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Direct casting of Rapid Prototyping resins for luxury production: influence of burn-out and processing parameters on the final quality

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Abstract*— Jewelry and fashion industry has shown and increasing interest towards Rapid Prototyping (RP) techniques as an answer to several design challenges, both for the production of final components and as a tool in the traditional investment casting process. Even though RP allows the production of complex patterns to be used for direct casting this opportunity is not fully exploited at the moment, mainly due to a lack of knowledge on the material properties and proper processing conditions. Being the traditional investment casting process required to be adopted, studies have been conducts either to modify resin properties or to reconsider or adapt process parameters. The understanding of resins properties and their mutual relation with process conditions and materials is an additional critical aspect, representing the ideal starting point for the process optimization. Aim of this work is to focus on the use of RP resins in the luxury casting. Through the materials characterization and the analysis of their properties, the limits deriving investment and burn-out are identified and process criticisms overcome.

I. INTRODUCTION

Rapid Prototyping (RP) and Additive Manufacturing (AM) techniques are usually widely used into those sectors into which complex shapes and relatively low production are required. Due to its peculiarities Jewellery industry is perfectly matching the opportunities offered by AM techniques, exploiting the possibility of producing unique designs.

Moreover market studies have shown that the demand for jewellery has become more and more fragmented and the future market will increasingly be driven by more demand for bespoke, personalised and innovative design of high quality jewellery [1]-[3], resulting in the need for extreme flexibility, ability to respond rapidly to changing demands, and implementation of a streamlined product development and manufacture process. The most important technology in production of gold jewellery and of fashion items is investment casting (~80% of gold jewellery production and more than 50% of the non precious items applied in the fashion sector). Characteristic traditional features of this branch are large series of items to be produced with a minimum of costs and in short times (providing high flexibility)[4]. A flow chart diagram of the traditional investment casting process is show in Figure 1.

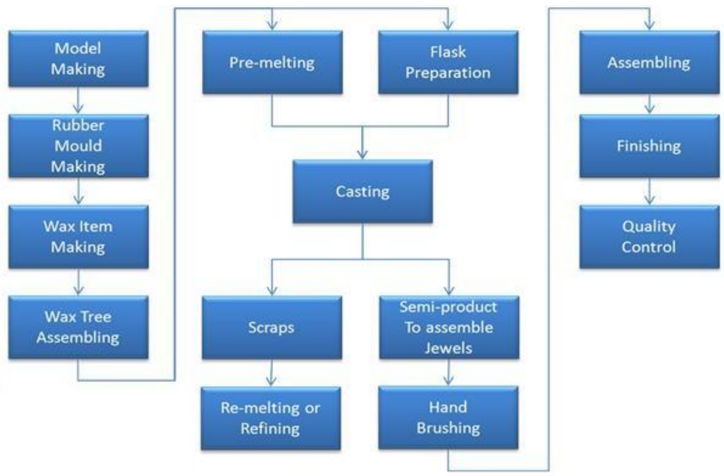

Fig. 1 Investment casting process flow chart

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The process starts with the preparation of a metal prototype by handcrafting based on a sketch or drawing, followed by preparation of a rubber mould which is then used to produce wax pattern. The waxes are assembled on a so-called tree or grape and invested in a refractory mould material (investment material). The moulds are dried, de-waxed by moderate heating and are ready for casting after burnout at high temperature.

Moving from a traditional sector, where handcraft skills were the key point of a quality production, into a more industrialised sector, CAD design and RP techniques became more and more interesting for the jewellery industry, allowing the time-efficient realization of highly innovative, personalized and unique design. In many manufacturing companies CAD data are then transferred to Rapid Prototyping equipment which allows for fabrication of pattern directly from the CAD data [5]. The RP processes, mainly represented by wax 3D printers and stereo-lithographic apparatuses, are most of the times fully integrated into the traditional process, either to produce the master model or to produce replicas to be directly assembled on the tree. This last process, commonly referred to as "direct casting" is highly interesting opening several possibilities in terms of shapes and production flexibility.

Besides some wax 3D printers are used, great interest is oriented towards the use of stereo-lithographic systems, thanks to their well-known accuracy and reliability, building up pattern geometries that are much more detailed and filigreed than those that can be obtained by the traditional wax pattern fabrication technique [6]. Obtaining right process conditions for direct casting of rapid prototyping resins will mean being able to obtain high quality jewellery with a more personalized and innovative design.

The wide application of these techniques to the jewellery production has been mainly hindered by two factors [7]:

- The de-waxing/burnout step does not work for moulds where Rapid Prototyping waxes or resins are used; leading to ash-residues in the mould after burnout. The so-called 'direct casting' with Rapid Prototyping waxes/resins then suffers from severe porosity in castings, caused by reaction with the investment that is catalysed by the ash residues in the mould. Another severe problem exists with cracking of mould material during heating due to incompatibility of thermal expansion of these types of waxes/resins and the investment [7]-[9].
- The design created by the technology is extremely difficult-to-cast with complete form-filling due to the detailed, filigree nature of the design. There is a lack of scientific knowledge about the complex interrelationships between casting process and equipment parameters, alloy and investment material properties, sprue and gating geometries and the desired outcome: laminar metal flow, minimum turbulences during pouring and complete pattern filling [10],[11].

Several studies, have been carried out to understand the relationship between RP patterns and investment casting outcomes, trying to overcome problems related to burning out of moulds containing RP resins and obtaining a good surface quality of cast and surface finished patterns, which has been identified as one of the major goals in many market analysis [12]-[14]. A way to fit standard investment casting process to the use of RP resins, mainly focusing on the adjustment of burn-out cycles, was also investigated [15].

Burn-out is recognized as one of the most critical steps for both traditional and resins investment casting. This step is influenced by several parameters, recognized to highly influence the final result and are commonly optimized in traditional casting to get better final results, among them the main are investment powder composition, water/powder ratio in the investing process and the burn-out cycle [16].

Several studies, as [17] and [18], have been demonstrated that commonly used $CaSO_4$-bonded SiO_2 refractories are highly sensitive to presence of carbon residual or reducing atmosphere, lowering their decomposition temperature. Calcium sulphate decomposition is one of the main sources of gas porosity in the investment casting process, leading to the production of unacceptable components.

Aim of this work is to give an overlook on the thermal behaviour of resins and their thermal degradation and merging those results with those obtained via practical experiments and casting trials. This approach is aiming to give an understanding of the mechanism taking place during the burn-out step and transfer this information into real operative advices.

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II. EXPERIMENTAL

Dealing with a traditional process, mainly characterized by handcraft skills and knowledge, a dual approach has been followed, coupling an analytical examination of material properties with casting trials. Thermal and physical information on the materials involved helps in the understanding of mechanism taking place in the process; experimental trials are then needed to translate into a macroscopic scale what observed through scientific analysis.

A. Materials Analysis

After preliminary analysis, considering a wide range of rapid prototyping resins specific for the direct casting into the jewellery process, two specific materials showing good compatibility with the process have been selected.
Polymers properties are strictly related to their chemical nature. In order to completely characterize the selected material considering the final application a key point is analysing its thermal behaviour. Thermal analysis studies the effect of temperature on the intrinsic properties of a polymer, leading to the determination of its working temperature, glass transition, melting point and degradation behaviour. Differential Scanning Calorimetry (DSC) analysis has been performed using Q20 TA Instruments. Additionally, to determine degradation temperatures and burning residual, thermo-gravimetric analysis (TGA) has been carried out using Q500 TA Instruments equipment. The expansion of the resins has also been analysed. The importance of the parameter in the final quality of the patterns has been clearly demonstrated in a previous work [8]. Material tendency to change volume in response to a temperature change can be measured deriving a coefficient of thermal expansion, obtained as the volume to temperature change ratio. This property has been investigated using Perkin Elmer Dilatometer Equipment. Expansion was tested on samples built both in longitudinal and transversal direction in order to detect any anisotropic behaviour of material and construction method.

Another key-point is the understanding of the mutual interaction between resins and investment. A practical experiment has been set up in order to further deepen the knowledge of this materials coupling. After burn-out, flasks were cooled down and cut, cavities were investigated using scanning electron microscopy (SEM) coupled to EDS.

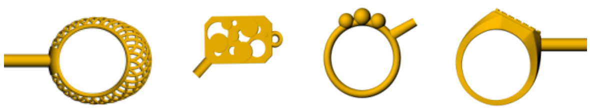
B. Casting trials

A standard tree configuration has been set-up using different patterns' features in order to test both massive and filigree-like objects, big and small sections, curved and flat surfaces.

Analysed parts consist of three different rings, reproducing filigree-like patterns, massive objects and section changes and one pendant. In the following table 1 pattern are classified according to their thickness, identified with an Area/Volume index [19].

This ratio, usually used in the sand casting process, is enabling to get and evaluation of selected pattern accordingly to their volume (resin content) and the surface exposed towards the investment and thus exposed to possible reactions.

Table 1 Identification and Area/volume index value for patterns used.



A/V index	3.45	2.05	1.64	1.48

Patterns have been produced using DIGITALWAX 029, blue laser stereo-lithographic rapid manufacturing system, with a slicing size of 30 µm, a medium low value that represent a good compromise between geometry accuracy and building speed using to commercial resins identified as Resin A. A surface evaluation of the obtained parts has been performed, paying attention to surface smoothness, detail reproduction and defects recurring in the castings.

The standard tree is composed by 6 objects, with light patterns (high area/volume index) at the top and heavy patterns (low A/V index) at the bottom. All castings have been performed using standard Sterling Silver.

Preliminary computer simulation works provided the optimization of sprue systems, casting and flask temperatures [10], [11]. Process conditions in terms of UV curing and feeding system were set following optimized conditions demonstrated in [14].

Castings have been performed using Topcast TVC10 vacuum pressure casting machines, metal and flask temperatures set at 985°C and 500°C respectively. Standard 100x150 mm (3.94x5.91 in) flasks have been used; investment was prepared using vacuum mixer. As pointed out in other studies [8] , [9] when direct casting resin patterns, the most critical step is the de-waxing/flask burn-out.

Two different investment powders have been tested, a specific “resins-casting purpose” investment, designed for having high expansion and high strength (investment A) and a “high quality” general purpose investment (investment B). Both materials were tested with different water/powder ratio: 36:100, 38:100 and 40:100. Optimization of W/P ratio for each investment was carried out using the producer recommended burn-out cycle. Using optimized investment conditions, different burn-out conditions have been tested.

Burn-out cycle 1 (BO1) consists of three different dwells at 150°C, 400°C and 750°C, reached with an average superimposed speed of 1.9 °C/min and kept for 4 hours, flasks are then cooled down to casting temperature. Flasks handled according to Burn-out 2 (BO2), 2 hours before casting, were turned upside down with the feeding system on the top. BO1 and BO2 were carried out in a Nabertherm furnace equipped by forced ventilation system.

Burn-out 3 (BO3) was carried out same as BO2, but in static furnace. Thermal profile of the two furnaces has been measured via thermocouples during the whole process in order to ensure the same thermal profile during the cycle. Cast parts obtained in different conditions have then undergone surface analysis, using stereo-microscope; LEICA ME5 microscope with 6.3X magnification has been used. Patterns also underwent metallographic inspection, after cutting, mounting and polishing.

Taking into account the actual burn-out conditions and the interactions between resins and investment, some practical analysis have been carried out in order to further deepen the knowledge of the process.

III. RESULTS

A. *Resin Analysis*

A scientific approach to physical and chemical characteristics of polymeric materials allows to get information on their properties and can lead to a better understanding of the direct casting of resins.
The following Figure 2 reports in detail the thermal analyses carried out.

a

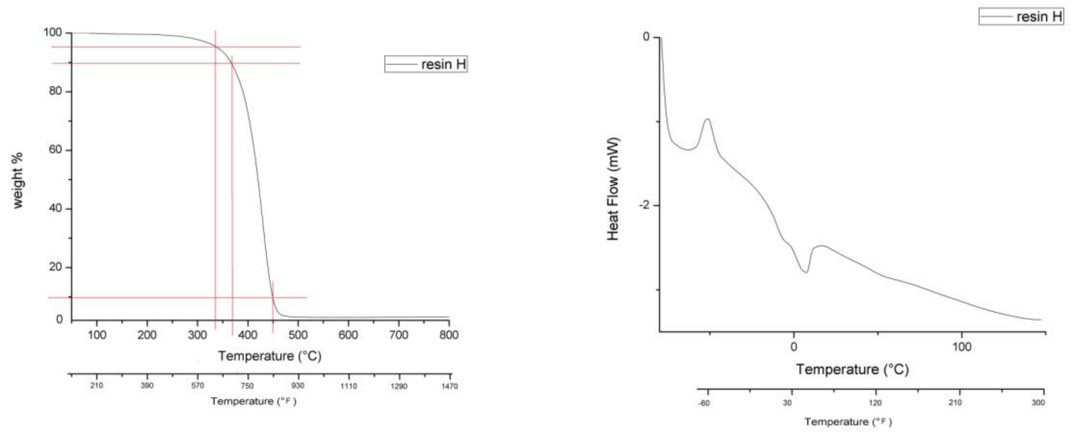


Fig. 2 TGA and DSC analysis of Resin A

In order to have additional information on the degradation process of the resin material, some coupled TGA-IR analysis were carried out, sampling decomposing gases and analysing their composition. Considering Resin A,

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obtained results show a higher rate of decomposition at 400°C where peaks analysis reveals the presence of moisture, radical groups and CO_2.

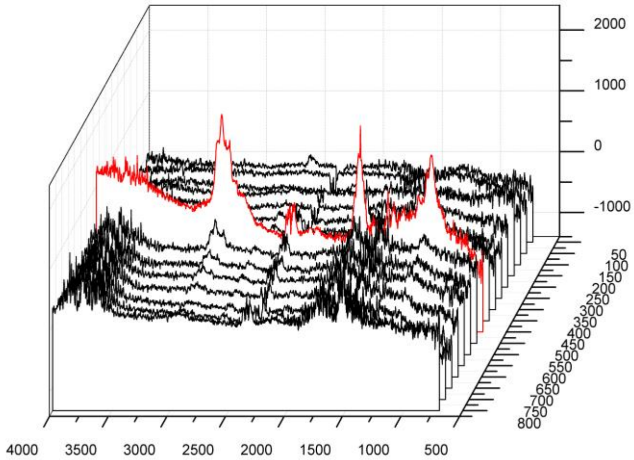

Fig. 3 Infra-Red analysis of the decomposition gases sampled during TGA of selected resin.

Dilatometric analyses have been carried out on two different samples, built in transversal or longitudinal directions in order to detect any anisotropic behaviour of the system or of the material itself. No significant differences have been detected between the two samples. In the following picture the thermal expansion coefficient (CTE) of resin A is plotted versus temperature.

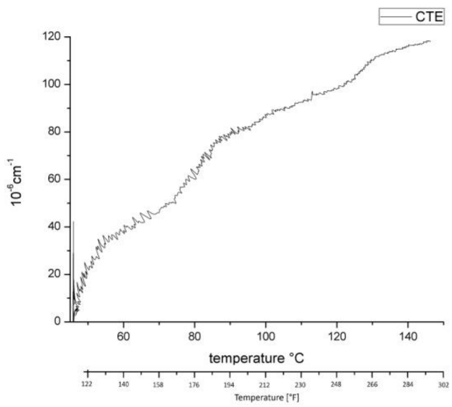

Fig. 4 Coefficient of thermal expansion vs. temperature.

CTE analysis shows two different trends of expansion: at first a higher rate of expansion up to 80°C, then the second one with a lower rate from 80°C

B. Casting trials

Investment

Water/powder ratio is an important parameter in standard lost wax casting and it becomes even more critical considering the direct casting of RP resins. Several castings have been performed using flasks prepared with different w/p ratio, varying it in the range of suggested values in order to cover both light and heavy patterns conditions. For medium-light patterns an increasing of the water content in the investment results in a rougher surface. W/P ratio effect was considered for both investments A and B. In the following Fig. 5 a comparison between 36:100, 40:100 water /powder for investment B and 40:100 for investment A is reported.

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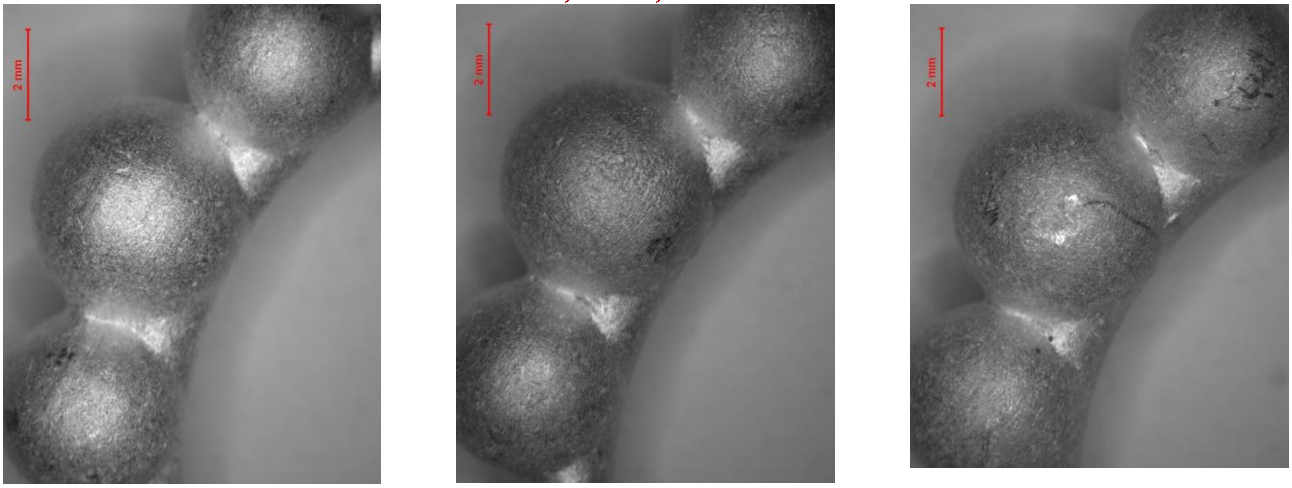
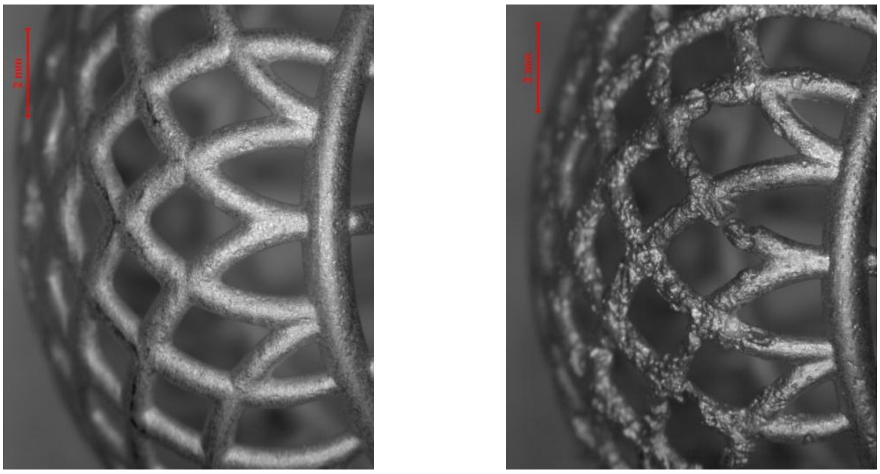


a) *b)* *c)*

Fig. 5 Surface details for cast sphere rings obtained using 36:100 (a) and 40:100 (b) water/powder ratio on general purpose investment B and 40:100 (c) on specific investment A.

The behaviour is even more amplified when considering light patterns, such as the filigreed ring shown in Fig. 6, representing a critical object due to its higher Area/Volume index. Filigree like objects tend to be more subject to resin/investment interactions due to their higher specific surface.



a) *b)*

Fig. 6 Surface details for cast cage rings obtained using 36:100 (a) and 40:100 (b) water/powder ratio on general purpose investment B.

Burn-out cycle effect

Burnout cycles are a key part of the process. Water present in the investment needs at first to be eliminated effectively, trying to prevent its absorption by the resin parts (potentially deforming the surface of the mould). However the correct burning of the resins and the following disposal of the ashes has to be achieved. In traditional castings, the use of furnaces equipped with fan for air recirculation during burnout may provide different results in terms of quality of final pattern. It is then highly interesting to investigate the influence of such convection, specifically on resin direct casting.

The choice of burnout cycle should consider parts of which the tree is made up of, finding a balance between the output obtained on “heavy” thick parts and ”light” filigree-like ones. Most-likely one burn-out could give exceptional results on thin parts, performing poorly on heavy pieces. The following Fig 7 shows the comparison of casting results on a light flat pattern for different cycles.

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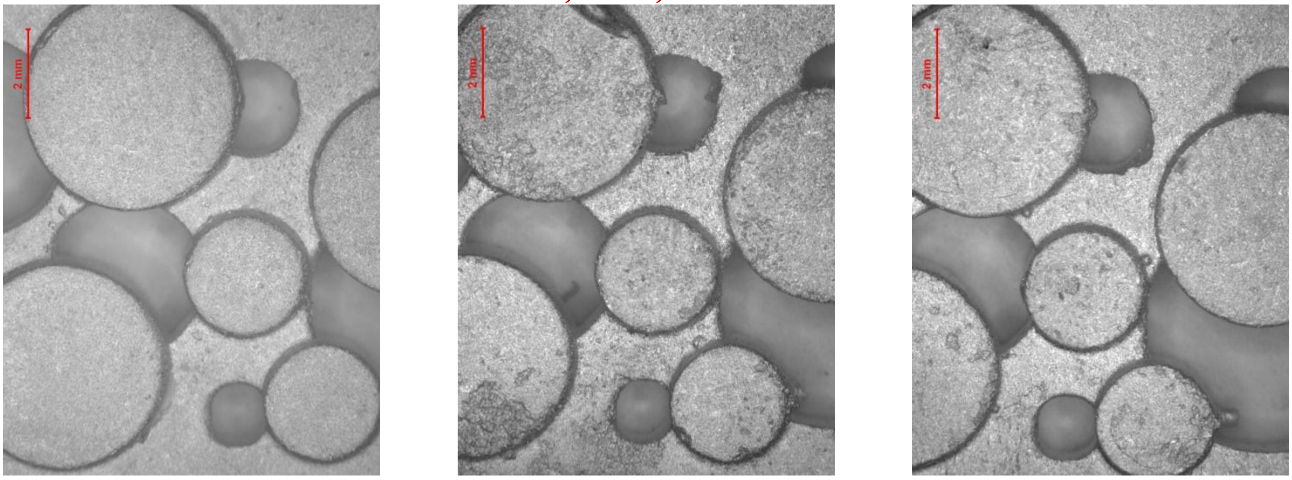
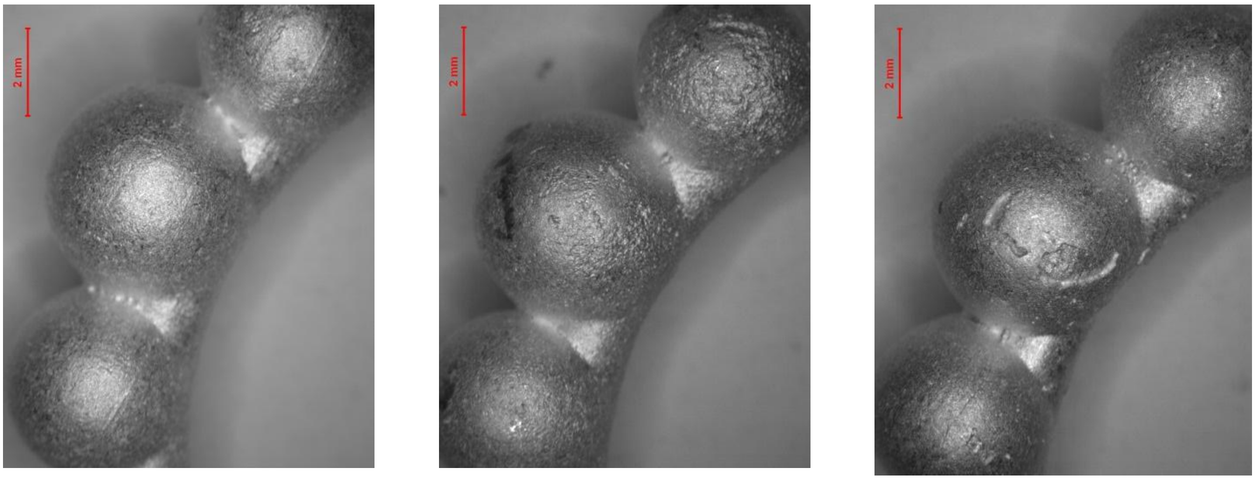


a) *b)* *c)*

Fig. 7 Surface quality of flat patterns obtained with BO1(a), BO2(b)and BO3 (c) cycle, using investment A at 38:100 w/p.

Surface quality worsens in case of no forced ventilation in the furnace. Comparison between BO1 and BO2, same average temperature increase rate and furnace conditions, shows strong differences: this is probably related to flask turning at the end of the cycle and better atmosphere interchange while opening the furnace. A similar approach is used to identify the best cycle for heavier patterns.



a) b) c)

Fig. 8 Surface quality of heavy ring patterns obtained with BO1(a), BO2(b)and BO3 (c) cycle, using investment A at 38:100 w/p.

Considering medium-heavy patterns, the use of a non-convection furnace results in rougher surface of the cast parts. The advantage of using a convection furnace clearly reflects also on the final surface quality and porosity of the cast parts: the removal of carbon residual and of the (resins) decomposition gases seems to be highly improved. Gas porosity content has been evaluated through metallographic investigation.

C. Investment Analysis

Investment analysis

In order to have a deeper understanding of the mechanism taking place during the burn-out and of the mutual interaction between resins and investment a practical experiment has been set up. Cutting cavities before the casting and observing them via using SEM and EDS. Investment analysis were carried out in the same conditions considered for the casting trials. EDS analysis carried out on the internal cavity, didn't detect presence of any carbon residual of ashes, but variable ratio in terms of $SiO_2/CaSO_4$ content.

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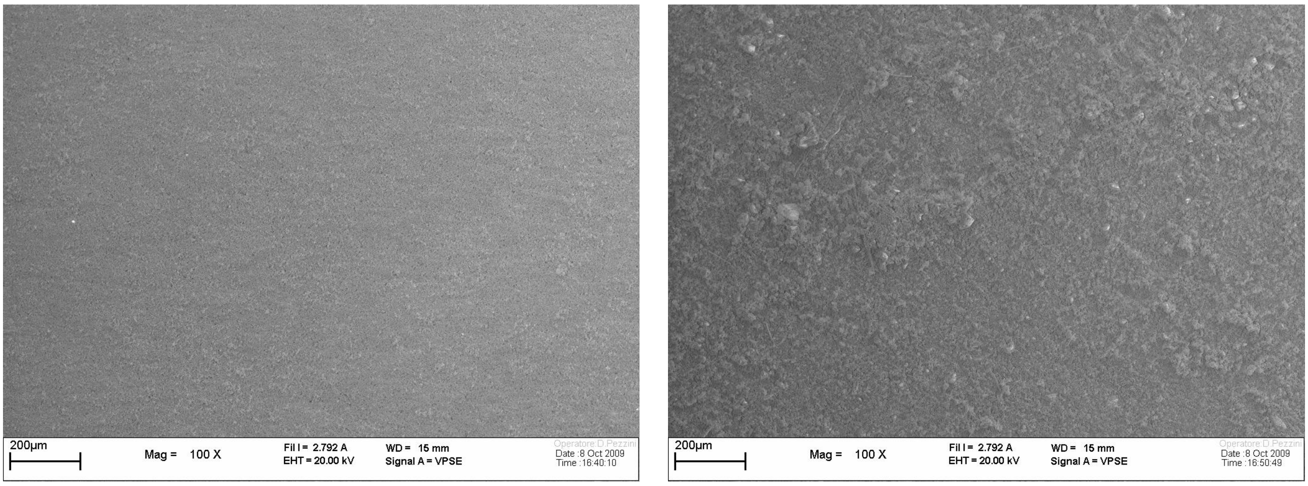
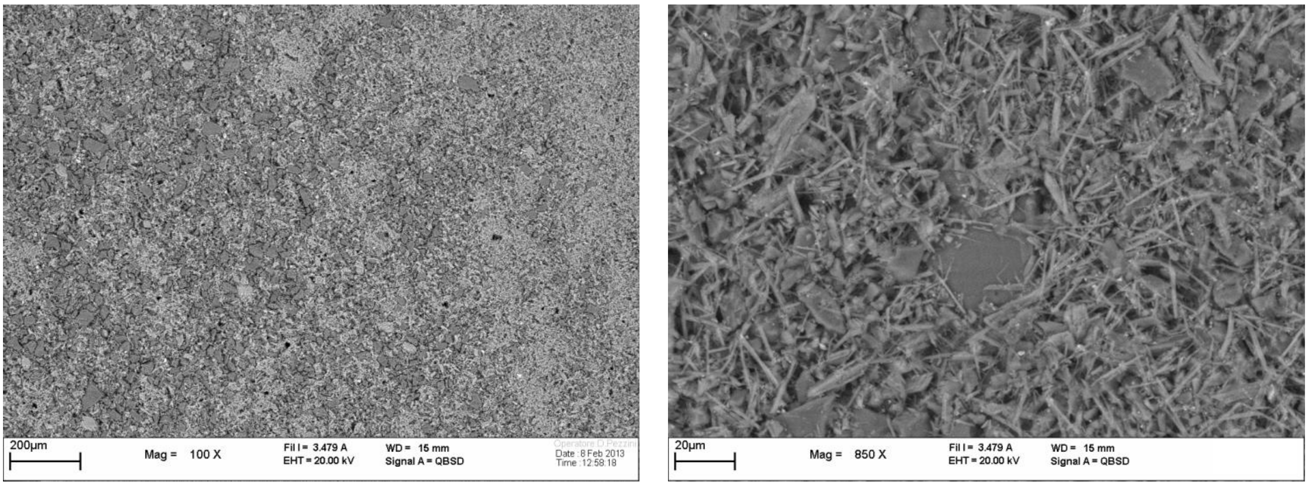
Following Fig. 9 is showing a morphological observation of the internal cavity derived from a massive resin. Flask was burnt-out performing cycle BO1with 38:100 (a) and 40:100(b) w/p ratio on a general purpose investment material.



a) *b)*

Fig. 9 SEM analysis of investment cavity obtained with 38:100 (a) and 40:100(b) w/p ratio

As for casting, the opportunity of different burning-out conditions has also been evaluated on investment analysis. Following Fig. 10 is showing the result obtained performing BO3 cycle on a 38:100, general purpose investment. In this case it easily detectable and altered area with rougher surface. Morphological analysis carried out using back-scattered electrons allows to identify surface non homogeneous areas.



a) *b)*

Fig. 10 SEM analysis of investment cavity obtained with 38:100 w/p ratio with BO3 cycle.

The investigation has led to the identification of a reaction layer into the investment, where some degradation mechanisms took place. The previous Fig. 10 (b) is showing a degraded area where silica lamellae, usually coated by a homogeneous CaSO4 layer, are exposed into the internal cavity showing a degradation of $CaSO_4$ binder in the case of non-ventilated furnace.

Merging results deriving from practical casting trials and those obtained in analytical way it is possible to derive some interpretations of the degradation process.
As shown in the TGA-IR diagram, the decomposition of the resin is producing CO_2. These conditions are however not always replicated into the real process where a shortage of oxygen supply may happen, mostly when the atmosphere in the furnace is not renewed. Thus, when optimal conditions are not fulfilled, instead of full

degradation into carbon dioxide, partial pyrolysis takes place and carbon monoxide is produced. Being CO lighter then CO_2 and air, it is presumably trapped into the cavity when flask is top down. Trapped gas is enhancing the thermal degradation of the investment, usually catalysed by the presence of carburizing atmosphere, mainly in the case of weakly bonded materials (high W/P). These two phenomena are a possible interpretation of the benefits deriving from the use of convection furnaces coupled with flask turning at the end of the burn-out cycle. "Ad hoc" process condition is so enabling the obtaining of good final quality on the cast parts.

IV. CONCLUSIONS

The knowledge of materials characteristic and properties is fundamental when introducing a change in the traditional production process. In fact, despite having demonstrated that with a good resin excellent results may be achieved, even the use of an excellent resin does not guarantee itself a final good result. Several complex reactions occur during the process and most of all there is the interdependency among the effects of different materials behaviours at high temperature and the following step of production. Burn-out represents a key part of the process: first of all the water has to be eliminated effectively, trying to prevent its absorption by the resin parts (potentially deforming the surface of the mould); then the correct burning of the resins and the following disposal of the ashes has to be achieved. The "right" cycle has to be accurately balanced within its temperature steps in order to address these issues, also according to the size/shape of the patterns mounted on the tree.

Using "ad hoc" processing conditions, impossible to be derived without having properly analysed the behaviour of the materials involved in the process independently and mutually, can therefore lead to high final quality of the as cast patterns, not necessarily distorting the process, but through a proper fine tuning in order to suit to the resins requirements.

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