ROBUST FLUID DISPENSER DEVICE DEVELOPMENT FOR RAPID PROTOTYPING EQUIPMENT

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Abstract. *Product development cycle is being reduced to fit increasingly more competitive markets. New manufacturing technologies are being developed to support project design and to anticipate market entry. Rapid prototyping and computer modeling techniques support these developments. Techniques to transform virtual models into real models available, but not cost effective, because they rely in very expensive equipment and tailored materials. A low cost technology, for the production of ceramic shells with casting capability of high melting point alloys, is then needed. Under the Rapid Casting concept, it aims to obtain products with real features in less than a week after validating the CAD model, using commonly available materials in casting industry. A fluid dispenser actuated by a ceramic PZT piezoelectric stack actuator (from a 3rd generation common-rail diesel motor injector) was developed. The system consists in an actuator and a print head that includes a nozzle, granting a low cost manufacturing solution and allowing full cleaning of all components in contact with the fluid and general good maintenance. The ultimate objective is to adapt this drop-on-demand micro fluid dispenser to a CNC router, with the objective of dispensing the liquid binder selectively in the desired areas, bonding successive layers of refractory ceramic powder, so producing cost effective ceramic shells for metal parts prototyping. The present paper illustrates the various tasks involved in the design and development stages for the development of a low cost technology for the production of free-form ceramic shells by layered manufacturing.*

Keywords*: Rapid Casting, Rapid Prototyping, Piezoelectric, Drop Fluid Dispenser*

1. INTRODUCTION

Markets nowadays are global and competitive. Although the success of a product depends largely on its quality, it is also constrained by how fast the product is able to position itself against the competition. In order to grant the shortest and most effective development cycle for a product, new manufacturing technologies appeared to support decision making and to materialize ideas in objects. Also a very big demand exists towards customization and the goods are increasingly produced by request, demanding flexibility from the producers.

Mass production of electronic goods deeply altered manufacturing technologies. Numerically controlled machine-tools were progressively adopted, the mechanical design was completely restructured and today it is almost completely processed in virtual computational environment, free from paper, integrating several competences and multidisciplinary teams, and engineers' proposals are validated using software simulations before any physical prototype is made.

Progress allowed manufacturing techniques to appear that have almost no geometric limitations so allowing production of virtually any shape. Building parts by superposition of successive thin layers, allowed the materialization of the prototype much faster than conventional model making techniques, and then these were called rapid prototyping techniques. These parts or models are now widely used in the areas of product design and development to demonstrate the viability of a product. Complex shaped parts can be manufactured with some degree of functional characteristics, although generally presenting lower performances when compared with parts obtained by conventional processes.

Foundry technology is very versatile to produce metallic components. The potential of the conventional foundry technology is however constrained for there is a long time gap from the design validation to the part delivery. But its ability to produce directly complex shaped parts, with few final finishing operations, strongly favors its use in a wide range of situations. In addition foundry permits metal scrap reclaiming, which is a characteristic not to despise nowadays.

Computer supported technologies in foundry allowed major improvements. Part design strongly benefited from software modeling for solidification of the metal can be foreseen in advance, allowing corrections in the model to be made and mould making techniques became faster. CAD systems are used to support the part’s geometry building, which is then available to be shared by any possible improvement.

Improvements arose from the use of rapid prototyping technologies. Either a pattern is obtained by rapid prototyping techniques, and then the mould is made by conventional processes, or the mould is directly obtained from a CAD file, creating a shell similar to the refractory ceramic shells of conventional lost pattern production (Araújo, 2008). Direct ceramic shell production by rapid prototyping techniques is possible, but challenging due to the dispenser obstruction risk imposed by the fluid characteristics.

The subsequent work begins presenting the main process possibilities and drawbacks, and then shows the development of a suitable low cost fluid dispenser to overcome the difficulties.

2. COMPLEX PARTS DEVELOPMENT FUNDAMENTALS

Casting is usually the correct choice to produce metallic components having intricate geometry for it is versatile, allows design freedom at low cost (Dickens et al, 1995) and sometimes the shape is impossible to be produced by other methods such as machining. Figure 1 shows a cylinder head that was designed to incorporate specific inlet port, coolant chamber, camshaft housing, valves and its auxiliaries (seats, guides and springs), spark plug and exhaust passage. The resulting complexity of the shape to be produced makes casting technology the natural choice.

Casting accuracy is not enough for a functional model; subsequent machining is then needed to obtain some of the desired features of a particular part (Barbosa et al., 1999). The features requiring more accuracy are then machined to fulfill design requirements. NC machining provides that accuracy, as long as the cutting tool can reach the area to machine. Nevertheless some features must be good enough for acceptance in as cast condition, eventually suffering hand finishing operations, as it is the case of the inlet (I) and exhaust (E) channels in Figure 1 (Monteiro and Martins, 2007).

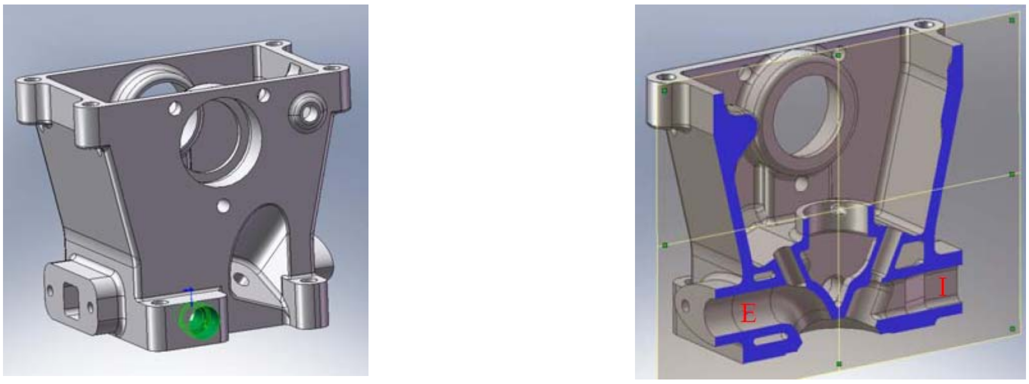


Figure 1 - Cilinder Head CAD model (left) and its section showing the inside intricacy (right).

2.1. Casting tools development

The geometries in a highly intricate model, both inner and outer, make the production of such a part a very difficult job. The interior shapes create a critical inner core making problem, due to its complexity and the reduced accessibility, imposing casting limitations. There are a number of methods to produce the tools needed to cast a complex shape component, but only a few are able to allow rapid tooling to be achieved. A good solution is the result from the combination of foundry technology and rapid prototyping (Bassoli, 2007). One rapid tooling method consists on making a rapid prototype and using it as a permanent mold to give origin to the moulds. Another method consists in the use of the prototype as a sacrificial pattern, following the lost pattern method.

To overcame core and mould making difficulties, rapid prototype technologies provide a further method of production that is very convenient to use when single or a few components are to be manufactured (Saraiva et al., 2002). If the negative shape of the desired part is modeled in a CAD system, the mould may be directly produced using Rapid Prototyping. The pattern is not but the CAD model itself, and the entire mould can then be produced using adequate equipment and techniques. 3D printing technology may be used, for it is available and cost effective (Wieser, 2003). In this process the prototype is built by superposition of successive layers printed by a conventional inkjet printing process, using starch and plaster based powders. The printing fluid, mainly water, agglomerates the powder particles to form a part, and the non agglomerated powder is removed and recycled. Figure 2 shows a mould assembly where a plaster based Z Corporation powder, ZP®131, was used (Melo, 2009) to cast the part shown in Figure 1. The use of powdered material permits the actual mould building without physical supports. Actually this process can use any material type under the powder form and a compatible binder (Sachs et al, 1997). The general process is called DSPC (Direct Shell Production Cast) and is used to obtain directly ceramic moulds, similar to the shells commonly used in the investment casting process, where the metallic models are obtained by casting a metallic alloy into the ceramic shell (Alves et al, 2001). Because powders are used with grain sizes around 100 µm, the final surfaces obtained always have some roughness. Nevertheless, sand grain size used in most casting processes is even larger, and so surface roughness in as cast condition is not much affected when a rapid mould is used. To achieve accuracy in cast parts machining operations follow the casting operation, as in common sand casting processes (Monteiro et al, 2009). The virtual model of the actual part can then also be used to feed a CAM system to produce the machining program.

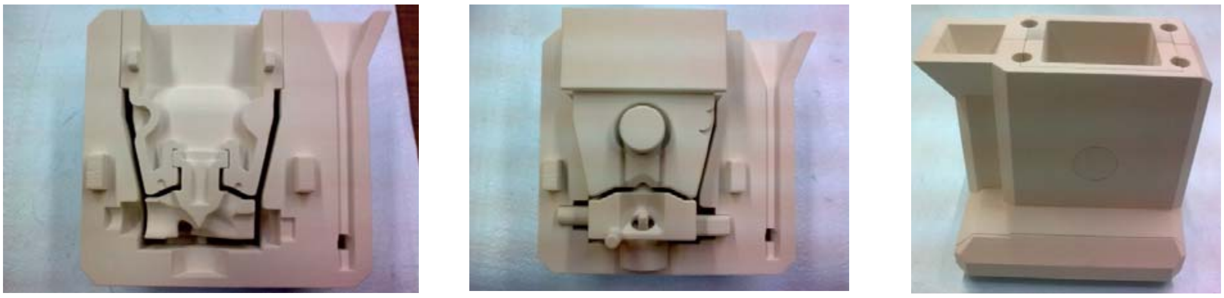


Figure 2 - Rapid prototyped mould showing the complexity of the assembly needed to produce the part.

In theory the entire assembly could be made in a single block, avoiding assembling problems. It is however difficult to remove the non agglomerated powder dust from the inside of the mould due to the complex shape of the part. Then, to make sure that no non agglomerated powder remains inside the cavity, the mould must be built in pieces, somehow following the conventional mould making process. Nevertheless this process allows an easier definition of the parting surfaces, for there is not a solid pattern to be removed, as it is the case in the permanent mould process. The molten metal is then poured through adequate channels built in the outer case of mould, including the pouring basin, the sprue and the runner to provide a molten metal path to the cavity as shown in Figure 2. However complex, the inner core shown in Figure 3 (shaping the combustion chamber, the inlet and exhaust passages and the valve and injector seats), was made in only one part. The exceptional printing detail provided by the technology may be observed in Figure 3. An effective removal of the gases produced during pouring operation is expected in order to obtain sound castings.

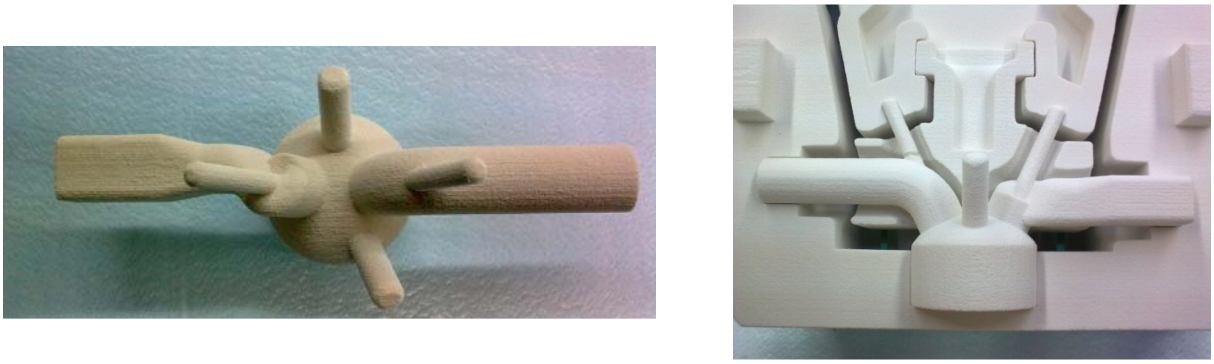


Figure 3 - Combustion chamber, inlet and exhaust passages inner core (left) placed in position (right)

At moderate or high temperatures the permeability of the shell obtained using a 3D Printing equipment is incompatible with the vapor released from the mould moisture and the smoke coming from the burning starch (Figure 4), both being the cause for the casting defects to appear in the part (Figure 5). As expected the inner walls show worst behavior in respect to defect occurrence because the evacuation of the gases produced is much more difficult. Then the conclusion driven from the experiment is that it is possible to produce casting mould shells directly, although the process is limited to low temperature melting alloys.

Figure 4 - Excessive moisture and smoke being released from a 3D Printed Rapid Mould

Figure 5 - Casting defects in an aluminum part originated by excessive moisture and smoke release: Outer walls (left) and inner walls (right) aspect.

2.2 Rapid Manufacturing of Ceramic Shells

Refractory powder materials may replace successfully the starch and plaster based materials, but they require different binder solutions, to achieve the mould requirements of foundry technology. Its use depends on the adherence of the fluid binder with the powders that constitute the base material. The silica sol, also known by colloidal silica, is an odorless material, flavorless and non poisonous. This material consists of ultra-fine silicon dioxide (SiO_2) particles dispersed in water. Because the particles are very small, between 10 and 20 nm, gravity force is unable to make them precipitate. This material offers good dispersion and permeability characteristics due to its low viscosity. When the existent water in the colloidal silica evaporates, the three-dimensional traverse linkage of the connection of <O-Si-O-Si>, allows a strong adhesion of the colloidal particles to the powder surface, which makes colloidal silica perfect to be a binder fluid (Araújo, 2008).

Alumina or silica powders are very common materials in foundry applications. A good adhesion of the powder is obtained with controlled amounts of colloidal silica. At room temperature a good glue has a binding strength from 10 to 100 times superior to colloidal silica, but around 1000 ºC, the colloidal silica is in the top of the list of binder agents with larger binding strength. All the organic adherent resins would have already been burned and many of the inorganic resins like sodium silicate, that form strong connections at room temperature, would be melted at these temperatures. The binding strength of colloidal silica increases with the calefaction, doubling its room temperature strength. After being allowed to cool until room temperature, colloidal silica maintains most of its cohesion strength. Figure 6 presents some results obtained by using colloidal silica and alumina powder as binder and support material respectively. It was possible to obtain solid strips, because the silica particles deposited adhere locally to the powder and the water is dispersed through the entire volume of powder. The result is a green mould that may be heated later to reach full mould strength.

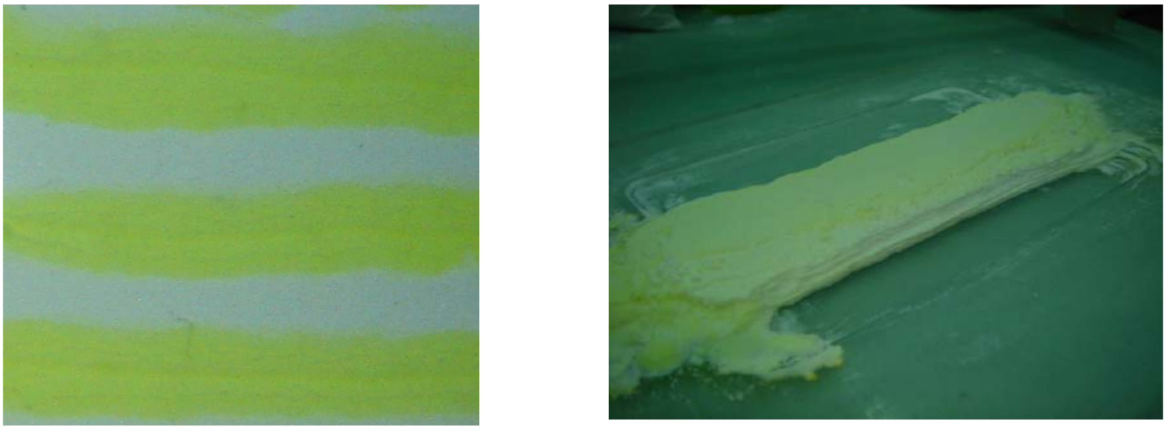


Figure 6 - Alumina powder agglomeration by colloidal silica: printed surface showing the printed and non printed strips (left), and the volume effect after non agglomerated material removal (right).

The use of a common inkjet printer head is limited however, because it is a weak component that is easily obstructed by the binder, and so has limited longevity and doesn't allow any type of repairing, cleaning or maintenance. In order to use a different kind fluids in the same machine, a robust dispenser is needed in which the actuator does not enter in contact with the fluids. The actuator to be used must fulfill the requirements of robustness and availability. Furthermore, the dispenser device to be developed should be of easy and rapid maintenance or replacement and affordable.

3. ROBUST DISPENSER DEVELOPMENT

There are a lot of available devices similar to those used in inkjet technologies, and some common devices deserve consideration. Third generation common-rail internal combustion motors use a piezoelectric actuated diesel injector (see Figure 7 and Figure 8). The piezoelectric actuator is inside the injector shown Figure 7, and is not seen.

It is a robust device but it needs the implementation of adequate equipment in order to operate it, namely an electric pulse power source and the development of adequate dispensing heads. It is necessary to build a dispenser head to create and eject the drops, because the original injector head will also be obstructed by the colloidal fluid. Resolution may be sacrificed to robustness and reliability, because accuracy will be obtained by machining the features that need it. Drops' volume is expected be larger in comparison with those of common printers' drops, because the intention is to obtain high robustness with manufacturing capacity to be limited to the hundreds of micrometers.

Figure 7 – Piezoelectric actuated diesel injector actuator. The injection head is not present.

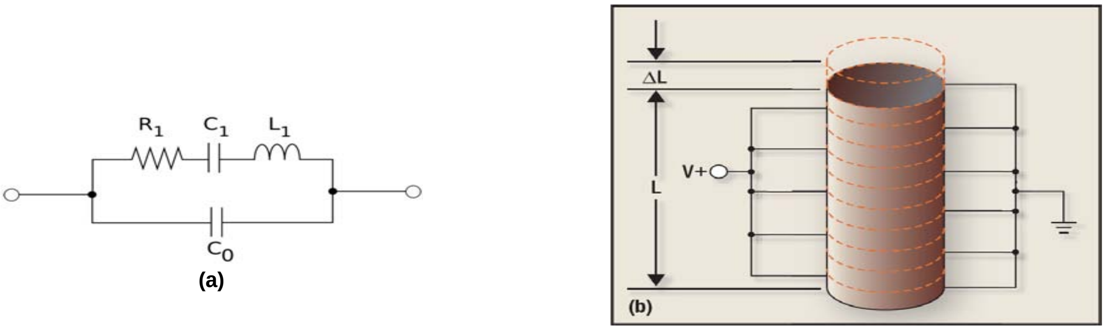


Figure 8 - Piezoelectric actuator equivalent circuit (a) and mounting schema

3.1 Developing a printing head

The printing head has several mandatory elements: one or several drop outlet channels, a connection to the fluid reservoir, a mobile component to contact the fluid when actuated by the piezoelectric actuators, and several channels linking all these elements. Full and simple cleaning of the fluid circulating channels must be possible, or the jellification of the colloidal silica will obstruct them impeaching the printing action. The actuator should be safeguarded of possible contaminations by fluid material, or it will become clogged with colloidal silica, so damaging the whole system permanently. A first CAD virtual model can be seen in Figure 9. It was developed to establish the viability of fabrication of geometries with the available tools and limitations. Cleaning is a crucial design requirement, for the system function depends on it. Liquid supply channels are interrupted by the passage of the stem actuator, so forcing the liquid ahead through the out channel, to be deposited over the powder surface. The model precision must be enough to avoid leaking problems, disturbance of the fluid flow and difficulties in achieving control of the amount ejected. The out channel must be a labyrinth to create resistance to undesired drop ejection. The device has been built in two halves in order to allow easy cleaning, and the channels are easily machined in the parting surface. After validating the requirements imposed to the dispenser head, the actual construction took place. Transparent acrylic was chosen to build the first actual dispenser head, in order to allow the observation and evaluation of the fluid behavior through the channels, as for instance air bubbles production, affecting the operation of the ejector.

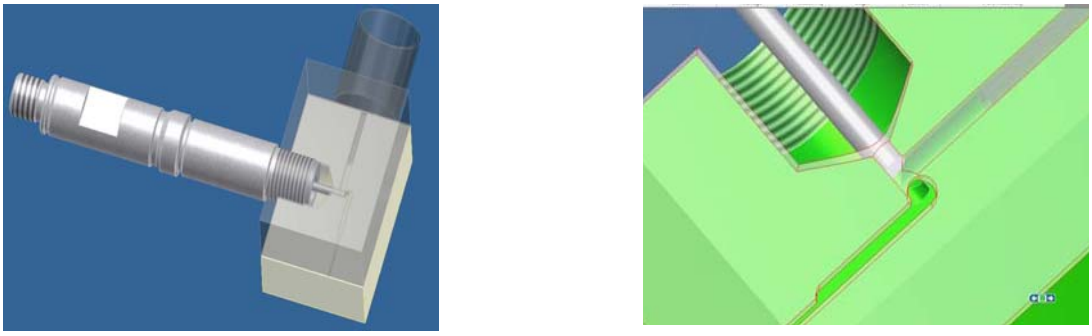


Figure 9 - Fluid dispenser arrangement (left) with channels and stem detail (right)..

3.2 Electronic dispenser controller

To control the piezoelectric actuator an electronic controller was built. The use of piezoelectric materials also implicates advanced electronics to take advantage of their potentialities. To adapt a fuel injector from the automobile industry has the intention of taking advantage of a very competitive and proven off-the-shelf product. This kind of actuator is easily found, but few performance data are available, making it mandatory to develop experimental work to find out the correct values to feed the system, such as voltage range, peak current, pulse frequency and so on.

To control the piezoelectric actuator a power source was built to allow different regulations intending to check and find the setting variables with better results for the controlling purposes. Basically it consists of a pulse generator, a VARIAC and AC/DC converter, in order to control the voltage and current applied to the piezoelectric, using the pulses generated by the power source.

The power source was built to allow variation of the generated pulse frequency (from 38 Hz to 15 kHz) and the pulse width (in multiples of 6.4 μs). The applied voltage to the piezoelectric actuator may be varied through the VARIAC. The equivalent circuit for a piezoelectric actuator is similar to a parallel circuit between a serial RLC and a condenser as shown in Figure 8. To develop a proper controlling circuit, the piezoelectric injector actuator characteristics were been measured using a RLC Philips bridge, model PM6304. The data collected is presented in Table 1. Figure 11 presents the PCB card connecting all user interfacing components and devices, display and buttons. It is possible to vary the frequency and the pulse width manually using the buttons. The card was built so that hereafter it can be linked to a computer through a serial gate.

The power circuit consists of two insulated gate bipolar transistors (IGBT), implemented in a way that when a pulse is generated the applied voltage to the piezoelectric actuator be positive to deflect it, and when the pulse ends the IGBT is turned off and the other one is turned on to apply a negative voltage to the piezoelectric actuator. This topology, schematized in Figure 11, was chosen because it was verified that the piezoelectric actuator behaves like a condenser, remaining energized and not answering to the new pulses. Figure 12 shows the rectifying bridge and the two IGBT used in the construction of the power source.

Table 1 - Injector piezoelectric characterization

Frequency [Hz]	50	100	1 10^3	10 10^3
Capacitance [μF]	2.441	2.565	2.408	2.432
Resistance [Ω]	1.290 10^3	620.5 10^3	66.11	6.55

3.2 Testing the piezoelectric actuator

The piezoelectric actuator was tested using the power source developed (see Figure 13). First a single short positive voltage (red) pulse was applied to the IGBT, then a positive current (blue) pulse to turn the piezoelectric conductive, followed by a negative current pulse to turn the piezoelectric non conductive. The voltage (black) reaches a peak in the piezoelectric actuator, which suffers elongation so acting over the stem.

Figure 14 shows the result when a single larger pulse width (25.6 μs) is applied to the IGBT. Voltage in the piezoelectric actuator terminals stabilizes around half the DC bus voltage as expected, and the stem was kept actuated.

Figure 15 shows the piezoelectric response to multiple sequential pulses. The stem was actuated accordingly.

These tests were been run at 20 V, setting the VARIAC to 10% of the maximum voltage available. It seems enough for the situation where there is no need for the stem to overcome a counterforce. Tests are going to be made along the entire voltage range available, to characterize the actuator's behavior. The platform so developed will allow the authors to maintain full control of the dispenser device, and improve it as desired.

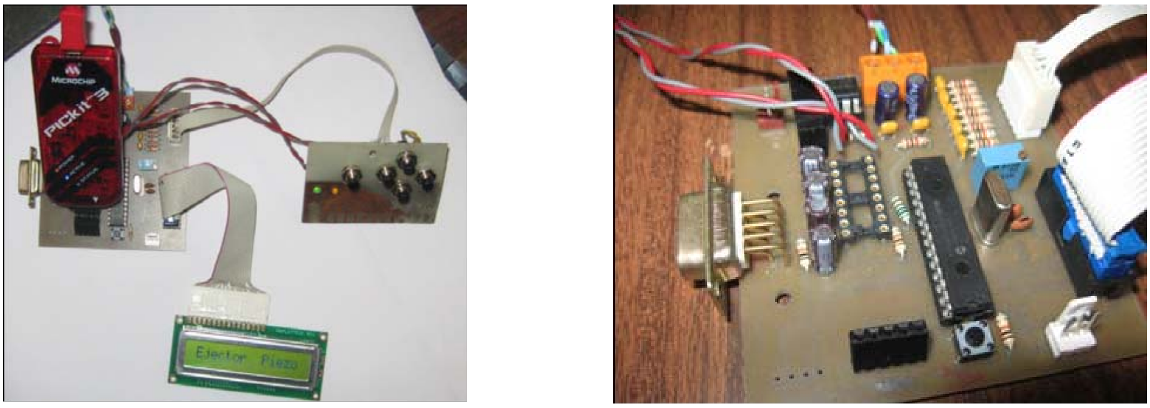


Figure 10 – Electrical pulse source generator to control the piezoelectric actuator

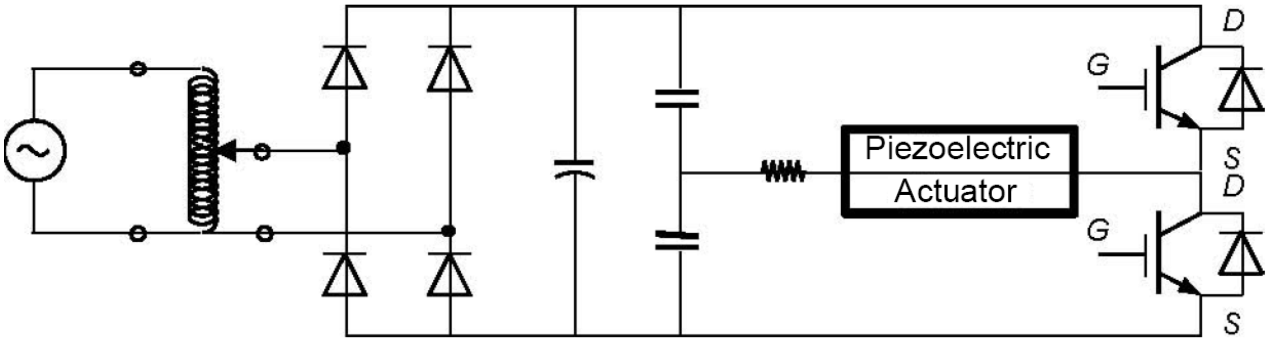


Figure 11 - Electrical power circuit.

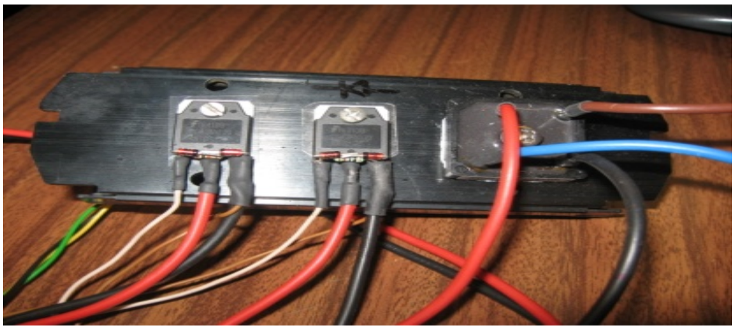
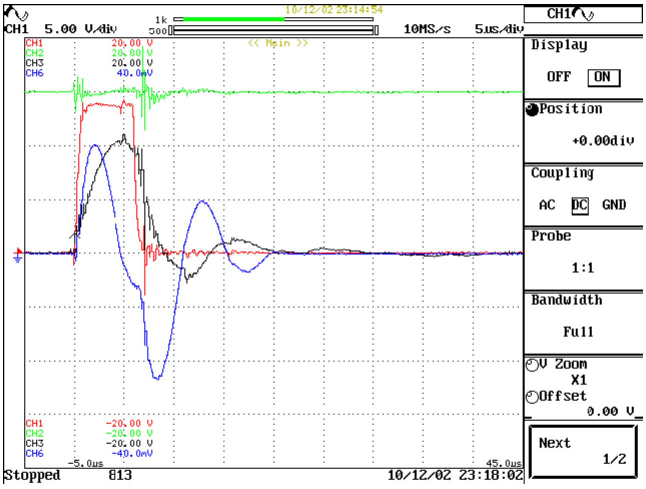
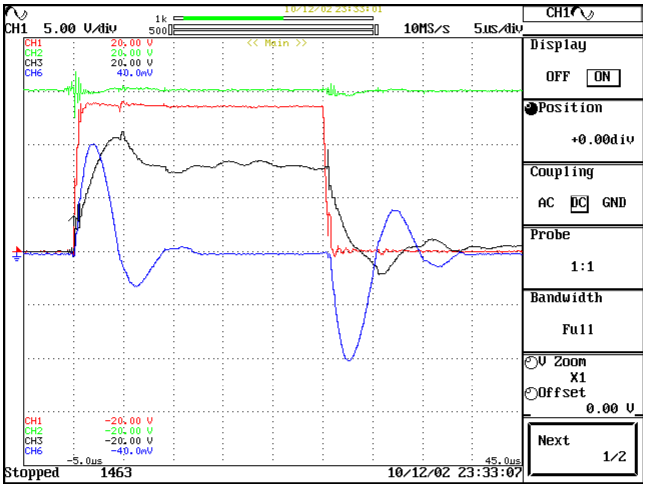


Figure 12 – Rectifier bridge and IGBT arrangement



Blue – Current consumed by the piezoelectric actuator
Red - Applied pulse in the IGBT gate
Black - Voltage in the piezoelectric terminals
Green - DC in (bus) voltage

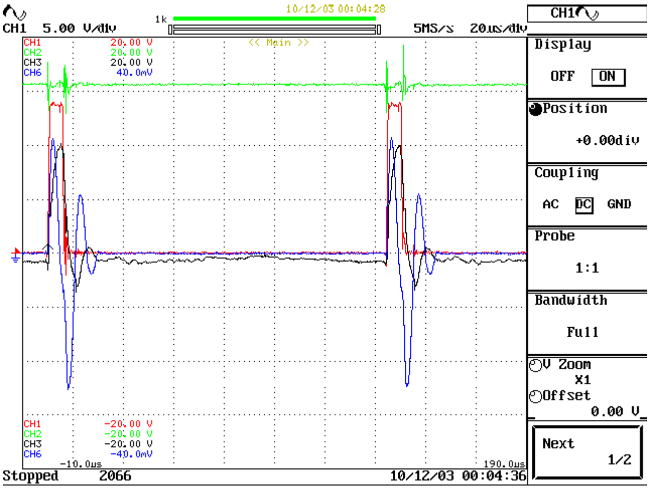
Figure 13 – Oscilloscope registers of the source testing.
A single short pulse was applied



Blue – Current consumed by the piezoelectric actuator
Red - Applied pulse in the IGBT gate
Green - DC in (bus) voltage

Green - DC in voltage (rectifier out bus)

Figure 14 – – Oscilloscope registers of the source testing.
A single large pulse was applied



Blue – Current consumed by the piezoelectric actuator
Red - Applied pulse in the IGBT gate
Green - DC in (bus) voltage

Green - DC in voltage (rectifier out bus)

Figure 15 – Oscilloscope registers of the source testing.
Sequential pulses were applied

4. CONCLUDING REMARKS

The use of Rapid Prototyping to produce casting moulds and cores makes it easier to implement design changes in the actual manufactured components. Modifications of the design are easily introduced into the actual parts in an early development stage and enable successful rapid tooling.

Direct metal pouring of moderate or high temperature melting alloys into plaster/starch moulds is not advisable especially when the shape to be obtained is intricate. The gases produced during the filling of the mould result in casting defects. Refractory base materials and binders should be used to avoid this problem.

To use 3D printing equipment with alternative binders may lead to the printer head obstruction. Alternative fluid dispenser devices must be used in order to achieve consistent successful parts. Low cost devices can be built using off-the-shelf high performance proven components such as piezoelectric actuators from motor engine injectors.

The experimental results obtained demonstrate the possibility of low cost device development. A versatile power source was built to control the piezoelectric actuator, allowing the regulation of the variables controlling the adjustment to the best combination.

Knowing beforehand there are powder-binder materials compatible couples, the construction of a low cost prototyping equipment to produce ceramic casting shells directly from a computer CAD model seems to be viable, within common precision foundry results for rapid production of individual or small series metal parts.

As future work developments, the following proposals are being given attention:

- The redesign of the injection apparatus to allow multiple heads simultaneously;
- Electronic optimization of the power source developed;
- To test further powder-binder couple materials for different applications;
- To integrate the device into the existent rapid prototyping equipment.

It is expected that the future development of the power source prove the advantage of piezoelectric actuators technology, for the exceptional qualities recognized to them, but alternative devices using solenoid injector actuators may also be considered to enlarge the application perspectives and the available devices.

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6. RESPONSIBILITY NOTICE

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