Academic Science

International Journal of Electronics, Electrical and Computational System
IJEECS
ISSN 2348-117X
Volume 6, Issue 8
August 2017

A Review on Investment Casting Ceramic Shell Building Process

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ABSTRACT

Investment Casting is one of the oldest known processes to produce metal castings. Automotive, aircraft and defense industries require highly precise metal components which are made by means of ceramic shell technology. The present paper reports various investigations made in the shell building process. Different types of refractory fillers have been tried to form the primary layer of the shell and the corresponding advantages and disadvantages were also studied. Further, distinctive additives have been added to the secondary layers of the ceramic shell to improve its properties and reducing dewaxing time so as to speedy the shell building process.

KEYWORDS

Investment Casting; Ceramic Shell; Facecoat; Backupcoat; Slurry

1. INTRODUCTION

Investment casting (IC) is employed for producing premium quality parts possessing complicated shapes and thin sections [1]. The metals which could not be machined easily are effortlessly made by this process. It manufactures components which are dimensionally very accurate and have excellent surface finish [2]. Some distinctive applications of IC include manufacture of aircraft engines, air frames, turbine blades, jewelry, dental parts, etc. The various stages involved in the IC process are: creation of disposable wax pattern, construction of ceramic shell around the wax pattern, dewaxing and firing the ceramic shell and metal casting into the ceramic shell [3]. Each of the aforementioned stages is very crucial in the IC process as they influence the casting quality. The main disadvantage of the IC process is that it is very labour-intensive, which ultimately leads to increase in manufacturing costs of the produced parts.

In IC process, the building of ceramic shell around the wax pattern is mainly time-consuming. These ceramic shells are usually made from ingredients namely, the binder, refractory filler, additives and stucco material [4]. The refractory coating plays a very intimate role in the IC process. It provides refractory protection to prevent metal penetration inside the shell and perfect surface smoothness to the cast parts. The shell is created by dipping the wax pattern into a slurry of liquid refractory material and then, sieving coarse dry refractory grains over the wet drained layer over it. Once the layer is dried, the sequence of dipping and sieving is repeated several times, so as to produce a desired shell thickness over the wax pattern.

Usually, the ceramic shell should be thick enough to withstand the thermal stresses of pouring of hot molten alloy inside it. In other words, it should have sufficient fired strength. It should also possess sufficient green strength to prevent shell cracking during wax removal process. Literature reveals that most of the shell cracking occurs at edges and sharp turnings. The cracking of the investment casting ceramic shell occurs when the thermal stress generated during dewaxing stage is more than the green strength of the ceramic shell. The green strength of the ceramic shell is not constant throughout the shell as the coverage of stucco is not same everywhere. At edges and sharp turnings, coverage of stucco is relatively less, which leads to reduced shell

thickness at these sections. Ultimately, the green strength is less at these sections compared to regular section. Besides sufficient shell thickness, the shell should be adequately porous and permeable to allow hot gases evolved during melting of alloy to escape outside the shell so as to prevent casting defects. If a desired shell thickness with permeable structure is achieved by applying less number of coats over the wax pattern, at the same time maintaining the slurry rheology, then it would boost the efficiency of the IC process. The aim of this research paper is to review different techniques applied to improve the features of the ceramic shells starting from the prime coat onwards to the backup coats in the IC process. The findings of the researchers would be very useful in selection of the material and control of slurry parameters during shell building process.

2. PRIMARY FACECOAT OF THE CERAMIC SHELL

The primary layer of the ceramic shell is built over the wax pattern and it is very much essential that the wax pattern is free from surface imperfections and die release agent. If the surface of the wax pattern has traces of the die release agent, then the primary slurry will not be able to stick to the wax surface resulting in localized thinning and poor surface finish of the facecoat layer [3]. Thus, the wax pattern must be carefully cleaned with a degreasing solution before dipping in the primary slurry to make sure that the primary slurry sticks to the wax pattern surface and consequently, primary coat lift up tendency is avoided. Further, the wax pattern should be washed thoroughly with continuous water supply so as to remove the degreasing agent from it. Correct quantities of wetting and anti-foam agent should be added to the primary slurry because inaccurate quantities of these agents cause localised roughness and pimples on the casting surface due to unevenly coverage of the slurry over the wax pattern surface and creation of foamy slurry mixture producing pimply surface on the cast part [5]. The refractory filler materials chosen for building the slurry should have extremely little amount of iron content because high iron content causes increase in metal-mould reaction thereby producing defective castings.

The proper pH of the primary slurry should be maintained otherwise slurry gelling will take place and this affects the slurry viscosity producing spalling of the primary coat due to reduced slurry's binding strength. A slurry gels owing to presence of salts from water additions, bacteria growth, leakage of electrolytes in the refractory filler materials, etc causing clusters in the slurry. Primary slurry's viscosity/density influences the surface texture of the casting. If it is too low, the melt make a way into the pores of the stucco. If it is too viscous, a localised thick coat is formed which causes the dipcoat to break off at some stage in dewaxing stage or casting owing to inadequate bonding between the primary and secondary layers. Further, the draining time of the primary coated assembly should also be checked. Neither too low nor too long of draining time is desirable as it may produce a very thin facecoat allowing the primary stucco to penetrate into it or the stucco would not stick on the dried primary layer thereby causing delamination.

Yuan et al [6] added yttria as primary refractory filler in IC shells for casting enormously reactive Titanium aluminide (TiAl) alloys. Liquid polymer was added to the slurry for improving the strength of the ceramic shell. The polymer content was varied through different percentages i.e. 0%, 6% and 30% respectively and the ceramic samples were also fired at temperatures namely, 1000°C, 1200°C and 1400°C. From their investigation, it was found that change in polymer content between 0% and 30% didn't affect the ceramic shell strength before and after firing. On the other hand, the firing temperature above 1200°C strongly affected the strength and it drastically amplified between 1200°C and 1400°C owing to increased sintering. On increasing the percentage of polymer in the primary slurry, thicker primary coats were formed and shell permeability also increased which is beneficial for entire mould filling. Fig. 1 shows that increase in liquid polymer content leads to an increased thickness of the primary layer. The firing temperature also strongly influenced the friability of the shell. The friability decreased while increasing firing temperature from 1000°C to 1400°C. Silica from the secondary coat was found to pass through the primary layer and disseminated into the alloy.

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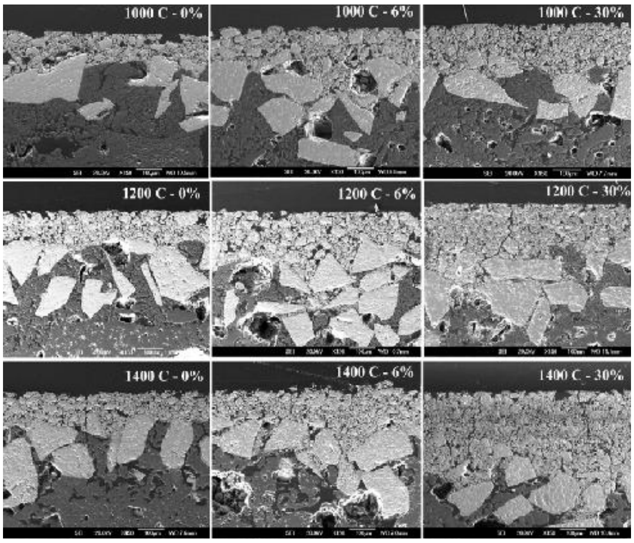

Fig. 1. The cross-section of moulds with various polymer content fired at 1000°C, 1200°C and 1400°C [6].

Further, Yuan et al [7] determined the interactions between $CaZrO_3$ refractory face coat filler and Al_2O_3 stucco during shell firing. It was found that Al_2O_3 stucco reacted with $CaZrO_3$ filler and formed $(Zr,Ca)O_2$ and $CaAl_xO_y$ when fired at temperatures about 1650°C. However, no interaction effect was seen when ZrO_2 was used as stucco, only a few cracks appeared in the primary layer. They further studied the reaction between $CaZrO_3$ refractory flour and Al_2O_3 stucco and found that six-fold dendritic microstructures appeared in the casting of TiAl alloy due to penetration of oxygen, Si and Zr ions from the primary layer into the TiAl alloy to form intermetallic compounds.

Cheng et al [8] mixed Y_2O_3-ZrO_2 blended facecoat refractory flour with three dissimilar binders so to test slurry stability and consistency, sintering properties and its chemical inertness while casting Ti alloys. The slurry life was judged on the basis of its viscosity, sintering properties of the primary layer were analyzed using dilatometry, XRD, a friability test and secondary electron microscopy (SEM). Furthermore, a sessile drop test was used to study the chemical inertness of different facecoats.The results illustrated that when alumina-sol was used as binder in the slurry, the slurry life was found to be longest of about three days, followed by the commercially available zirconia-sol based slurry of about 6 hours and the yttria sol based slurry giving a shortest life of about 1.5 hours. The primary layer sintering properties of alumina-sol based slurry was found to be enhanced. No noticeable facts about the facecoat chemical inertness were observed on the change of the binder system.

Zhao et al [9] investigated the effect of different primary slurry refractory fillers namely, Y_2O_3, ZrO_2 and Al_2O_3 and shell mould temperatures namely, 300°C, 600°C and 900°C on the fluidity of titanium alloy. The fluidity, a key of castability, was assessed by a fluidity spiral pattern as shown in Fig. 2. It was found that the Y_2O_3 based primary coating exhibited the best fluidity and weakest interfacial reaction as compared to other two primary coating materials. The interfacial reaction was found to be progressively rigorous with increase in mould preheat temperature. However, the fluidity did not increase on increasing the mould preheat temperature due to the effect of interfacial reaction. The fluidity increased to a great extent at 900°C, whereas it decreased at 600°C, signifying that the fluidity is influenced by the interaction between the interfacial reactions and chilling effect of the mould.

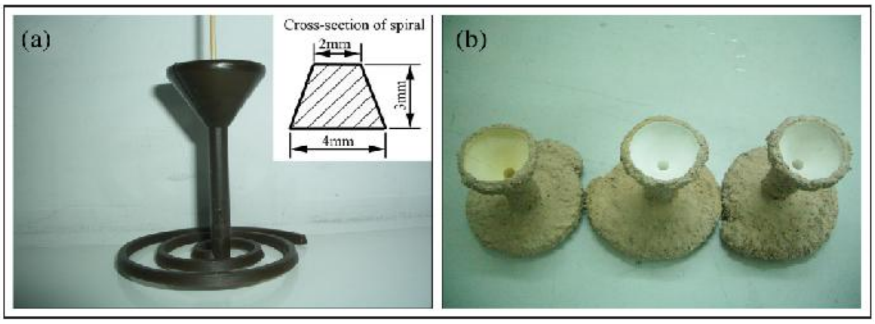

Fig. 2. Wax pattern (a) and ceramic moulds (b) for a fluidity[9]

Yuan et al [10] developed a zirconia facecoat to substitute presently used zircon/silica facecoat slurry material in IC of TiAl alloys. The rheological properties of the zirconia slurry namely, pH, viscosity and plate weight were found to be stable. The zirconia mould's mechanical properties were found to be comparable with that of standard zircon or silica based moulds with advanced permeability which is good for casting of TiAl alloys. It was also found that the friability of the zirconia face coat was much better in comparison to that of yttria based face coat. An investigation was also made about the interaction effect between the zirconia facecoat and TiAl alloy at three different shell pre-heating temperatures i.e. 500˚C, 1000˚C and 1200˚C. The shell was found to be inadequately filled (Fig. 3) when the pre-heating temperature of the shell was 500˚C. When the shell pre-heat temperature was increased to 1000˚C, the shell was found to be completely filled with only a few vein defects on the casting surface. No filling defects were seen when the shell pre-heat temperature was raised to 1200˚C. On the other hand, it was found that increase in shell pre-heat temperature caused Si penetration from the backup layer to the facecoat and then within the alloy during casting. Further, melt solidification time also increased due to high shell preheat temperature which increased the diffusion of Zr, Si and O into the melt from the shell. Thus, it was suggested that the shell pre-heat temperature should be less than 1200˚C.

Fig. 3. The top part of cast bars of different mould pre-heat conditions [10]

3. SECONDARY COATS OF THE CERAMIC SHELL

The imperfections in secondary slurries are caused due to high viscosity/density of the slurries, incorrect dipping/draining or stuccoing.The strength of the ceramic shell is determined by the secondary layers. The

existence of inter-stucco voids and stucco penetration through layers help in removal of gases during casting [11]. Usually, the thicker shells have additional strength and large grain sized stucco are used to increase the shell thickness.

Wang et al [12] investigated the properties of an IC shell constructed by using needle coke additions into the secondary slurries. It was found that the needle coke accumulation increased the shell thickness by a factor of 30% on flat section and 60% at sharp edges as compared to that of full fused silica mould (Fig. 4). Thus, the number of secondary layers applied to the wax pattern is reduced which saves production time as well as money. In the needle coke modified system, the additional shell thickness, particularly at edges, gave a higher load bearing capacity. It also exhibited higher green strength than that of the full fused silica system. However, the hot strength of the needle coke modified shell decreased markedly as compared to the green strength due to the burn out of the needle coke. The void left after needle coke combustion is not a considerable defect which would diminish the hot strength of the shell.

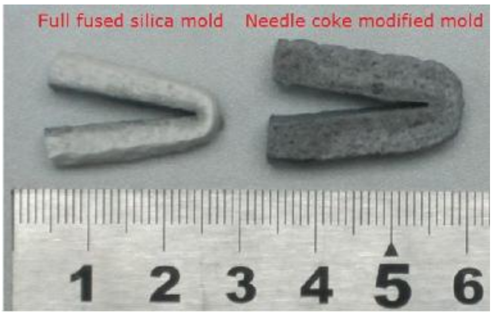

Fig. 4. Thickness comparison of two shell samples

Lu et al [13] explored the feasibility of hybrid fibre (aluminium silicate and polypropylene) addition into the secondary ceramic slurry to improve the properties of an IC shell. It was found that the bending strength of the green shell significantly enhanced by hybrid fibre addition and the maximum augmentation of 35.7% was obtained with 1.0 wt% fibre addition over the conventional unreinforced shell. However, the bending strength of the fired shells first increased and then decreased with an increase of fibre content. The largest bending strength of the shell was found to be 4.96 MPa containing 0.6 wt% fibre additions (Fig. 5). When the percentage of fibre content was lower than 0.4 wt%, the fibre-reinforced shell showed lower self-load deformation at higher temperatures as compared to that of unreinforced shell. The permeability of the shell was found to be significantly increased by hybrid fibre addition and the permeability increased with increase in fibre addition.

Natural fibers are easily and cheaply available all over the world. Saw dust is one of the most commonly used natural fibers and till now, it has been widely used as filler for improving the mechanical and thermal properties of composites [14]. Saw dust refers to small-sized dusty wood waste produced by sawing of wood. Its physical properties include low density, low cost, high porosity, high water retention and resistance to breakage. Pattnaik [14] added sawdust particles into the backup coats of the ceramic shell. It was found that the thickness of the sawdust-modified shell increased by 16% at regular section and 38% at sharp corner as compared to that of the conventional ceramic shell for a five-layered shell system. The sawdust-modified ceramic shell exhibited higher green strength and lesser fired strength. The apparent porosity and permeability of the sawdust-modified ceramic shell were also higher than the conventional ceramic shell. Further, it was found that the tensile strength and impact strength of the Al-Si alloy castings obtained from the sawdust-modified shells were comparatively higher by 6.4% and 20% than those obtained from the conventional shells.

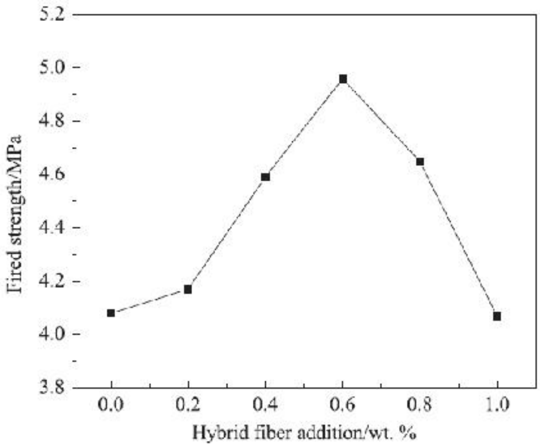

Fig. 5. Effect of hybrid fibre addition on bending strength of fired

Further, Pattnaik [15] did a comparative study about the feasibility of coconut fibres and saw dust individually into the ceramic slurry. It was found that the density, viscosity and plate weight of the coconut fibre-modified slurry were more than that of the polymer-modified and saw dust modified slurry for equal weight percentage of additives. The thickness of P-type, C-type and S-type ceramic shells increased with increase in percentage of additives. The shell thicknesses of C-type and S-type ceramic shells were overall 23.27 % and 14.78 % more than the P-type ceramic shell at regular section. Similarly, C-type and S-type ceramic shells showed 44.9 % and 34.2 % more thickness from that of P-type ceramic shell at sharp corners. The porosity and permeability of P-type, C-type and S-type ceramic shells increased with increase in percentage of additives. However, highest porosity and permeability was found in S-type ceramic shell which was followed by C-type ceramic shell. The flexural green strength of P-type shell increased with increase in percentage of liquid polymer up to 6%. However, it was found that the green strength of C-type and S-type ceramic shells increased with increase in additives from 2% to 5%, thereafter it decreased. It was found from visual inspection that the cracks were generated on the C-type and S-type ceramic shells when the additive percentage was increased to 6%. The tensile strength was highest for the Al-7%Si alloy casting obtained from S-type ceramic shell which also showed least apparent porosity.

IC ceramic shells should have adequate strength, porosity, collapsibility and reliability. Most of the researchers worked on adding additives in the ceramic slurry for enhancing the property of the ceramic shells. Yahaya et al [16] used modified coarse consisting of (0-30) % activated charcoal as back-up stucco and applied to the secondary layers 3-6 only. Dewaxing of the shells was done in a microwave dewaxing test rig and then, they were fired. It was found that the dewaxing time decreased, as the activated charcoal percentage in the shells increased. When the activated charcoal percentage was increased to 30%, some cracks were seen on the outer edges of the shell. As a result of this, 25% was selected as optimum quantity of activated charcoal which could be added to the coarse stucco without causing shell cracking. The porosity and collapsibility of the shell was found to be improved, whereas shell’s strength and density decreased by the addition of modified stucco.

4. CONCLUSIONS

Based on the present review, the following conclusions can be drawn:

- The rheological properties of the ceramic slurries such as density, viscosity, pH, etc play a very important role in building the quality of the ceramic shells. These properties depend on the composition of the ceramic mixture, type of binder used, amount of solids in the mixture, temperature, humidity, etc.

- The primary layer should be made from the best quality materials as it remains in direct contact with the molten metal and should produce accurate surface of the pattern and chemical stability at the metal-shell interface.
- The IC ceramic shells should exhibit certain properties such as adequate green and fired strength, suitable thermal shock resistance, sufficient permeability, high chemical stability, dimensional stability, etc. These properties depend on the buildup process of the secondary layers of the shell.
- Continuous research is going on improving the properties of the shell using artificially or naturally available additives so that production time and cost of shell preparation can be reduced.

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