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CASTING FLOW DYNAMICS IN THE INJECTION MOULDING SYSTEM OF CERAMIC MATERIALS

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ABSTRACT

The aim of this work is to qualitative assess the hydro-dynamic mechanisms which regulate the flow of the ceramic mass inside the cylinder during the pressing phase of the injection moulding system, through the comparison of different hinging methods. Three different hinging methods were compared: straight bar; straight bar with variable section; shaped "spiral" bar. Each sample was made of wax, surrounded with refractory coating material, preheated and then positioned in the pressing furnace. Two ceramic roughs of different colours were sectioned and reassembled to obtain a unique ceramic rough made of two different colours. The castings were then recovered, photographed and analyzed. The macroscopic evaluation of all the pieces revealed the absence of bubbles or missing parts. In all the samples, it was possible to recognize clearly the colour difference between the two masses used for pressing: the presence of curvatures or section's variations in the casting channels did not jeopardize the complete filling of the mould by the material, the formation of bubbles or missing parts. Only the T bar specimen showed perturbation in the ceramic flow. The results show that there are no qualitative differences in the various hinging methods for the injection moulding of ceramic materials.

KEYWORDS: dental ceramics; injection moulding systems; flow dynamics; hinging methods

LIST OF ABBREVIATIONS:

A = area (m^2)
g = gravity constant (m/s^2)
h = height (m)
l = length (m)
P = pressure (N/m^2)
Q = flow (m^3/min)
r = radius (m)
Re = Reynolds' number
v = velocity (m/s)
η = viscosity (Pa·s)
ρ = density (kg/m^3)

Other eventual abbreviations are indicated at their first appearance in the text.

1. INTRODUCTION

Ceramics are widely used in restorative dentistry because of their characteristics of low thermal conductivity, abrasion resistance and biocompatibility [1,2]. The mechanical and aesthetical characteristics, as well as the relative facility of use have undoubtedly provided the greatest contribution to the diffusion of this class of materials. Today the construction of ceramic restorations is part of the routine of all dental laboratories.

Over the years, several authors have proposed different processing techniques in order to improve the mechanical qualities of ceramic restorations, or to ease the working of the material. McLean and Sced, in 1976 [3] proposed a technique for the realization of the restorations that foresees the sintering of the material on a platinum matrix (sheet) adapted by hand on the stump. Tanaka and Clark, in 1988 [4–6] suggested the adaptation of a gold sheet to the stump by means of a working cycle in an isostatic chamber containing a high viscosity liquid. Adair and Grossman in 1984 [7], proposed the use of lost wax casting for the construction of restorations without metallic structure: the technique involved the use of a glass material reinforced with mica crystals that was poured by centrifugation in a mould made in phosphate-binder refractory material. In the late ‘80s, Wohlwend and Scharer [8] introduced the high temperature injection moulding technique using a ceramic material reinforced with leucite crystals. This technique provides, similarly to what happens for casting glass-ceramic, the realization of a wax model, which must be hinged and subsequently coated with a phosphate-based refractory material. However, unlike the cast glass-ceramic, the injection of the ceramic material inside the cylinder is carried out using a dedicated apparatus equipped with controls on the variables time, pressure and temperature. Nevertheless, all these techniques have not been widely widespread due to their complexity and uncertain results on marginal accuracy [8–13].

The introduction of resinous materials has contributed to the resolution of problems related to marginal adaptation, even in the long term [14], significantly implementing the system's diffusion. Today it is possible to manufacture products with metal framework using, for the aesthetic covering phase, the high-temperature injection moulding technique rather than the conventional layering technique. The presence of the metal structure makes it possible to create products designed according to conventional criteria; moreover, the use of a technique that allows the reproduction of a wax model is particularly useful, since it is possible to reproduce in a faithful and fast way the occlusal scheme designed during the diagnostic waxing phase. The formation of conventional opaque ceramics for direct injection on metallic structures allows improving the predictability of the results in complex rehabilitations; furthermore, these systems allow reducing the production costs and standardizing the laboratory phases. The modern approach to prosthetic rehabilitations of the oral cavity requires a careful diagnostic waxing. This initial project is necessary for the reduction of the abutment teeth through the cutting guides and for the realization of provisional crowns. These aids allows to verify the occlusal scheme designed in the waxing, before proceeding, if the clinical response is favourable after 3 or 6 months, to the realization of the final product. The diagnostic waxing can be fully exploited with the injection technique since, besides guiding the realization of the metal framework, it can allow the exact moulding of the occlusal patterns obtained through the injection of the ceramic. Regarding the aesthetic aspects related to the lack of ceramic layering, remarkable improvements have been brought about the introduction of different masses for colour chrome, value and shade. The paramount aspects in a casting system are the morphology and the size of the pouring channels [15,16].

To the authors’ knowledge, no study in literature analyzed the methods of pivoting in ceramic casting systems and their effects on the ceramic flow dynamics. Therefore, the aim of the present work is to conduct a qualitative analysis on the hydro-dynamic mechanisms that regulate the flow of the ceramic mass inside the cylinder during the pressing phase of the injection moulding system, comparing different hinging methods.

2. MATERIALS AND METHODS

Three different pivoting methods were compared, so were created three main samples of simplified hinging morphology and then various samples with more elaborate morphology.

The three main samples were:

1. Straight bar (sample 1) of 15 mm in length and 5 mm in diameter (Fig. 1);
2. Straight bar with variable sections (sample 2) of 6 mm of length for 5 mm of diameter, a narrowing to 3 mm of diameter for a length of 6 mm, and a further widening to 5 mm of diameter for 3 mm of length (Fig. 2);
3. Shaped bar according to the "spiral" system (sample 3) with a constant section pin of 4 mm for a length of 40 mm (Fig 3).

Each sample was made of wax by the same calibrated operator; the coating material (Imagine h.e. Press, Pforzheim, Germany) was prepared according to the instructions provided by the manufacturer and was poured into the cylinders in order to obtain one cylinder for each sample. After the coating’s toughening, the cylinders were placed in a preheating oven (k9 ewl, KaVo, Biberach/Riß, Germany), preheated for 60 minutes at 850 ° C and left for further 60 minutes to obtain the complete elimination of the wax. The cylinders were then positioned in the pressing furnace, which was also preheated to 700 ° C.

To evaluate the flow dynamics of the material within the casting systems, two roughs of different colours were selected (Waiss and MT5, Imagine h.e. Press, Wieland Dental + Technik GmBH & Co., Pforzheim, Germany) (Fig. 4); each cylindrical rough was cut in half lengthwise. The halves were coupled to reconstitute an entire ingot made of two parts of different colours (Fig. 5). After forming, the castings were recovered from the refractory

coating by sandblasting at 0.15 MPa with plastic balls. All samples were photographed and analyzed using Image J 1.32j software (Wayne Rasband National Institute of Health, USA).
The materials used for the study are listed in Table 1.

Table 1 Materials used for the study

Type	Name	Producer/distribution
Ceramic	Imagine h.e. Press	Wieland, Pforzheim, Germany
Pre-heating oven	KaVo k9 ewl	KaVo, Biberach/Riß, Germany
Image software	Image J 1.32j	Wayne Rasband, National Institute of Healt, USA

Fig. 1 – Straight pouring channels

Fig. 2 – Channel with variable section

Fig. 3 – Spiral-casting channel

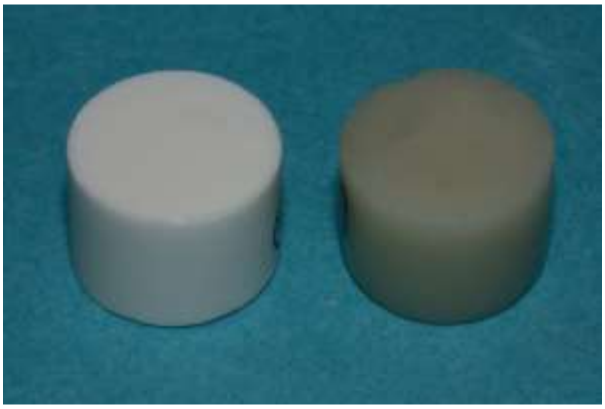

Fig. 4 – Roughs before the separation

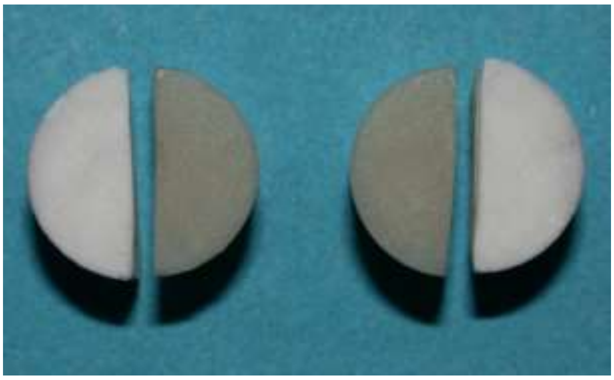

Fig. 5 – Roughs after separation along the longitudinal axis

3. RESULTS

The macroscopic examination of the pieces detected the absence of bubbles or missing parts. The complete filling of the mould by the material was not prevented neither by the presence of a variation of the section related to the casting channel nor by the presence of curvature (Fig 6-7-8A-8B). In all the samples (1, 2, 3) it was possible to recognize the colour difference between the two masses used for pressing in a clear and precise way (Fig. 9); in the samples with morphology that was more elaborate the masses did not mix along the whole casting channel (Fig. 10-11A-11B-12). In T-shaped systems there are no substantial differences, too (Fig. 13).

Fig. 6 – Straight channels after casting

Fig. 7 – Channel with variable section after casting

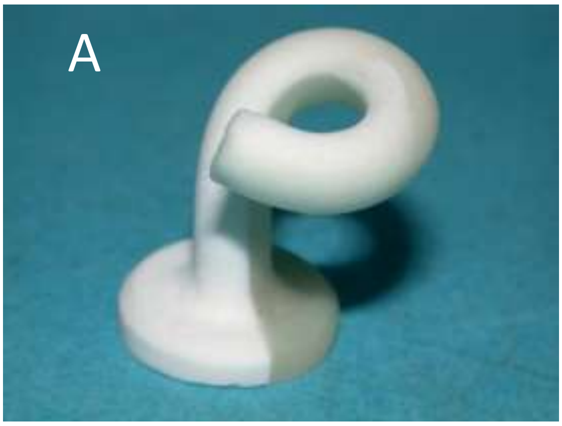

Fig. 8 (A, B) – Spiral channel after casting

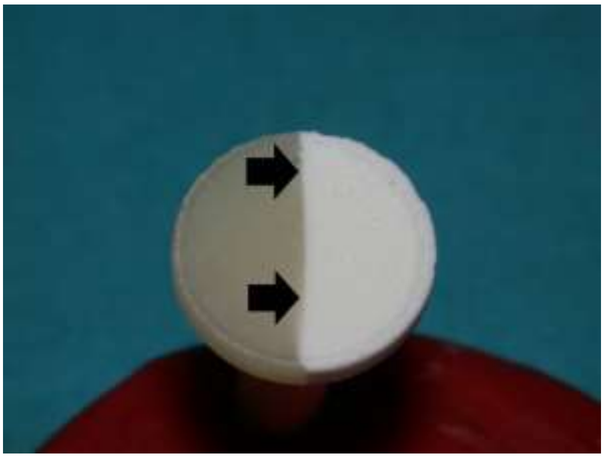

Fig. 9 – The casting button clearly showing the two roughs division (black arrows), maintained after casting

Fig. 10 – Example of casting with variable section channel and horizontal plate. The black arrows show the limit between the two materials. There are no evident areas of high turbulence

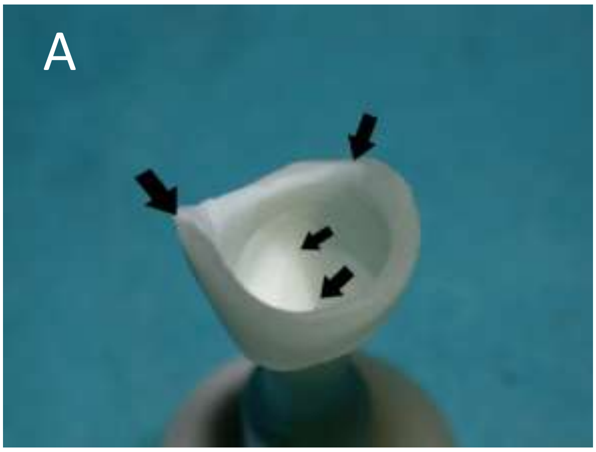

Fig. 11 – (A) The black arrows show the two materials well separated on a cap. (B) Global view of the pouring channel and the cap

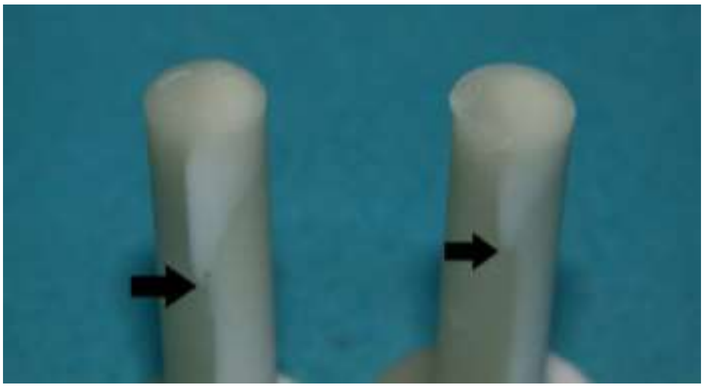

Fig. 12 – A modest turbulence area caused by the backscattering of the material in straight pouring channels (black arrows)

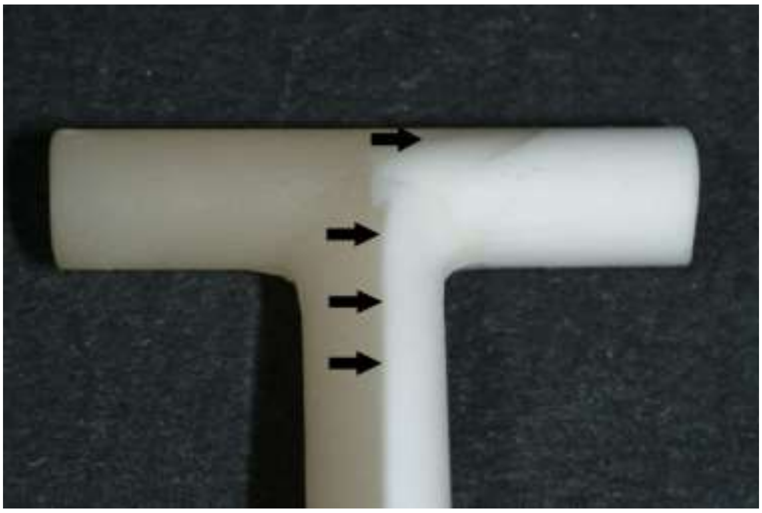

Fig. 13 – In the T-bar system can be observed the same reaction of the direct pin system (black arrows)

4. DISCUSSION

From the results' analysis, it can be observed that sudden variations of section and direction do not represent a significant problem for high-viscosity and low-density materials like the melted ceramic (Fig. 14).
They otherwise can constitute a problem in casting molten alloys with low viscosity and high density. Both in the samples with simple morphology and in those with a diversified morphology the introduction of variations in the section of the casting channel, in fact, does not introduce turbulence in the motion of the material inside the cylinder. Only at the terminal portion of the jet can be detected a slight tendency towards the mixing between the differently coloured parts (Fig. 15). It has to be pointed out that in the T-shaped systems, the use of less material than required by the piece to be cast entails a difference in the behaviour of the flow dynamics. In the highlighted case (Fig. 16A-B), the absence of reaction forces due to an insufficient thrust bore by the lack of material provoked an appreciable perturbation in the ceramic flow.

Fig. 14 – Global view of all the analyzed sophisticated systems

Fig. 15 – The median section of the straight pin shows a good conservation of the laminar motion of the materials during casting procedure (black arrows)

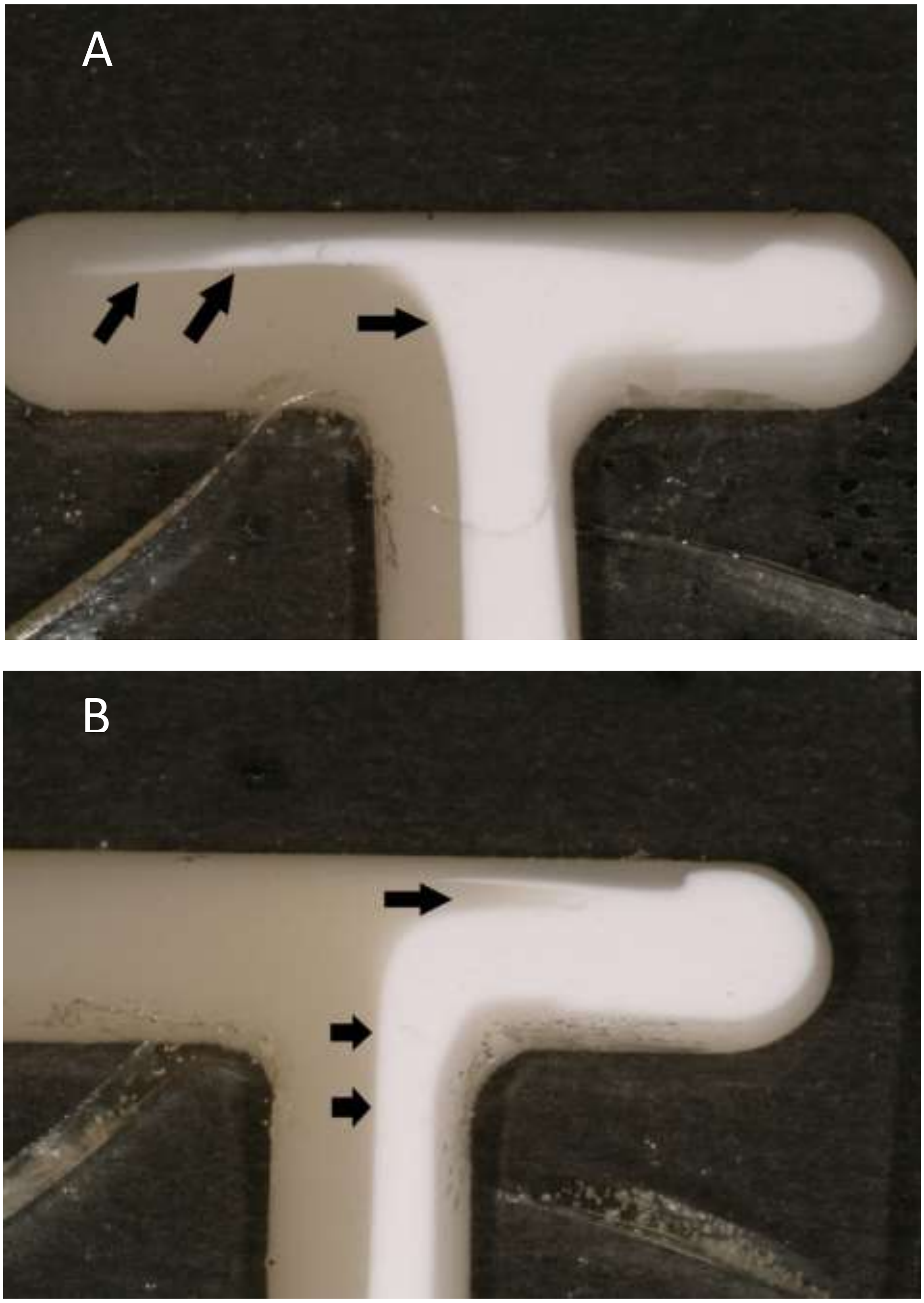

Fig. 16 (A, B) – T-bar casting system with an insufficient amount of material. The areas of material with different colours are evident, indicating the presence of turbulence during casting (black arrows).

The high-temperature pressing techniques exploit the same principles of lost wax casting. Although they are widely applied in daily practice, in the literature scenario they are poorly considered under the hydro-dynamic profile.

The defects that normally make a conventional casting incongruous are often related to the wrong position of the wax model inside the cylinder and/or to the fact that the molten alloy moves with a turbulent flux rather than laminar flux [15,16]. The existence of turbulences is often due to the incorrect evaluation of the dimensions of the casting channels. The diameter has a pivotal influence on the flow of the alloy. From the law of Hagen-Poiseuille, it is clear that the flow of a *real* fluid is directly proportional to the fourth power of the radius of the conduit and is inversely proportional to the length of the cylindrical channel:

$$Q = \frac{\Delta P \pi r^4}{8 \eta l}$$

In other words, the radius has a major influence with respect to the length of the conduit on the flow of the molten metal. In correspondence with a minimal shrinkage of the channel, therefore, a considerable reduction of the flow can be obtained. Moreover, at the level of a bottleneck, a shrinkage increases the speed of the molten alloy (hypothetically assuming that it behaves like an *ideal* fluid: incompressible and with a null coefficient of viscosity), according to the continuity equation:

$$Q = Av = costant$$

The increase in the speed with which the alloy flows inside the mould is only apparently a favorable factor: it represents only one of multiple factors on which the dimensionless Reynolds' number (*Re*) depends. From the calculation of the Reynolds' number, it is possible to determine if the motion of a fluid inside a circular duct is laminar or turbulent. In fact, Reynolds' law establishes that:

$$Re = \frac{2r\rho v}{\eta}$$

The factors on which the Reynolds' number depends are represented, therefore, in addition to the velocity of the fluid (v), the radius of the conduit (r), the coefficient of viscosity of the fluid (η) and its density (ρ). Experimental evidence shows that inside a duct with perfectly smooth walls, the flux of a fluid becomes turbulent if the value of Re is higher than 2000, this limit drops to 500 if the walls of the channel are rough or if its diameter presents abrupt variations. Experimental evidence reveals also that during the casting of molten alloys through centrifugal system the laminar flow is present when $Re < 2000$ and the turbulent flow appears when $Re > 3000$, instead [16]. In the high-temperature injection moulding system, the melted ceramic is pushed into the cylinder by a force that derives from the vector sum of two competing vectors, represented by the force of gravity and the force exerted by the piston. The cohesive force existing within the ceramic mass is opposed to gravity, so it prevents the material from spontaneously pouring into the cylinder. The vector generated by the action of the piston therefore becomes decisive during pressing and the mass moves in a relatively straight direction that places the preferential sector at the geometric centre of the cylinder. The presence of bends and / or section variations within the casting channels modifies the mass trajectory, generating instantaneous vectors at the interface between the mass and the cylinder wall. These vectors, considered in the context of the casting techniques of metallic materials, are undesirable because they provoke turbulences within the molten alloy; the melted ceramic, on the other hand, exhibits a different behaviour towards both the variations of the conduit section and the bends. The flow, in fact, remains laminar in all the samples and this result, considered in light of the relationship proposed by Reynolds, probably derives from the high viscosity of the mass in the fluid state and the following low speed with which the mould filling takes place. For a finer interpretation of these results, it is important to highlight that for the experimental set-up of this work, were used preformed wax workpieces of an equal diameter to those normally used in the waxing techniques for casting with metallic materials. The roughness of the inner walls of the mould was similar to the one found inside a cylinder destined to cast an alloy, too, since it depends on the interaction of the surface of the wax model with the coating material.

5. CONCLUSION

The results of the present work show that there are no qualitative differences on the flow of ceramic materials between the various hinging methods for the injection moulding system.

The introduction of alterations both in the section and in the path of the casting channel system does not generate turbulence within the melted ceramic mass. This condition is related to the fact that the ceramic in the molten state has a high viscosity, so the filling of the cylinder takes place at a relatively low speed. However, the presence of sudden variations in the section of the casting channels should be avoided due to the increase in pressure that is generated upstream of the bottleneck and the consequent possibility of cheating some pressing systems.

Finally, there is the imperative need to use a quantity of material slightly higher than required for the complete filling of the pouring channels. This in order to avoid that an insufficient quantity of material may cause an insufficient thrust (so an absence of reaction forces) into the mould that generate a considerable perturbation in the ceramic flow.

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