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A technical note on the characterization of electroformed nickel shells for their application to injection molds

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Abstract

The techniques of rapid prototyping and rapid tooling have been widely developed during the last years. In this article, electroforming as a procedure to make cores for plastics injection molds is analysed. Shells are obtained from models manufactured through rapid prototyping using the FDM system. The main objective is to analyze the mechanical features of electroformed nickel shells, studying different aspects related to their metallographic structure, hardness, internal stresses and possible failures, by relating these features to the parameters of production of the shells with an electroforming equipment. Finally a core was tested in an injection mold.

Keywords: Electroplating; Electroforming; Microstructure; Nickel

1. Introduction

One of the most important challenges with which modern industry comes across is to offer the consumer better products with outstanding variety and time variability (new designs). For this reason, modern industry must be more and more competitive and it has to produce with acceptable costs. There is no doubt that combining the time variable and the quality variable is not easy because they frequently condition one another; the technological advances in the productive systems are going to permit that combination to be more efficient and feasible in a way that, for example, if it is observed the evolution of the systems and techniques of plastics injection, we arrive at the conclusion that, in fact, it takes less and less time to put a new product on the market and with higher levels of quality. The manufacturing technology of rapid tooling is, in this field, one of those technological advances that makes possible the improvements in the processes of designing and manufacturing injected parts. Rapid tooling techniques are basically composed of *a collection of procedures that are going to allow us to obtain a mold of plastic parts*, *in small or medium series, in a short period of time and with acceptable accuracy levels*. Their application is not only included in the field of making plastic injected pieces [1–3], however, it is true that it is where they have developed more and where they find the highest output.

This paper is included within a wider research line where it attempts to study, define, analyze, test and propose, at an industrial level, the possibility of creating cores for injection molds starting from obtaining electroformed nickel shells, taking as an initial model a prototype made in a FDM rapid prototyping equipment.

It also would have to say beforehand that the electroforming technique is not something new because its applications in the industry are countless [3], but this research work has tried to investigate to what extent and under which parameters the use of this technique in the production of rapid molds is technically feasible. All made in an accurate and systematized way of use and proposing a working method.

2. Manufacturing process of an injection mold

The core is formed by a thin nickel shell that is obtained through the electroforming process, and that is filled with an epoxic resin with metallic charge during the integration in the core plate [4] This mold (Fig. 1) permits the direct manufacturing by injection of a type a multiple use specimen, as they are

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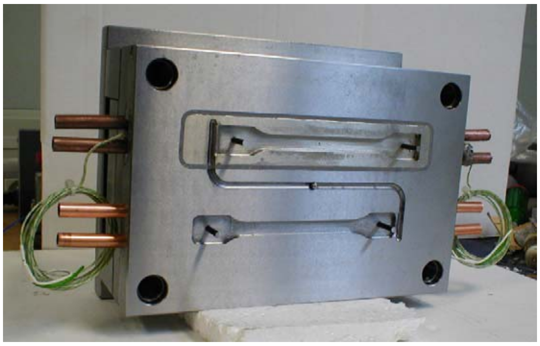

Fig. 1. Manufactured injection mold with electroformed core.

defined by the UNE-EN ISO 3167 standard. The purpose of this specimen is to determine the mechanical properties of a collection of materials representative industry, injected in these tools and its coMParison with the properties obtained by conventional tools.

The stages to obtain a core [4], according to the methodology researched in this work, are the following:

(a) Design in CAD system of the desired object.
(b) Model manufacturing in a rapid prototyping equipment (FDM system). The material used will be an ABS plastic.
(c) Manufacturing of a nickel electroformed shell starting from the previous model that has been coated with a conductive paint beforehand (it must have electrical conductivity).
(d) Removal of the shell from the model.
(e) Production of the core by filling the back of the shell with epoxy resin resistant to high temperatures and with the refrigerating ducts made with copper tubes.

The injection mold had two cavities, one of them was the electroformed core and the other was directly machined in the moving platen. Thus, it was obtained, with the same tool and in the same process conditions, to inject simultaneously two specimens in cavities manufactured with different technologies.

3. Obtaining an electroformed shell: the equipment

Electrodeposition [5,6] is an electrochemical process in which a chemical change has its origin within an electrolyte when passing an electric current through it. The electrolytic bath is formed by metal salts with two submerged electrodes, an anode (nickel) and a cathode (model), through which it is made to pass an intensity coming from a DC current. When the current flows through the circuit, the metal ions present in the solution are transformed into atoms that are settled on the cathode creating a more or less uniform deposit layer.

The plating bath used in this work is formed by nickel sulfamate [7,8] at a concentration of 400 ml/l, nickel chloride (10 g/l), boric acid (50 g/l), Allbrite SLA (30 cc/l) and Allbrite 703 (2 cc/l). The selection of this composition is mainly due to the type of application we intend, that is to say, injection molds, even when the injection is made with fibreglass. Nickel sulfamate allows us to obtain an acceptable level of internal stresses in the shell (the tests gave results, for different process conditions, not superior to 50 MPa and for optimum conditions around 2 MPa). Nevertheless, such level of internal pressure is also a consequence of using as an additive Allbrite SLA, which is a stress reducer constituted by derivatives of toluenesulfonamide and by formaldehyde in aqueous solution. Such additive also favours the increase of the resistance of the shell when permitting a smaller grain. Allbrite 703 is an aqueous solution of biodegradable surface-acting agents that has been utilized to reduce the risk of pitting. Nickel chloride, in spite of being harmful for the internal stresses, is added to enhance the conductivity of the solution and to favour the uniformity in the metallic distribution in the cathode. The boric acid acts as a pH buffer.

The equipment used to manufacture the nickel shells tested has been as follows:

- Polypropylene tank: 600 mm × 400 mm × 500 mm in size.
- Three teflon resistors, each one with 800 W.
- Mechanical stirring system of the cathode.
- System for recirculation and filtration of the bath formed by a pump and a polypropylene filter.
- Charging rectifier. Maximum intensity in continuous 50 A and continuous current voltage between 0 and 16 V.
- Titanium basket with nickel anodes (Inco S-Rounds Electrolytic Nickel) with a purity of 99%.
- Gases aspiration system.

Once the bath has been defined, the operative parameters that have been altered for testing different conditions of the process have been the current density (between 1 and 22 A/dm^2), the temperature (between 35 and 55 °C) and the pH, partially modifying the bath composition.

4. Obtained hardness

One of the most interesting conclusions obtained during the tests has been that the level of hardness of the different electroformed shells has remained at rather high and stable values. In Fig. 2, it can be observed the way in which for current density values between 2.5 and 22 A/dm^2, the hardness values range from 540 and 580 HV, at pH 4 ± 0.2 and with a temperature of 45 °C. If the pH of the bath is reduced at 3.5 and the temperature is 55 °C those values are above 520 HV and below 560 HV. This feature makes the tested bath different from other conventional ones composed by nickel sulfamate, allowing to operate with a wider range of values; nevertheless, such opera-

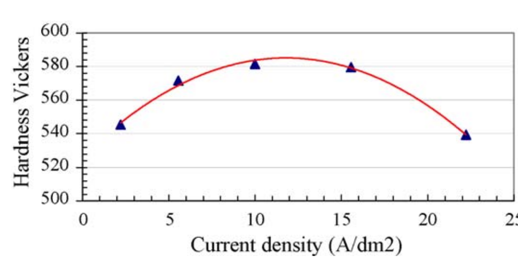

Fig. 2. Hardness variation with current density. pH 4 ± 0.2, $T = 45$ °C.

tivity will be limited depending on other factors, such as internal stress because its variability may condition the work at certain values of pH, current density or temperature. On the other hand, the hardness of a conventional sulfamate bath is between 200–250 HV, much lower than the one obtained in the tests. It is necessary to take into account that, for an injection mold, the hardness is acceptable starting from 300 HV. Among the most usual materials for injection molds it is possible to find steel for improvement (290 HV), steel for integral hardening (520–595 HV), casehardened steel (760–800 HV), etc., in such a way that it can be observed that the hardness levels of the nickel shells would be within the medium–high range of the materials for injection molds. The objection to the low ductility of the shell is compensated in such a way with the epoxy resin filling that would follow it because this is the one responsible for holding inwardly the pressure charges of the processes of plastics injection; this is the reason why it is necessary for the shell to have a thickness as homogeneous as possible (above a minimum value) and with absence of important failures such as pitting.

5. Metallographic structure

In order to analyze the metallographic structure, the values of current density and temperature were mainly modified. The samples were analyzed in frontal section and in transversal section (perpendicular to the deposition). For achieving a convenient preparation, they were conveniently encapsulated in resin, polished and etched in different stages with a mixture of acetic acid and nitric acid. The etches are carried out at intervals of 15, 25, 40 and 50 s, after being polished again, in order to be observed afterwards in a metallographic microscope Olympus PME3-ADL 3.3×/10×.

Before going on to comment the photographs shown in this article, it is necessary to say that the models used to manufacture the shells were made in a FDM rapid prototyping machine where the molten plastic material (ABS), that later solidifies, is settled layer by layer. In each layer, the extruder die leaves a thread approximately 0.15 mm in diameter which is compacted horizontal and vertically with the thread settled inmediately after. Thus, in the surface it can be observed thin lines that indicate the roads followed by the head of the machine. These lines are going to act as a reference to indicate the reproducibility level of the nickel settled. The reproducibility of the model is going to be a fundamental element to evaluate a basic aspect of injection molds: the surface texture.

The tested series are indicated in Table 1.

Table 1
Tested series

Series	pH	Temperature (°C)	Current density (A/dm^2)
1	4.2 ± 0.2	55	2.22
2	3.9 ± 0.2	45	5.56
3	4.0 ± 0.2	45	10.00
4	4.0 ± 0.2	45	22.22

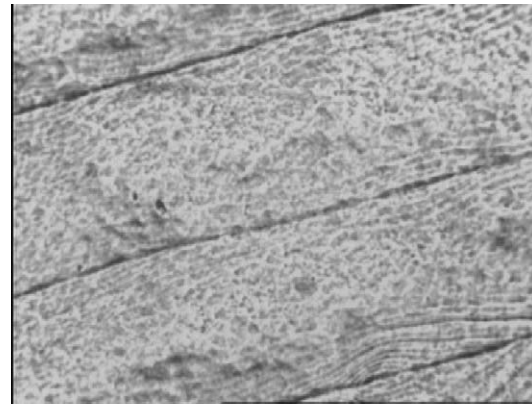

Fig. 3. Series 1 (×150), etch 1.

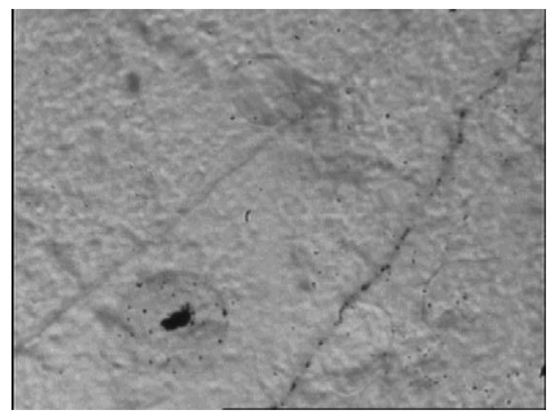

Fig. 4. Series 2 (×300), etch 2.

Fig. 3 illustrates the surface of a sample of the series after the first etch. It shows the roads originated by the FDM machine, that is to say that there is a good reproducibility. It cannot be still noticed the rounded grain structure. In Fig. 4, series 2, after a second etch, it can be observed a line of the road in a way less clear than in the previous case. In Fig. 5, series 3 and 2° etch it begins to appear the rounded grain structure although it is very difficult to check the roads at this time. Besides, the most darkened areas indicate the presence of pitting by inadequate conditions of process and bath composition.

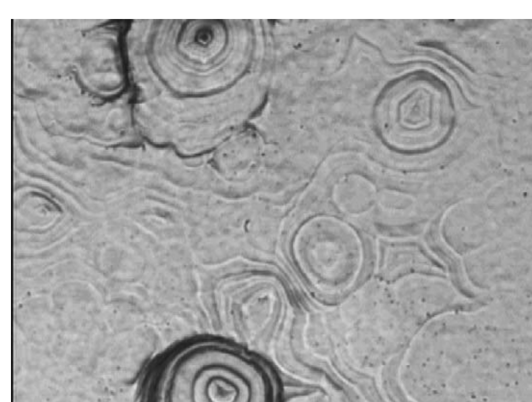

Fig. 5. Series 3 (×300), etch 2.

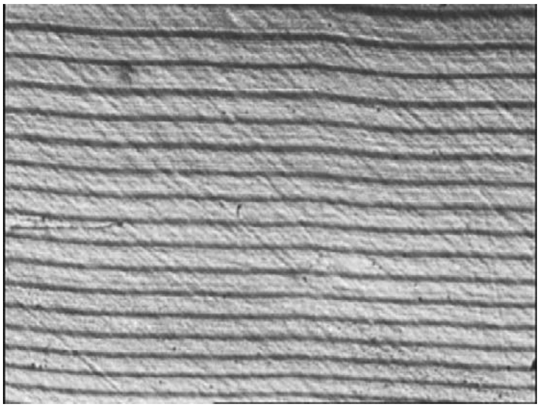

Fig. 6. Plane transversal of series 2 (×600), etch 2.

This behavior indicates that, working at a low current density and a high temperature, shells with a good reproducibility of the model and with a small grain size are obtained, that is, adequate for the required application.

If the analysis is carried out in a plane transversal to the deposition, it can be tested in all the samples and for all the conditions that the growth structure of the deposit is laminar (Fig. 6), what is very satisfactory to obtain a high mechanical resistance although at the expense of a low ductibility. This quality is due, above all, to the presence of the additives used because a nickel sulfamate bath without additives normally creates a fibrous and non-laminar structure [9]. The modification until a nearly null value of the wetting agent gave as a result that the laminar structure was maintained in any case, that matter demonstrated that the determinant for such structure was the stress reducer (Allbrite SLA). On the other hand, it was also tested that the laminar structure varies according to the thickness of the layer in terms of the current density.

6. Internal stresses

One of the main characteristic that a shell should have for its application like an insert is to have a low level of internal stresses. Different tests at different bath temperatures and current densities were done and a measure system rested on cathode flexural tensiometer method was used. A steel testing control was used with a side fixed and the other free (160 mm length, 12.7 mm width and thickness 0.3 mm). Because the metallic deposition is only in one side the testing control has a mechanical strain (tensile or compressive stress) that allows to calculate the internal stresses. Stoney model [10] was applied and was supposed that nickel substratum thickness is enough small (3 μm) to influence, in an elastic point of view, to the strained steel part. In all the tested cases the most value of internal stress was under 50 MPa for extreme conditions and 2 MPa for optimal conditions, an acceptable value for the required application. The conclusion is that the electrolitic bath allows to work at different conditions and parameters without a significant variation of internal stresses.

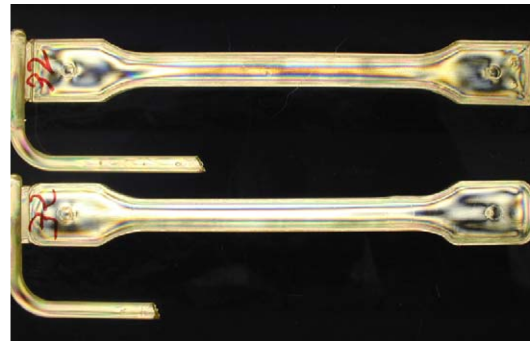

Fig. 7. Analysis by photoelasticity of injected specimens.

7. Test of the injection mold

Tests have been carried out with various representative thermoplastic materials such as PP, PA, HDPE and PC, and it has been analysed the properties of the injected parts such as dimensions, weight, resistance, rigidity and ductility. Mechanical properties were tested by tensile destructive tests and analysis by photoelasticity. About 500 injections were carried out on this core, remaining under conditions of withstanding many more.

In general terms, important differences were not noticed between the behavior of the specimens obtained in the core and the ones from the machined cavity, for the set of the analysed materials. However in the analysis by photoelasticiy (Fig. 7) it was noticed a different tensional state between both types of specimens, basically due to differences in the heat transference and rigidity of the respective mold cavities. This difference explains the ductility variations more outstanding in the partially crystalline materials such as HDPE and PA 6.

For the case of HDPE in all the analysed tested tubes it was noticed a lower ductility in the specimens obtained in the nickel core, quantified about 30%. In the case of PA 6 this value was around 50%.

8. Conclusions

After consecutive tests and in different conditions it has been checked that the nickel sulfamate bath, with the utilized additives has allowed to obtain nickel shells with some mechanical properties acceptable for the required application, injection molds, that is to say, good reproducibility, high level of hardness and good mechanical resistance in terms of the resultant laminar structure. The mechanical deficiencies of the nickel shell will be partially replaced by the epoxy resin that finishes shaping the core for the injection mold, allowing to inject medium series of plastic parts with acceptable quality levels.

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