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PRADYUMNA R
Die Design Group, Defence Metallurgical Research Laboratory (DMRL), P O Kanchanbagh, Hyderabad, INDIA, r_pradyumna@hotmail.com

BAIG M A H
Die Design Group, Defence Metallurgical Research Laboratory (DMRL), P O Kanchanbagh, Hyderabad, INDIA, mahbaig@dmrl.drdo.in

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CERAMIC CORES FOR TURBINE BLADES : A TOOLING PERSPECTIVE

PRADYUMNA R[1] & BAIG M A H[2]

[1,2]Die Design Group, Defence Metallurgical Research Laboratory (DMRL), P O Kanchanbagh, Hyderabad, INDIA
E-mail : r_pradyumna@hotmail.com, mahbaig@dmrl.drdo.in

Abstract - Blade/vane components used in aerospace turbines are of twisted aerofoil shape, made by the process of investment casting, using Ni based super-alloy materials. These castings operate at turbine inlet temperatures (TET) close to the melting point of the alloy, in order to maximize thermal efficiency and thrust of the engine. The castings are made hollow, with intricate features such as turbulator, pin-fin, etc built-in to maximize the effect of heat transfer during forced cooling through internal passages. The hollow geometry in the castings is produced during the investment casting process by using a suitable ceramic core made from Silica or Alumina based mixes. These ceramic cores are high pressure injected by forcing the ceramic mix into dedicated molds or dies. Development of such dies is an involved process by itself, addressing issues right from ceramic mix behavior to manufacturability of the injection mould. The present paper attempts to highlight issues related to tooling development for ceramic cores used in investment cast turbine blade/vane components.

Keywords - *Ceramic core, injection moulding dies, CAD, EDM, CMM Inspection.*

I. INTRODUCTION

Gas turbine engines used in aerospace applications are one of the most complex systems to design, develop and operate. To satisfy ever increasing demands of thrust, overall efficiency and fuel efficiency, these engines are being operated at increasingly higher turbine inlet temperatures, as this alone positively influences the above parameters [1]. Present day turbines operate at inlet temperatures very close to the melting point of the blade/vane material, which is generally made up of Ni based super-alloys. In order to withstand such high temperatures, these components are internally cooled by passing pressurized air from the compressor through intricate passages within the blade geometry. Fig. 1 shows 3-Dimensional (3D) CAD model of a typical hollow turbine blade.

The turbine blade geometry falls under the category of sculpted aerofoil shape, whose profile is progressively twisted from the base (root) to the tip. Relative twist of successive profiles, their longitudinal and transverse deviations with respect to an imaginary stacking axis, are stringently specified and must be achieved during the manufacture of the blade through the complex process of investment casting. The internal cavity of the blade is also of aerofoil shape and all the above stringent requirements apply equally to the cavity.

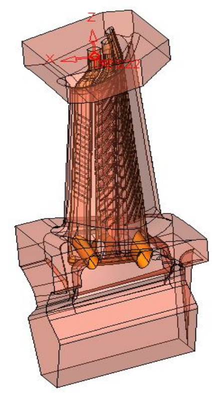
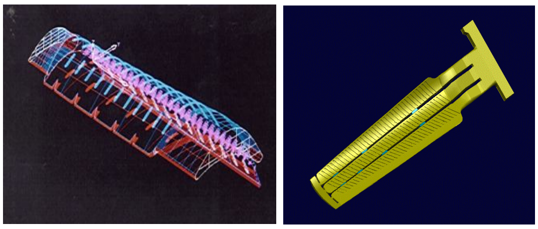


Fig. 1 : CAD model of a typical hollow turbine blade

The complexity of the internal geometry can be gauged from the fact that at the thinnest section, the wall thickness (metal portion) of the blade has to be as small as 0.5 mm [2]. In order to enhance cooling, other intricate features are added to the internal geometry to bring about advanced cooling effects such as impingement cooling, pin-fin cooling, etc. During casting, the internal geometry is produced by the use of a silica or alumina based ceramic core, embedded in the wax pattern. Subsequently, the ceramic core is removed using chemical leaching methods to get hollow geometry.

II. GEOMETRY OF CERAMIC CORES OF A HOLLOW BLADE/VANE COMPONENT

Fig. 2 shows two of highly complicated geometries of ceramic cores used for generating advanced cooling effects in the turbine blade and vane castings. The features designed in the internal geometry enhance the cooling effectiveness of the casting in the following manner [3]:



(a) (b)

Fig. 2 : Typical geometry of ceramic cores for aeroengine turbine (a) blade and (b) vane

- Impingement Cooling : An aggressive cooling technique wherein the leading edge of the aerofoil is cooled by a series of jets impinging on the internal walls.
- Pin-Fin Cooling : Pin-fins are incorporated in the very narrow trailing edge of the blade leading to increased cooling by the flow of coolant air around the pins.
- Dimple Cooling : Considered as an alternative to pin-fin cooling, this technique involves creation of a series of dimples on the internal walls of the cast blade
- Rib Turbulator Cooling : An array of angled rib features created on the main internal surfaces of aerofoil , especially effective in serpentine type cooling passages
- Film Cooling : Cooling air exiting from various locations on the blade (especially the leading edge) forms a thin layer on the external surface, effectively preventing direct contact with the hot air

Presence of these features makes the internal geometry of a turbine blade more complicated than the external aerofoil design itself. It is the responsibility of the tooling expert to strive for reproducing these features during tooling development for ceramic cores so that engine designer's intent is truthfully reproduced in the casting.

III. CAD MODELING OF CERAMIC CORE GEOMETRY

Generating a 3D CAD model is the first step in the development of tooling. Aerofoil geometries have a special place in CAD modeling, due to extensive and judicious user inputs needed for smoothing the sectional profiles, which are subsequently interpolated to form curvature continuous smooth surfaces. In addition to these, a ceramic core is characterized by the following :

- Wide variations in the thickness of the geometry
- Innumerable fine features such as rib turbulators, pin-fins, channel-walls, etc.
- Feature dimensions as small as 0.5 mm
- Rounding fillets as minute as R 0.25mm
- Extensive trimming requirements on aerofoil surface, necessitating robust software and computer hardware
- Design and incorporation of core print features as per casting process needs
- Non-isotropic process shrinkages at green & fired stages and compensation needed in the tooling
- Care necessary in finalizing component CAD models as any error gets carried to the tooling and ultimately to all the components produced with it

IV. MAKING CERAMIC CORES - MATERIAL AND PROCESS

Ceramic cores have to withstand metal pouring temperatures in excess of 1500^0C during investment casting and maintain their shape and strength till the liquid metal cools. Thermal shock resistance, high temperature strength, low coefficient of thermal expansion, leach-ability, etc. are some important parameters to look for while choosing materials for this application. Generally, Silica or Alumina based mixes are used for ceramic cores. Si_02 or Al_20_3 in powder form is mixed with a suitable wax binder and injected at high pressure into a die/mould using the technique of Ceramic Injection Moulding (CIM). The green component is carefully ejected, de-bindered and subsequently sintered at high temperatures to get the ceramic core component. This component is located in a pattern die and injected with wax to get an embedded pattern, which is subsequently subjected to the investment casting process. Post-casting, the embedded ceramic material in the casting is removed through chemical leaching process to get a hollow blade/vane casting [4].

V. MANUFACTURE OF CERAMIC CORE DIES:

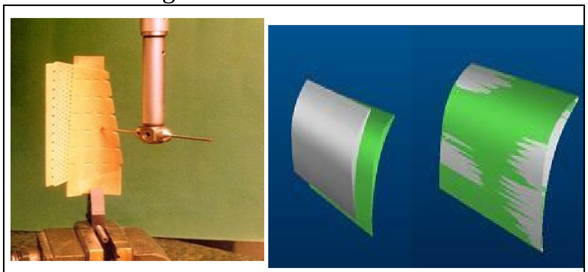
A. Issues in Ceramic Core Dies:

1) Shrinkage and Warpage (Distortion)

This is one of the most crucial aspects of die design for ceramic core development. The dimensional tolerances on the casting external and internal geometry being extremely stringent for aerospace applications, there is a need to control the dimensions of ceramic cores to within a very close tolerance band. In the CIM process, ceramic mix is injected into a suitable mould at high pressures of 400-600 bars and at temperatures of about 80-90 ^0C. In the process of cooling, the injected component undergoes shrinkage and the component dimensions are reduced in dimensions accordingly. Subsequently, the green component is de-bindered at ~ 600 ^{0}C and sintered at ~ 1200 ^{0}C. During these processes, the ceramic core undergoes substantial shrinkage and warpage due to the effects of relaxation of residual stresses and differential volumetric shrinkage phenomenon [5]. These effects have to be quantified and compensated for in the die cavity, if dimensionally acceptable core components have to be consistently produced. In practice, it is seen that these effects are non-isotropic in nature and geometry-specific. Hence, precise quantification for a specific geometry is necessary for successful development of the ceramic core die. In the absence of availability of commercial simulation packages to predict CIM process effects on dimensional aspects, tool designer is constrained to resort to actual inspection and analysis of ceramic cores for these values.

2) Inspection of Green and Sintered Ceramic Cores

Inspection of ceramic cores and casting is necessary for specifying the shrinkage and warpage (S&W effects) occurring during the total process of investment casting. The shape of a ceramic core being twisted aerofoil, during dimensional inspection of the component the following deviations have to be established using best-fit methods :



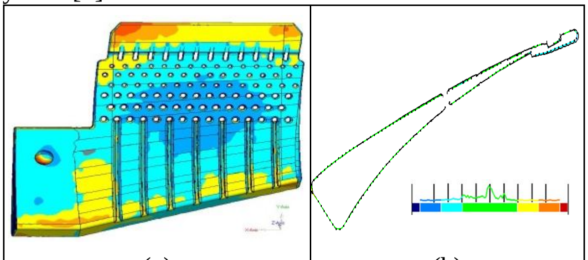
(a) (b)

Fig. 3 (a) CMM inspection of a fired core and (b) CAD based best-fit analysis

- Deviation all along the profiles at specified stacking heights (Z-axis) against nominal values
- Linear shift of each sectional profile from the stacking axis in X & Y directions
- Rotational (twist) deviations

Although sintered ceramic cores are quite fragile, it is still possible to inspect sectional profiles using touch-probe CMM (Coordinate Measuring Machine) based technique, by using very low probing force settings on the equipment. However, CMM inspection method requires well defined orthogonal reference planes for inspection, which are usually not possible to be included in component design due to limitations of geometry and size. Even if these reference planes are designed into a core component, in the process of de-bindering and sintering, distortions occurring in these reference planes render them ineffective for accurate measurement and matching. Therefore, CMM inspection method depends on approximate orientation of the component along the imaginary stacking axis, scanning along required sectional profiles, generating measured component surface using these profiles and elaborate manual 3D best-fit trials on CAD to arrive at an acceptable match for deviation data generation [6]. (Refer Fig. 3) However, this method is not practical for cores in green state due to their extreme fragility.

With the arrival of Laser based non-contact CMM, inspection of these components has become simplified, especially in green condition as there is no contact between the component and the measuring system [7].



(a) (b)

Fig. 4 : Deviation color mapping of a ceramic core using Laser CMM (a) entire surface and (b) sectional profile

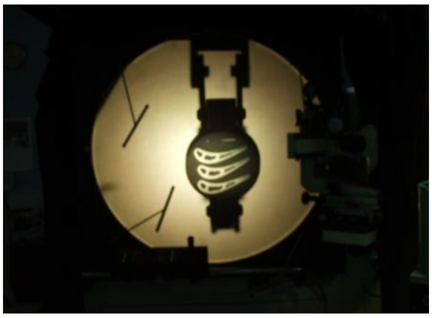


Fig. 5 : Inspection of cut-sections of turbine blade in optical profile projector

This equipment has the advantage of extracting point cloud data on the entire surface of the component running into thousands of points, which can be best-fit against a 3D nominal model of the component and generate color mapping of deviations for a one-look decision on acceptability as well as generating detailed sectional deviations (Refer Fig. 4) and shrinkage data. However, accuracy of the equipment is of the order of 25µm as against 1-2 µm for a touch-probe CMM and is also affected by the reflectivity of the surface.

Casting level shrinkages can only be estimated by destructive inspection methods. A turbine blade casting is measured externally on touch-probe CMM at pre-defined locations to generate sectional data, wire-cut at the exact locations, specimens polished and inspected for both external and internal geometry on optical profile projectors (Refer Fig. 5). This data is analyzed in CAD against designed geometry to generate shrinkage, X-Y shift & twist of profiles and wall thickness data.

In addition to the above, certain other equally important issues need to be addressed before an attempt can be made to develop a ceramic core die. The following are some of them :

- Die design related issues such as requirement of multiple inserts, retraction angles of inserts, etc.
- Parting line and parting surface design for die inserts based on component geometry
- Core print design suitable for the investment casting process, its incorporation in die and manufacturability
- Die fill-ability issues due to large variations in thickness of component geometry, presence of intricate features and ability to form fine features
- Surface finish requirements of die vis-à-vis ease of component removal
- Ejection of green component without introducing stresses which can later relax and lead to warpage

Fig. 6 : Soft tooling through rapid prototyping

B. Soft Dies Development through Rapid Prototyping

During initial stages of ceramic core technology development at DMRL, shrinkage behavior of ceramic mixes were analyzed using strip shaped ceramic core using a specially developed injection moulding die. The results of the study confirmed the non-isotropic nature of shrinkage. Since a strip cannot represent influence of aerofoil geometry on S&W effects and attempting a core die development without this crucial data was pointless, rapid prototyping (RP) technology was utilized. The ceramic core for a vane casting, as shown in Fig. 1(b), was considered and 3D models of the proposed die layout were created using advanced CAD software. These cavity forming inserts were rapid prototyped in ABS plastic material using Fused Deposition Modeling (FDM) technology(Refer Fig. 6), coated with electro-less nickel, assembled in a suitable housing, subjected to low pressure injection of ceramic material and processed for analyzing shrinkage. Some of the important feedback from the RP die was as follows :

- Close to realistic non-isotropic shrinkage values for green as well as sintered component
- Die fill-ability and feature formability issues
- Component ejection related issues
- Inputs on parting line selection during design
- Effect of abrasiveness of ceramic mix on die surfaces
- Defect formation in low pressure injection and its effect on shrinkage

In spite of the fact that RP based soft dies are useful to quickly make dies and analyze for shrinkage, it is necessary to opt for metallic dies of easily machinable material for realistic analysis of S&W effects. An associated problem with ABS based RP soft dies is the life of the die which lasts not longer than 10-15 injections.

C. Low Hardness Ceramic Core Die in Aluminum

Initial trials using Aluminum based dies looked promising due to the ease of machining on 3-axis CNC milling machines. However their utility was short lived due to following reasons:

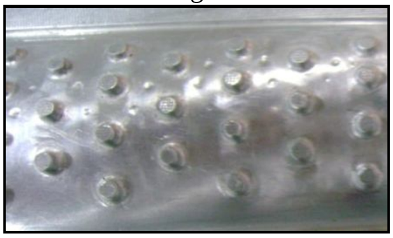


Fig. 7 : Surface degradation in ceramic core die made in aluminum

- Difficulty in achieving surface finish of high order to prevent sticking of high pressur injected ceramic mix, especially around minute features such as pin-fins
- Rapid degradation of surface (Refer Fig. 7)
- Crushing phenomenon due to high clamping loads leading to cavity dimensional changes and flaring-up of pin-fins & other features leading to component ejection problems

In spite of the above problems, useful injection trials could be carried out on the die for a limited number for about 100-150 high pressure injections and accurate shrinkage estimation could be arrived at.

D. Medium Hardness Ceramic Core Die in P20 Steel

In the case of P20 steel of ~ 40 HRC hardness, hybrid approach was tried for machining of cavity blocks. Initial 3-axis CNC milling was carried out till semi-finish stage and final finish machining was done using EDM sinking method, using specially designed, manufactured and qualified electrodes in Cu-W material (Refer Fig. 8 (a) and (b)). The problems associated with CNC machining such as formation of fillet radii around pin-fins & chamber walls, polishing on the surface, etc. has been mostly overcome due to the absence of cutter marks in the EDM sinking process.

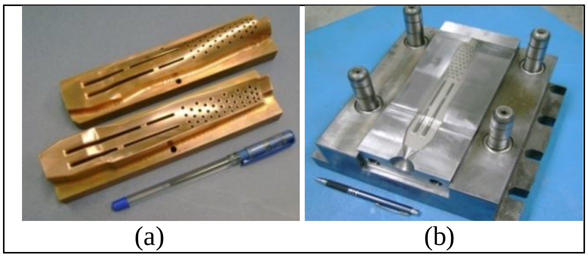


Fig. 8 : EDM electrodes and ceramic core die

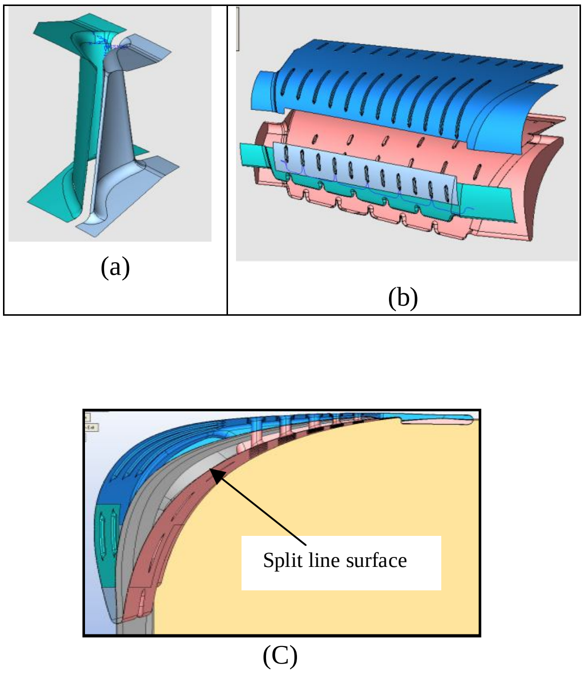


Fig. 9 : Typical parting strategy for (a) wax pattern, (b) ceramic core and split line technique for core features (c) split line technique

Increase in hardness in comparison with Aluminum die has given a substantial increase in die life of ~ 1500 injections, which is sufficient for limited series production of castings. Beyond this range, degradation of surface makes it impractical to use the die.

E. High Hardness (60 HRC) Ceramic Core Die in AISI D2 Steel

For volume production of ceramic components, through-hardened steel dies of ~ 60 HRC are needed. It is impractical to adopt CNC milling techniques for these dies due to the high hardness as well as requirement of fine cutter diameters of 0.5 mm to cater to the minute fillet requirements on features. Some of the critical steps in the development of ceramic core die is enumerated below:

1) Concepts for Parting Line Selection :

Typical parting line concept for external geometry of a blade is shown in Fig. 9 (a) , wherein the surfaces are split along a 3D smooth spline which is generated as a result of joining of all extreme points of cross-sections of aerofoil perpendicular to the die opening direction. Similar strategy is adopted in parting the external geometry of a ceramic core component (Refer Fig 9 (b)). As regards features of the ceramic core, a 3D parting surface is generated, suitably dividing the through thickness features and surface lying features, keeping in mind the electrode design and manufacturability through the EDM die sinking operation. This technique is known as the "split line" method and is unique to the ceramic core dies (Refer Fig 9 (c)).

2) CAD Modeling of Cavity Blocks

Once the external parting and split line methodology is finalized, the individual cavity forming blocks are designed.

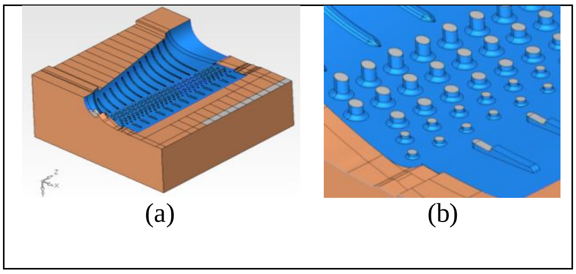


Fig. 10 : (a) Concave block of ceramic core and (b) Minute features with draft and fillets

Special care is taken to see that the split features match perfectly between the die blocks, all fillets and core print features are properly configured. Provision of draft is an important consideration at this stage to facilitate ease of removal of injected green core component avoiding built-in stresses. (Refer Fig. 10 (a) & (b))

3) Design of a suitable Mold Base

The ceramic injection dies are subjected to 40-60 tons clamping loads and upto 400-600 bars pressure. To withstand these forces, standard mold bases used in plastic injection moulding industry to DME/HASCO standards is chosen and suitably machined to house the cavity blocks Inserts requiring side retraction need finger-cam or similar mechanism to be incorporated in the mould base (Refer Fig. 11). Through hardened injection blocks of hardness similar to the cavity blocks is designed with suitable matching features to the injection machine plunger geometry.

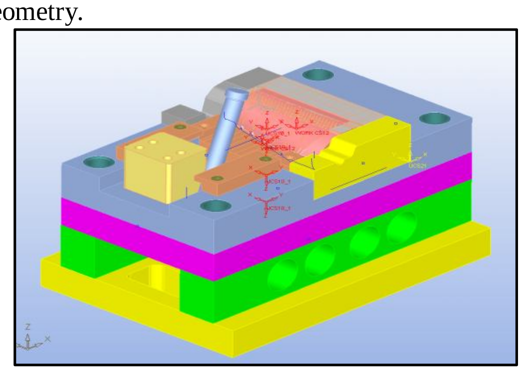
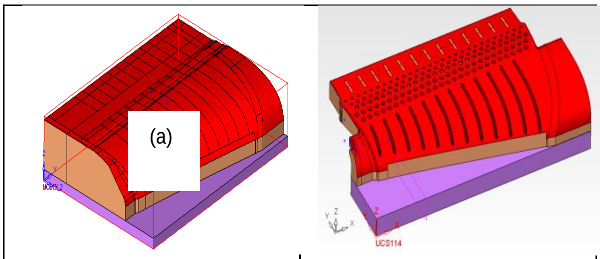


Fig. 11 : Design of mold base with finger cam



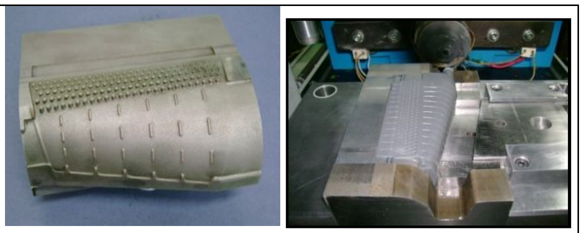
(a) (b)

Fig. 12 : CAD models of electrode design for (a) Split line and (b) cavity for concave die block

4) Design of EDM Die Sinking Electrodes

Electrode design, manufacture and qualification is a crucial step in the ceramic core die development process. Standard precision EDM sinking equipment such as Charmilles, Mikron, etc with micro-machining and orbital EDM capability is mandatory for the application. During design/manufacture of electrode, special care is given to the following aspects :

- Minute features with fillet radii of R0.5 mm and draft on features.
- Stages of EDM sinking and spark/orbital gap
- References to be created for accurate positioning in relation to the work
- Balance between MRR (material removal rate) and electrode wear as recommended in the technology tables of the EDM sinking equipment to determine optimal spark gap
- Separate sets of electrodes for parting line/surface creation and subsequently cavity creation (Refer Fig. 12 (a) and (b)) to achieve sharp edges preventing leakage of ceramic material and erosion of die blocks
- Material for electrode is generally electrolytic copper or Cu-W keeping in view fine features of the geometry which are likely to be chipped off in a graphite material
- Debris formation during sparking and a suitable passage for debris to prevent adhesion to the burning (sparking) area
- Dimensional qualification of electrodes in CMM inspection and polishing to the required level.



(a) (b)

Fig. 13 : (a) Convex die block at semi-finish leval and (b) Fully assembled ceramic core die on injection machine

5) EDM Machining of Cavity Forming Blocks

During the process of EDM sinking, extreme care is to be taken for selection and setting of parameters on the machine, suitable for the electrode design, MRR, electrode wear and surface finish required. Electrodes are located precisely in reference to the insert block references. After EDM process with every stage electrode, the inserts are CMM inspected to check for stock available for next operation, aerofoil profile deviations in terms of X-Y-Theta variations, electrode wear and surface finish attained. Orbital finishing is resorted to for superior dimensional and surface finish during the finish electrode sinking. After dimensional qualification, the individual inserts are mirror polished by manual means to around 0.1- 0.2 µm R_a and assembled onto the mould base, to complete the die development.

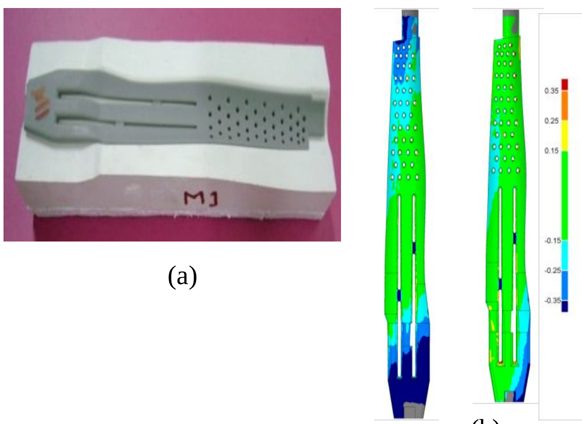
Thus, development of a ceramic core die is not limited to the tooling aspects per se, but encompasses knowledge regarding ceramic processing as well as inspection and analysis.

VI. ALLIED TOOLING

The responsibility of a tool designer extends beyond ceramic core injection moulding die development. Fixturing needs of the component also have to be addressed and necessary hardware developed for the completion of the tooling process.

A. Green Core Correction Fixture

Ceramic cores are extremely fragile, especially in the green condition. During ejection from the die, it is observed that significant amount of distortion is seen upon removal. Processing further to sintering stage will result in dimensional deviation beyond acceptable levels.



(a) (b)

Fig. 14 : (a) Green core correction fixture and (b) Ceramic core before and after setting in correction fixture with deviation color plot

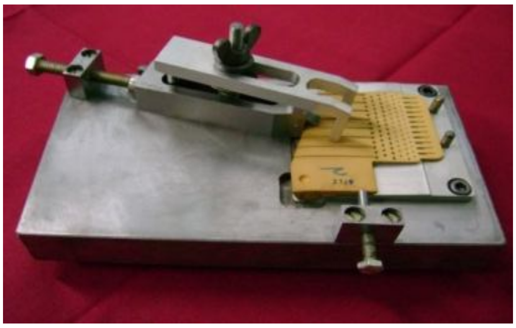


Fig. 15 : Core finishing fixture

A profile correction step before de-bindering and sintering is mandatory. Since all ceramic cores have to undergo this step, a large number of correction fixtures are needed. In order to address this issue, a mould with a geometry reciprocal to that of the correction fixture is developed and suitable self-setting ceramic mix is poured in to the mould to get multiple numbers of fixtures (Refer Fig. 14(a)). These are CMM inspected to qualify and used as correction fixtures by placing green cores and baking them in an oven at ~ 80^0C. Fig. 14(b) shows the effect of using green core correction fixture.

B. Core Finishing Fixture

Minute gaps between the parting lines of the die inserts result in 'flash" formation during injection and these cannot be removed at the green stage, due to fragile nature of the core. After sintering they remain as sharp edged features. If not removed, they can lead to formation of cracks in the casting. Dedicated fixtures, with well defined referencing system have to be developed for each ceramic core (Refer Fig. 15) to remove flash using desk-top, high accuracy 3-axis CNC milling machines.

C. CMM Nest Fixture

On a production scale, it is not required to inspect ceramic cores for all sectional profiles and features, considering the difficulty in orienting the component and time required to generate data. However, dimensional qualification of 100 % cores is needed from the point of view of casting, to assure higher yield. Nest fixtures based on 3-2-1 datum referencing methodology are developed, where 6-point locating fixture accurately orients and locates the ceramic core. Inspection reference is taken on the perpendicular planes of the fixture itself and a quick check on a limited number of pre-defined points will be sufficient for every core qualification.

D. Reference Grinding Fixture

Location of ceramic core in a pattern die requires precise reference surfaces, which are difficult to achieve in ceramic processing. Usually, a suitable clipping allowance is added to the core print during the design of the component. A specially developed grinding fixture is used to orient the component in a 6-point method, firmly clamped and reference surfaces are ground to make the component suitable for locating in a pattern die.

VII. CONCLUSIONS

Tooling development related to ceramic cores for aerofoil shaped hollow blade/vane castings for aero-engines is a highly involved process. Shrinkage and warpage compensation being a ceramic mix and component geometry specific factor, every blade design requires an experimental approach to accurately predict the value, wherein rapid prototyping and soft tooling techniques can be fruitfully employed. Volume production, however, necessitates development of injection moulding dies of hardness close to 60 HRC. Also, the tool designer has to address problems related to inspection and allied tools requirement to successfully help in ceramic core development.

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