature range of 1100-1250°C as cristobalite phase. The phase transformation from β to α-cristobalite occurs during cooling in the sintering stage along with volume changes (2.8%) that can cause microcracks in the ceramic core and decrease strength [4, 5]. Zircon ($ZrSiO_4$), with higher strength and stability than fused silica, is often added into ceramic cores to improve the flexural strength and the creep resistance of the silica-based ceramic cores [4]. Kazemi et. Al studied on the cristobalite crystallization of fused silica-based ceramic and its effect on mechanical and chemical behavior of injection moulded ceramic cores [6].

Mostly, zircon is obtained from zirconium silicate that is usually from marine sedimentations which even a small percentage of it consists entirely of unwanted impurities. S. Jones and his colleagues proved that the zircon phase has some impurities like alumina (Al_2O_3). Figure. 1 shows the alumina as the impurity phase within zircon. In addition, zircon has low thermal expansion to prevent dimensional changes of the final casted parts [7].

Figure. 1. Micrograph of an Al_2O_3 (region B) as an impurity phase found within zircon.

Furthermore, wettability is another parameter when molten metal is dealing with the ceramic core. A smaller wetting angle caused by the interfacial reactions would facilitate the penetration of the alloy molten metal into the ceramic cores through the capillaries on the cores, which may bring about inclusions, it is of great importance to investigate the interfacial reactions and wettability between super alloys and the ceramic materials. Whatever wettability between molten metal and ceramic core reduced, the reaction would be decreased. Therefore, the surface destruction was not observed. Sometimes, in pouring process, the velocity of molten metal flow causes the ceramic particles to be detached and no reaction was observed. In this occasion only some ceramic inclusions have been observed in the bulk of casting [8].

In other words, one of the significant parameter for the silica-based ceramic core is its chemical stability. Chemical reactions between molten metal and core during investment casting process can be major sources of inclusions and other contaminations like surface destruction and depletion in the internal surfaces of final casted parts [9].

This surface destruction which caused by the molten metal reaction, produces some intermetallic compounds that significantly reduces the mechanical properties of the casted parts. To overcome this problem, the ceramic cores must have enough strength when molten metal is pouring into the mound. In addition, the super alloys should be poured into special ceramic shells that avoid or significantly reduces this reaction [10].

Defects are formed by processes that occur at the interface between the liquid metal and the ceramic, as evidenced by the regions where the defects are found. Consequently, the reaction between the liquid metal and a ceramic core may be of vital importance. The alloy charge may also be a source of impurities which later solidify in the surface layer of the casting [11].

In this study, the effect of ceramic core on surface defects of a nozzle using in the gas turbine has been investigated.

2. Experimental method

In this research, two nozzles of gas turbine produced by investment casting. Each nozzle containing two airfoils hollowed with internal intricate shape which made by a ceramic core. In this study, a silica-based core containing 70% fused silica (SiO2) and 30% zircon (ZrSiO4) refractory materials was utilized. The low pressure injection mould ing method was used to produce complex shape of ceramic core. The green body of cores was sintered at temperature and holding time of 1240°C and 10 h, respectively. Two different types of cores were made using different particle size of zircon powders. The first sample contained fine zircon particle named FZP and the second sample contained 50% fine and 50% coarse zircon particle named CZP. Density of fused silica and zircon are 2.05 and 4.5-4.8 gr/cm3, respectively.

Characteristics of raw materials comprising the fused silica and zircon, are indicated in Table 1. The schematic of the cores is illustrated in Figure. 2.

Table1. Characteristics of raw materials containing fused silica and zircon powders

Ceramic Powder	Purity (wt%)	Important Impurities	(Type-wt%)	PSD (μm)		
				D10	D50	D90
Fused Silica	99.7	AL_2O_3	0.1	3.4	29.5	82.6
Fine Zircon	97	AL_2O_3	2	2.6	25	67.1
Coarse Zircon		TiO_2	0.2	5.4	44.2	145.2
		Fe_2O_3	0.06			
		Free silica	0.3			

In casting metal process, first, a ceramic mould was produced by investing process in which a wax cluster was shelled in a ceramic slurry solution, and finally, a ceramic mould was made after dewaxing and firing the cluster. Then, a molten metal was poured into the obtained mould in a vacuum furnace. In this case, the nickel based super alloy IN738LC with pouring temperature of 1440°C, was utilized. The chemical composition of alloy was shown in table 2. After the solidification process, the ceramic core was removed by chemical leaching. The leaching process was carried out in KOH 30% solution at 110 ºC. In order to analyze structural defects as well as internal surfaces of the nozzles, Borescope inspection and Radiography films were investigated.

In the following, the nozzles were cut off to evaluate their internal surfaces. In fact, the internal surfaces of samples were subjected to Visual test and compared with one another. Ultimately, microstructural observation of ceramic cores was done by Optical (OM) and Scanning Electron (SEM) Microscopes. EDS spectra (Energy Dispersive Spectroscopy) also was utilized for the quantitative analysis of elements. The images of the casting nozzles are shown in Figure. 3.

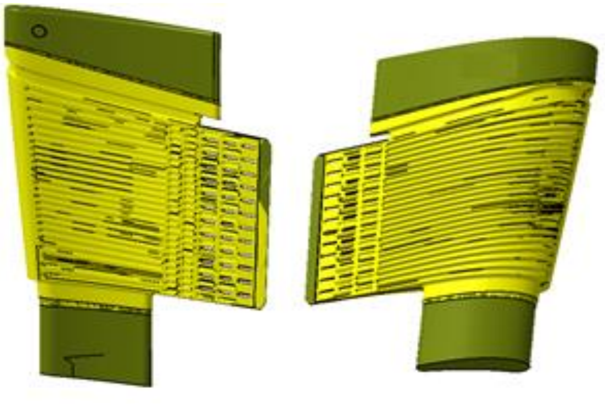

Figure. 2. The schematic of the ceramic core.

Table2. Chemical compositions of the alloy (wt%).

C	**Si**	**Co**	**P**	**S**	**Cr**	**Mo**	**W**	**Ta**
0.12	<0.001	8.2	0.0022	<0.0005	16.0	1.7	2.5	1.4
Nb	**Ti**	**Al**	**Fe**	**B**	Zr	**N**	**O**	**Ni**
1.1	3.2	3.3	0.04	0.01	0.06	0.003	0.0012	Balance

Figure. 3. Image of the studied nozzles.

3. Results and Discussion

The results show that in presence of CZP core, the internal surface of as-cast part was not very smooth. Borescope inspection proved that condition. In addition, some porosity and inclusion within the cavity of the casting part were observed during the inspection. While in the other nozzle with FZP core, the smoothness of inner surface was higher and no porosity or impurity was observed. Figures. 4 and 5 indicate the internal surface of the as-cast parts manufactured by ceramic core including fine and coarse zircon particles, respectively.

Figure. 4. The borescope image of the nozzle using FZP ceramic core.

Figure. 5. The borescope image of the nozzle using CZP ceramic core.

Figures. 6 and 7 indicate the radiography films of the FZP and CZP ceramic cores, respectively. According to Figure. 7, some radiographic defects can be seen in the CZP core. In fact, the heterogeneous distribution of coarse particles proves the final rough surface of the core in Figure. 5.

In this situation, refractory particles arrange together more non-uniformly that caused to poor distribution of the pores in size. In CZP ceramic cores, coarser porosity size as well as rough surface of the core can enhance interaction of melt-core and make a poor surface of the casting.

Figures. 8 and 9 illustrate visually inspection of the internal cut off section of airfoils produced by FZP and CZP ceramic core, respectively. As shown in Figure. 8, the core containing finer zircon particles has a smooth surface which can withstand in the casting process and doesn't show any defects. While according to Figure.9, in the presence of the coarse zircon particles in the CZP core, the molten metal can detach coarse particles and form defects on the surface of the casting.

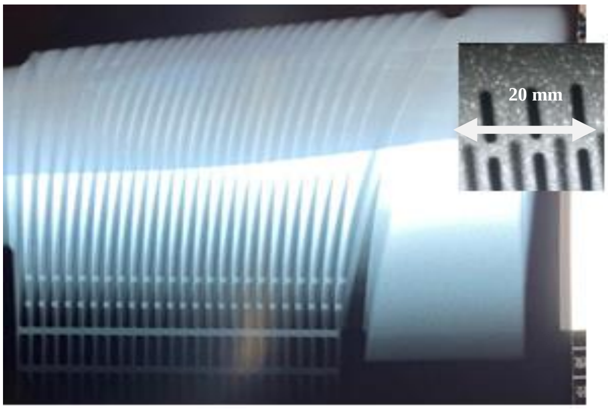

Figure. 6. The radiography film of FZP ceramic core.

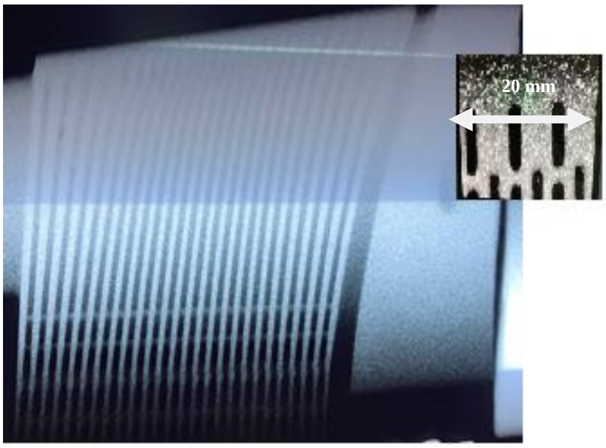

Figure. 7. The radiography film of CZP ceramic core.

It can be emphasized that the same sintering conditions, including sintering temperature and time for both cores (FZP and CZP ceramic core), had different effects on the sintered cores, which created different properties for each ceramic core.

According to S. Jones et. Al, in presence of coarse particles, small bridges between coarse particles of the core can cause poor connections between coarse particles. In the interfacial region, interaction between molten metal and ceramic, this low strength of coarse particle may reduce the resistance of ceramic against the cast metal [12].

It can be concluded that when the refractory particles were finer, due to more surface contacts of the particles, the sintering process and densification was done more appropriately. In other words, the sample containing finer zircon particles has a higher surface energy and surface-to-volume ratio than the other one. Due to the rheological properties of the liquid phase in the sintering process, finer particles with a more active surface can create more liquid phase at high temperatures. This liquid phase creates a more viscous flow through the porous channels between the finer particles with capillary pressure, which causes more contact and strength between the particles [13]. Indeed, capillary pressure is strongly related to pore size. As the pore radius decreases, capillary pressure can be exerted more, which causes more interaction between particles during sintering [12].

In general, the bonding of the fine particles is stronger, which makes the core more resistant to melt flow. In presence of coarse particles, the sintering and densification process was not done sufficiently.

In this case, the greater the porosity in the ceramic core, the weaker the bond between the particles. Therefore, these conditions led to the detaching of ceramic particles when exposed to the molten metal flow. In fact, the wettability between the molten metal and the ceramic core increases and a kind of reaction is observed.


Figure. 8. The internal image of the nozzle with fine zircon particles doesn't shows any reaction or positive metal defect.

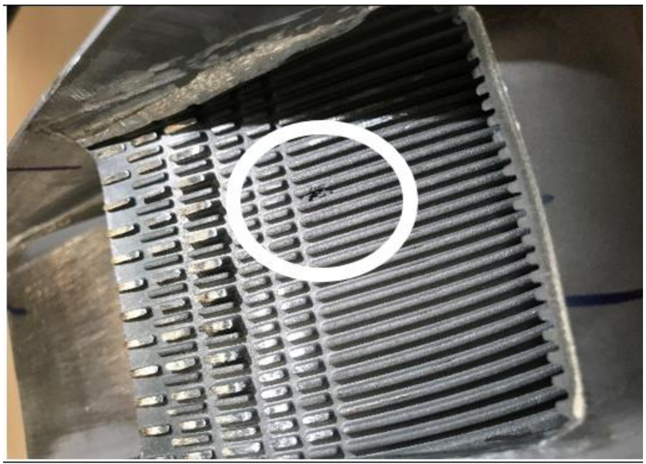
Figure. 9. The internal image of the nozzle with coarse zircon particles shows a positive metal defect.

Figure. 10 shows the section of the cast parts that prepared for Optical Microscopic investigation. Figures. 11 and 12 illustrate the microstructure of samples in fine and coarse zircon particles, respectively. As shown, when the core was produced with coarse particle size of zircon, a surface degradation layer was observed. The depth of this layer was about 220 µm. In comparison, when the ceramic core was made of fine zircon particles, this destruction surface has considerably reduced to approximately 25 µm.

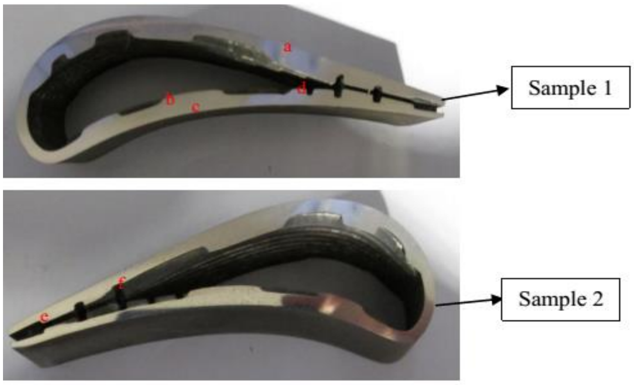

Figure. 10. Samples for Microscopic investigations.

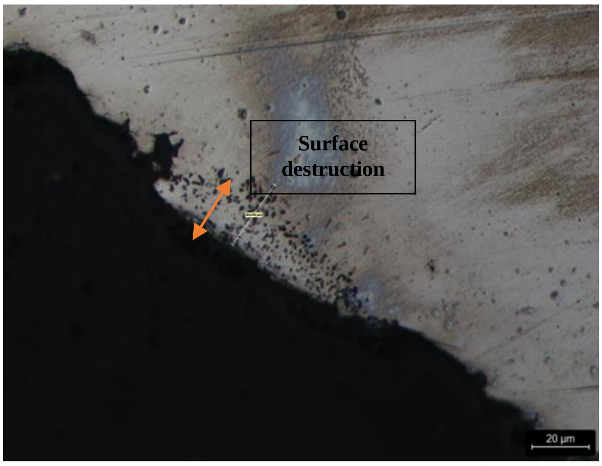

Figure. 11. Surface destruction is very minor (~ 25 µm) in the sample containing fine zircon particles.

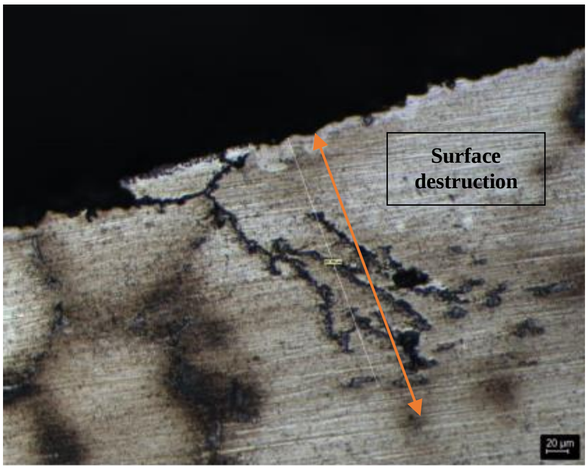

Figure. 12. Surface destruction is very severe (~ 220 µm) in the sample containing coarse zircon particles.

Figure. 13 depicts that the surface destruction investigated by SEM which reveals the impurities in the interfacial and base boundaries. Figure. 14 indicates EDS spectra that the most impurity observed in the reaction zones was aluminum and due to the observed reaction and destruction, it may relate to $Al2O_3$ as an important impurity in the zircon powder which emphasized in S. Jones's study [7].

It is worth mentioning that the composition of both samples was the same and only the size of the zircon powder particles was different. In fact, the impurities of fine and coarse particles were the same, but because of the more surface destruction in the sample containing coarse particles, EDS investigations were done only on this sample.

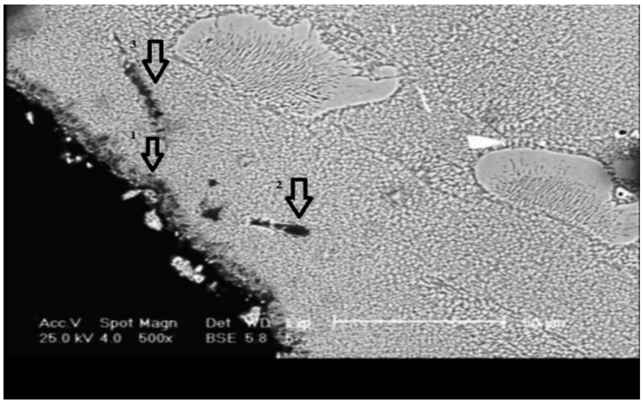

Figure. 13. SEM image of nozzle Surface destruction.

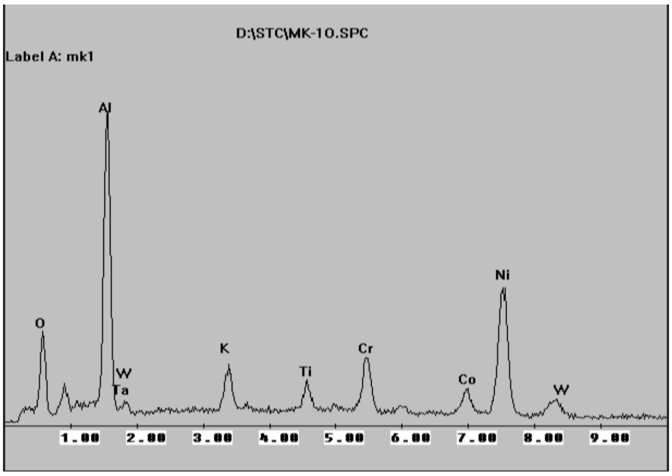

Figure. 14. EDS results.

4. Conclusion

In summary, the presence of surface destruction_on the internal surfaces of two gas turbine nozzles were inspected using Borescope, Radiography and Microscopic investigation. The results of assessment on radiography films, visual inspection and microscopic images showed that the size of the of ceramic particles significantly affects its surface strength. Chemical stability of the ceramic core is completely dependent on the size of the zircon particles. It should be emphasized that the same sintering condition, in which the sintering time and temperature were identical, had different effects on the sintered cores.

In fact, in ceramic core containing coarser zircon particles, the wettability between molten metal and ceramic core increased, and some kind of the reaction was observed. The finer particle size has increased the stability of the ceramic and the inertness of the core in contact with the molten metal. In other words, in core containing coarse particles, zircon particles detached from some regions of the internal surface. Consequently, some positive metal defects observed in final part. In addition, EDS result showed that the observed destruction is probably related to the core-metal reaction. In general, among the parameters of the production process, the size of zircon particles in ceramic materials is of great importance to prevent the desired metallurgical surface defects.

Data Availability
None.

Conflict of Interest
All authors are requested to disclose any actual or potential conflict of interest including any financial, personal or other relationships with other people or organizations that could inappropriately influence, or be perceived to influence, their work. Otherwise, Authors declare that they do not have any conflict of interest.

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Author's Contribution

Author 1- researched literature and conceived the study. Also designed of experimental. All authors reviewed and edited the manuscript and approved the final version of the manuscript.

Author 2- researched literature and conceived the study. Also designed of experimental and wrote the first draft of the manuscript. All authors reviewed and edited the manuscript and approved the final version of the manuscript.

Author 3- Revised the draft and expand the concepts. All authors reviewed and edited the manuscript and approved the final version of the manuscript.

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