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Research Article

Development of HPDC Advanced Dies by Casting with Reinforced Tool Steels

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High pressure die casting (HPDC) dies are nowadays manufactured with high quality forged steels. Cavities are made by electrical discharge machining (EDM) or by high speed milling. The average life of an aluminium HPDC die is about 125.000 injections. Refrigeration circuits have simple configurations, because they are produced by drilling the die with straight holes. They are limitations in the distances and diameters of holes. Sensors are placed where the geometry of the die permits an easy machining. In order to obtain complex figures, several rapid prototyping methods have been developed. However, there is a limitation in the life of the dies produced by this technique, from several parts to thousands. A new method to obtain semifinished high pressure die casting dies in a steel of higher mechanical properties and with the refrigeration circuits and sensors embedded into it is described in this paper. The method consists in producing a molten steel alloy with micro-nano-special ceramic particles inserted in it and casting the composite material in sand moulds of the desired geometry. The resultant solidified near-net shape die with the cooling tubes and sensors embedded into it. A use-life and a productivity about 50% and 10% higher are obtained.

1. Introduction

In the last years HPDC cast parts have developed a quick development due to the high automation, the new die materials, and sensoring and construction methods and also by the advanced control and foundry systems.

HPDC are generally made in H11 or H13 steel alloys by high speed machining combined with electrical discharge machining (EDM). Dies are expensive, due to the expensive tooling and the high energy and man power demanded in these operations.

Rapid prototyping processes are coming more and more employed in HPDC moulds, but they are employed normally for first series, because the properties obtained with those parts produced by this technology cannot obtain the same life time than with standard fabricated dies. According to bibliography [1–3], there are different direct metal part production methods to made dies by rapid prototyping process. Between them, the direct metal laser sintering (DMLS) and selective laser sintering (SLS) offers the possibility to adapt the cooling channels to the contour of a cavity without limitations in the form, optimizing die temperature control and increasing the die life. Cycle time reductions can be also obtained by optimizing the cooling circuits, and quality is increased by the nonquality parts reject reduction due to a better thermal stability of the die. However, there are several constraints to employ some alloys as the H11, and the metallurgical quality of produced parts is not as good as forged pieces used for dies.

There are also several indirect metal part production methods [4]. These processes have been employed for insert fabrication, but their applications are very limited.

The steel sand casting technique has been also appointed as a possible way to construct cavities and dies [5]. There is a reduction in the fabrication time, is necessary less raw material and machining operations are reduced. However, the application of those products is limited for first series and for

Table 1: Temper temperatures and materials.

	460°C	580°C	600°C
Base alloy	●		●
Reinforced alloy	●	●	●

the supporting parts of the dies, due to the limited lifetime of the dies and the necessity of machining the refrigerating circuits.

One of the main mechanisms that define the total life of a die is the thermal fatigue cracking [6, 7]. In order to increase die life, new hot work tool steels with improved properties for HPDC applications are being continuously developed [8, 9].

Between them, the metal matrix composites have the potential to increase the thermal fatigue property [10, 11].

This work deals mainly with the development of a foundry process to produce HPDC dies with customised internal refrigeration and high resistance new steel. The objective is to obtain an economical process to produce advanced HPDC dies.

2. Design of Experiments

The base material for the tests has been chosen from the most employed steels used by HPDC die makers. The alloy 1.2344 (H13) was finally elected.

Based on the previous experience, in order to reinforce the base material, a Fe(TiMo)C master-alloy produced by self-propagating high temperature synthesis (SHS) has been chosen to be added to liquid steel.

To compare the new developed material properties in function of different tempering temperatures, some test bars were casted, heat-treated, and machined. An industrial induction furnace was used to prepare 300 kg of molten steel from selected scraps. When the scraps were melted at 1650°C, the steel was dedrossed and a 7.5% in weight of Fe(TiMo)C master alloy was added until a good dissolution was obtained. Test bars were poured in sand moulds at 1.550°C. After the solidification, parts were demoulded and separated from runners and overflows. Test wars were quenched at 890°C for 2 hours and tempered at temperatures between 460 and 600°C for 2 hours. After sand blasting, parts were machined in a high speed milling machine.

For the mechanical characterization, standard EN-10002.1, EN-10045.1, and EN-10003.1 bars were machined to test tensile, resilience, and hardness properties, respectively. Wearing properties were also checked by pin on disk test. Thermal test bars have a dimension of 150 × 50 × 50 mm with internal channels of 20 mm of width, 5 mm of depth, and 110 mm length (see Figure 1(a)). The test bars were essayed in a test machine during 100.000 cycles and with a variation of temperature from 600 to 250°C every 30 s, by induction heating and followed then by water and air spraying.

The two cast materials were quenched at 890°C and tempered at different temperatures (see Table 1) in order to determinate the differences between materials and the optimum temper temperature for HPDC die applications.

Table 2: Tube sizes, fillers, and positions.

Ref.	Outside diameter (mm)	Inside diameter (mm)	Filler	Tube position
1	10	7	Gas	Vertical
2	18	9	Sand	Vertical
3	17	11	Sand	Vertical
4	8	5.4	—	Horizontal
5	21.5	16	—	Horizontal

In order to define a method to obtain directly from casting the cooling circuits a 125 mm radius and 300 mm length cylinder cavity to be produced into a chemically bounded sand mould was designed with placements for tubes. In this sand mould tubes with different diameters and materials were tested, with and without internal sand as protective material for the tubes, and also a continuous gas flow was introduced to cool the tube during casting solidification. Definitively, standard AISI 316 stainless steel tubes were chosen for the internal cooling circuits, due to the low mismatch in composition between base alloy and AISI 316. On the other hand, zirconia sand was selected as inside filler for the cooling tubes due to its high refractoriness.

We can observe in Table 2 the different tubes, fillers, and placement in respect to the parting line of the sand mould employed for casting trials as we can observe in Figure 2.

After pouring and subsequent solidification of the liquid composite material, casting part was cut and inspected to determinate if the tubes resisted the molten metal.

Optical microscopy has been used to determinate the structure of different alloys after heat treatments and also to determinate the coherency between the alloy and the tube material, in order to understand the obtained properties.

In order to test the materials in real production, a design and a cooling optimisation of real parts were made (see Figure 3(a)) and the patterns for sand mould were prepared, having in mind the support system for cores, as we can observe in Figure 3(b).

Internal tubes were cold deformed to obtain the desired forms and also in few cases arc welding technique was employed to obtain complex shapes.

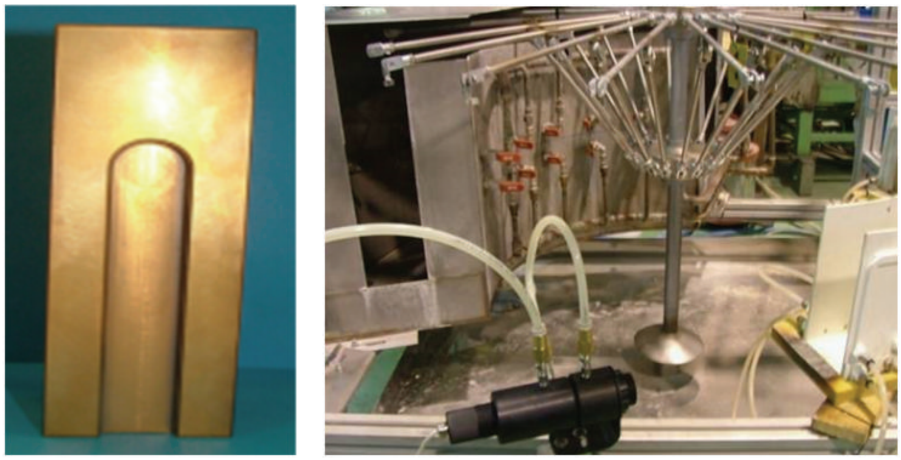
3. Experimental

In order to determinate a robust process, different cooling tubes in size and position and with and without internal insulating material (zirconia) defined in Table 2 were tested by using an induction furnace to cast steel over sand moulds with test tubes places into the mould cavity.

We can observe in Figure 4 how the tubes of Table 2 were placed in the sand test mould.

H13 base alloy was poured at 1560°C (see Figure 5(a)), and after solidification, the test cylinder was cut (Figure 5(b)).

We can observe in Figure 5(a) how the metal solidifies into the sand die and in Figure 5(b) how only tubes filled with



(a) (b)

Figure 1: (a) Thermal fatigue test bar, (b) thermal fatigue test machine.

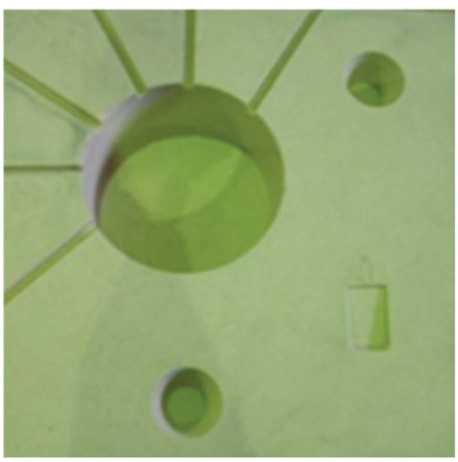


Figure 2: Die sand mould with placements for tubes.

Table 3: Resistance to metal penetration in tubes.

Ref.	Tube filling	Tube position	Resistant to metal penetration
1	Gas	Vertical	No
2	Sand	Vertical	Yes
3	Sand	Vertical	Yes
4	—	Horizontal	No
5	—	Horizontal	No

zirconia sand were capable of resisting the attack of molten metal.

The obtained results are resumed in Table 3.

With these results the external diameter of cooling tubes was set to 10 mm, the internal diameter to 7 mm, and zirconia sand as tube filler.

In order to define the real behaviour of the developed process, dies and cores for industrial validation were defined. Die sand mould patterns were constructed and internal cooling tubes conformed. The mould patterns are 5 mm oversized in comparison with finished die, due to the necessity of having enough material to machine the exterior of the casting to obtain the desired quality and dimensions.

Table 4: Base alloy composition (% in weight).

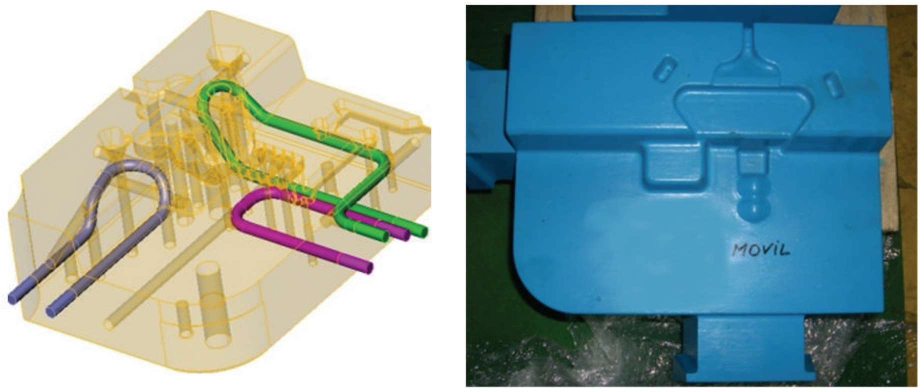
Element	C	Mn	Si	Cr	Ni	Mo
%	0.22	0.80	1.00	3.00	0.70	0.35

Demonstrators were tested with a H13 base steel having the composition shown in Table 4.

The Fe(TiMo)C master-alloy was produced by powder metallurgy and promoting a SHS reaction. The powders of Ti (48%, 100 μm size), C (12%, 1–3 μm), Mo (10%, 10 μm), and Fe (30%, 30 μm) were mixed and they were then pressed. The briquette was introduced into a reactor and was directly heated by an electrical current. Once reaction started, electrical current was stopped and there was an autopropagation of the reaction without any external energy contribution. We can observe in Figure 6 a master-alloy sample.

Using an insulation furnace, 250 Kg of H13 base alloy was melted at 1650°C. The master-alloy Fe(TiMo)C was added to molten steel in a 7.5% concentration in weight. When the master-alloy was dissolved in the base alloy, the composite material (steel + ceramic particles) was cleaned and poured at 1660–1665°C in the sand moulds.

Once the castings are solidified, cooled, and demoulded as we can see in Figure 7, in order to make easier, the machining is necessary to decrease the hardness by an annealing process. Annealing temperature was established in 980°C with 4 hours of residence time. After that, the parts were shot-blasted in order to eliminate the skin of the metal that had been in contact with the sand mould and also to detect possible superficial shrinkage cavities and other foundry defects, the risers of the feeding and filling channels were cut. We can observe in Figure 8(a) the annealing process



(a) (b)

Figure 3: (a) Cooling optimisation, (b) sand mould pattern.

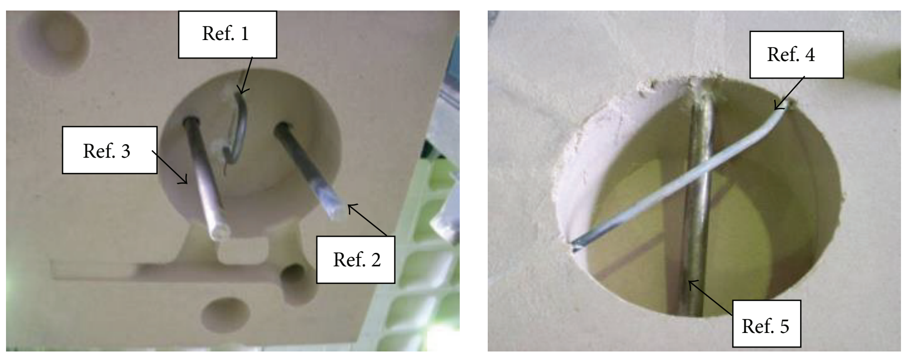


Figure 4: Placement of cooling tubes in the test sand mould.

in a heat treatment four and in Figure 8(b) one part after shot blasting, without risers, channels, and so forth.

When the part it's machined is possible to observe the external skin that has been in contact with sand mould, which it's very hard because it contains very hard oxides (see Figure 9(a)). After machining, the part is quenched in air at 890°C (4 hours) and tempered at 580–600°C (4 hours). The tempering heat treatment reduces the hardness of the part to 45–48 HRC. A very fine machining is often required in order to get final dimensions, due to the distortions caused by heat treatments on the part. In Figure 9(b) we can observe the final HPDC core sample.

4. Results and Discussion

The thermal fatigue bars were used to determinate the process parameters and properties of the obtained parts. To determinate the most suitable temper temperature, the conventional base alloy and the reinforced alloy were tempered at different temperatures. In Figure 20 we can observe how the hardness decreases when we increase the temper temperature in base alloy (B.Alloy) and reinforced alloy (R.Alloy).

In Figure 21 we can observe how in both cases the resilience value is increased by using a higher temper temperature.

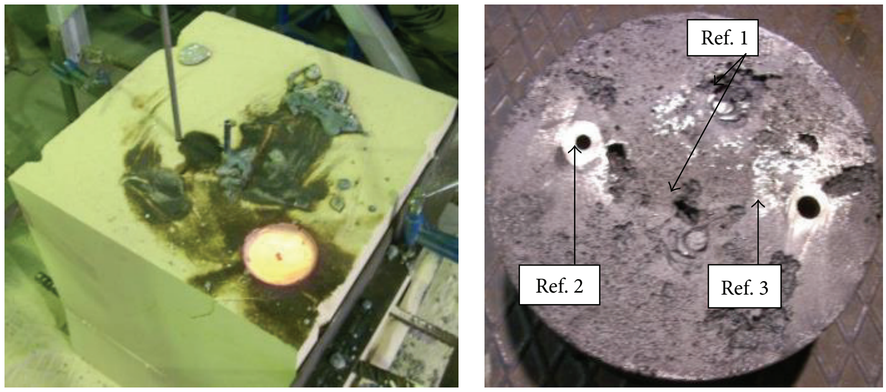
In order to determinate the optimum temper temperature, we can observe in Figure 22 how at 580°C and 600°C balance properties of hardness and resilience are quite similar.

Indeed, pin on disk tests have been performed with the alloys, showing that when we increase the tempering temperature, the wearing speed is increased. Also, the reinforced materials have a much better behaviour to wearing than base alloys, as shown in Figure 23.

With the previous results, the reinforced material with a temper temperature of 580°C has been elected to be tested in tensile test and to be employed in validation test. There is not a big difference between a temperature of 580°C or 600°C, because there is a balance between the obtained properties.

Table 5 shows the ultimate tensile strength and yield strength expressed in MPa and the elongation in % for the base alloy and for the reinforced alloy with a temper temperature of 580°C. We can observe a slight increase in the ultimate tensile strength (UTS), as well as an important increase of yield strength (YS). However the elongation drops from 19% to 11%.

As much as the main properties that influence the life of a die are the thermal shock resistance and the hardness, the two alloys were tested during 100.000 cycles in the thermal fatigue test machine. Test bars were analysed under magnetic fields in order to determinate the severity of the cracks generated by thermal shocks. The reinforced alloy did not show any crack



(a) (b)

Figure 5: (a) Sand mould with poured metal, (b) study of metal penetration.

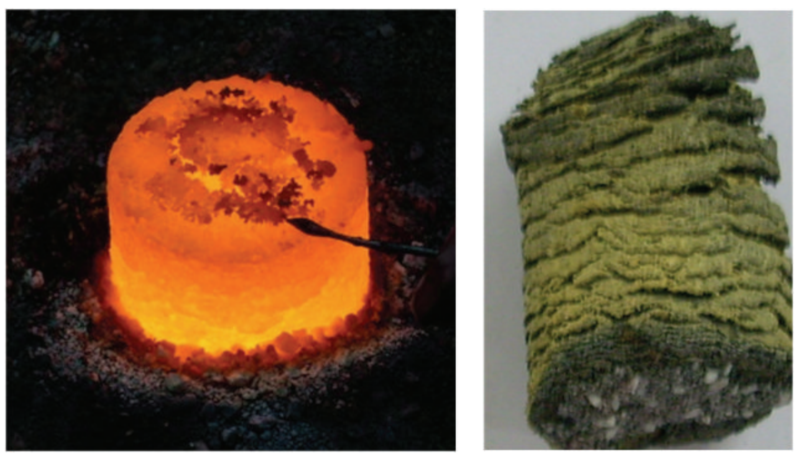


Figure 6: SHS produced Fe (TiMo) C master-alloy.

Table 5: Ultimate and tensile strength for base and reinforced alloy.

	UTS (MPa)	YS (MPa)	Elongation (%)
Base alloy (tempering temp. 580°C)	1.050	775	19
Reinforced alloy (tempering temp. 580°C)	1.070	980	11

after 100.000 cycles. We can observe in Figure 10 the base alloy test bar with cracks after sand blasting (Figure 10(a)) and under magnetic fields (Figure 10(b)).

4.1. Microstructure. The steel microstructure is based on a tempered martensitic matrix with inserted and dispersed ceramic carbide particles, as it can be seen in Figure 11(a).

In Figure 12 we can notice the difference between base steel and the reinforced one. The reinforced material has well distributed primary ceramic carbides.

4.2. Validation Tests. The best treated material was used to obtain real die casting pieces with a sampling die. Production and quality rates and total die life was compared with standard materials and cooling circuits. For that, validation tests were made at Fiasa with a comparable die with 4 identical cavities. Three cores were made with base alloy and another was made with the reinforced alloy (Figure 19). A very aggressive alloy for the die, an Al Si10 Mg with a Fe concentration minor than 0.1%, was selected in order to work in the worst conditions.

The minimum distance between the surface of the mould and the refrigeration tube was established in only 10 mm, where at least 25 mm is required in standard dies (see Figure 13).

A thermal camera was employed in order to determinate the different core external temperature, maintaining the same

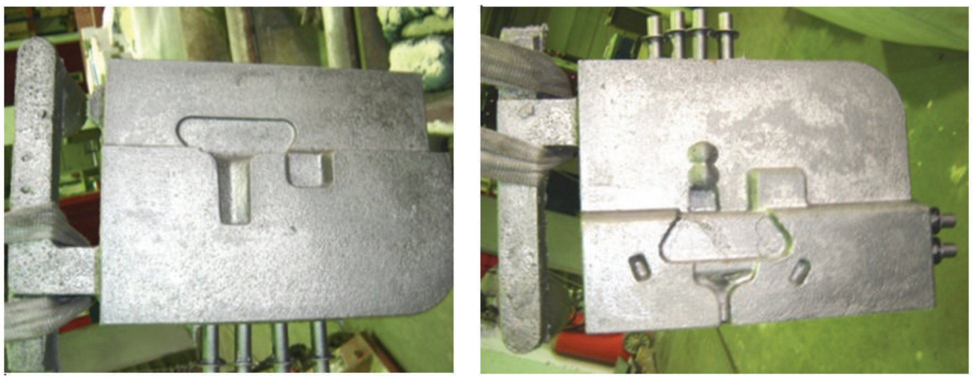
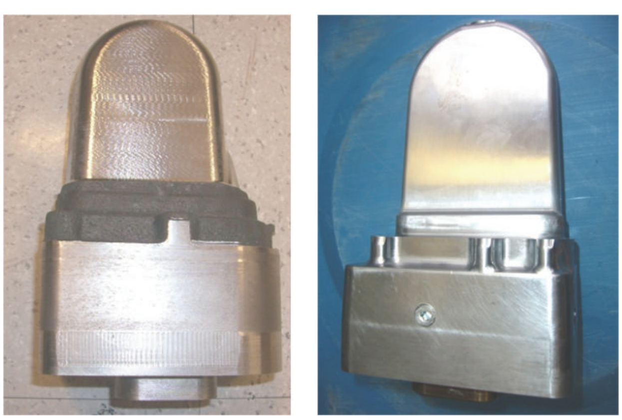


Figure 7: Example of cast HPDC parts with internal cooling circuits.

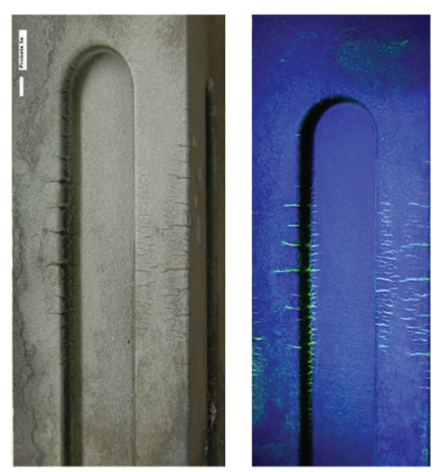
(a) (b)

Figure 8: (a) Annealing furnace, (b) shot blasted part with superficial defects.



(a) (b)

Figure 9: (a) Partial machined part with contact skin, (b) finished HPDC core.



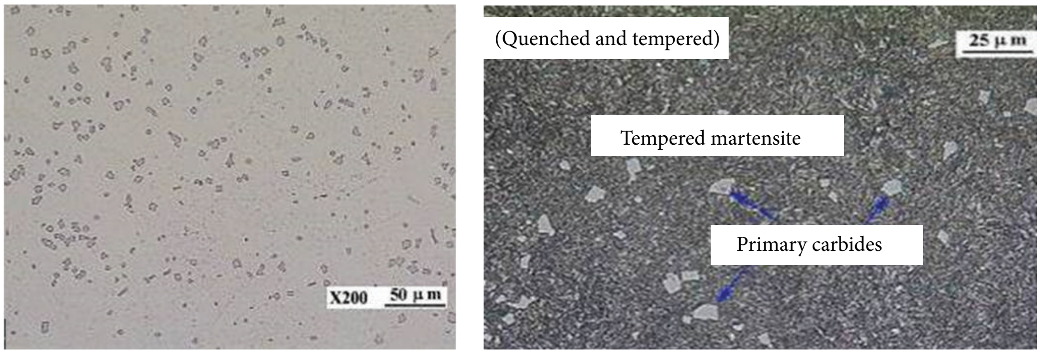
(a) (b)

Figure 10: Thermal stress produced cracks observed (a) under magnetic particles, (b) after sand blasting.

water flow in all the cores. We can see in Table 6 the average values in the same testing area.

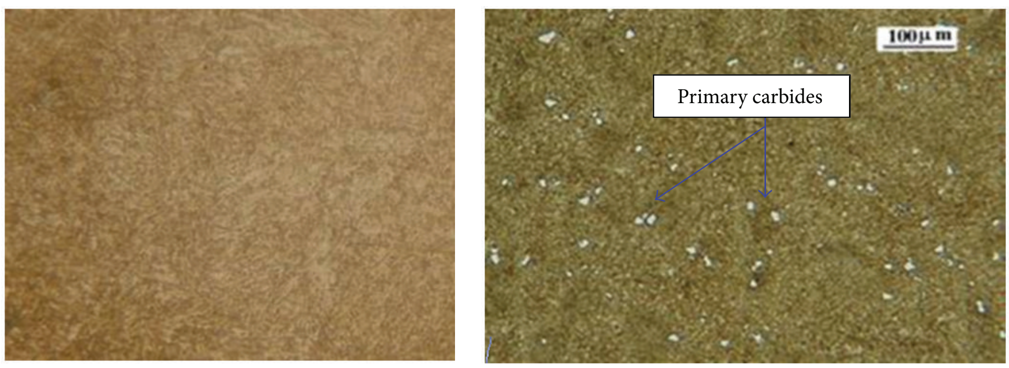
After only 3.505 injections, the cores were extracted and compared, in order to determinate the performance of the new alloy. In Figure 13 we can observe how the erosion has been much higher in the base alloy (Figure 14(a)) than in the reinforced alloy (Figure 14(b)).

Some heat cracks due to high thermal stresses were detected in the core area where the distance between the cooling circuit was nearer to the surface of the core (see Figure 15). The cracks copy the internal curve shape of the cooling circuit, and what it shows is that the minimum



(a) (b)

Figure 11: (a) Micrograph without attack, (b) attacked micrograph.



(a) (b)

Figure 12: (a) Micrograph without attack, (b) attacked micrograph.

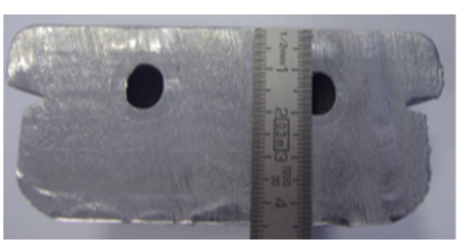


Figure 13: Reinforced alloy core with the internal cooling place at 10 mm and 20 mm from surface.

Table 6: External temperature of cores.

	Reinf. alloy core 1	Base alloy core 2	Base alloy core 3	Base alloy core 4
Temperature (°C)	140	178	180	180

distance from the cooling channel should be at least of 20 mm.

In order to study the cracks and the interphase between the internal cooling tubes and the reinforced alloy, the part was divided in 6 different areas (as shown in Figure 16).

Table 7: Micro-hardness of reinforced alloy core.

Ref. 1	Ref. 2	Ref. 3	Ref. 4	Ref. 5	Ref. 6
320	308	317	319	318	317

In Figure 17 we can observe how the cracks advance from the external surface of the core to the cooling circuit perpendicular to the surface.

Also we can see there is a metallurgical continuity between the tube and the reinforced alloy material, as shown in Figure 18. No porosity or brittle interphases are detected.

Micro-hardness (HV_{10}) values were measured in order to determinate a possible temper action in the core by repetitive injections. We can see in Table 7 the average values for the six different areas. Micro-hardness was determined by 3 measurements in 6 different points for every sample, from the external surface to the tube. There are not sensible differences between the values in the surface or in the inside area.

The average micro-hardness before testing the core in the foundry was 329 HV10. So there are not big differences between the samples before and after working.

The injected parts quality was compared also after 3.505 injections. A clear difference was determined in the injected part. The part obtained with the unreinforced material show a poorer surface quality, with cracks in the surface and thicker

(a)

(b)

Figure 14: (a) Base alloy core, (b) reinforced alloy core.

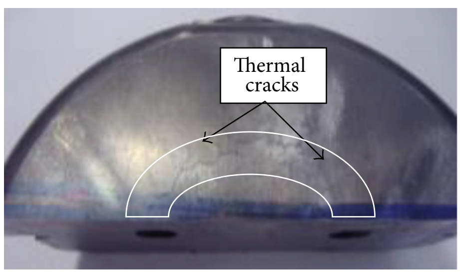


Figure 15: Heat cracks with the internal cooling circuit shape.

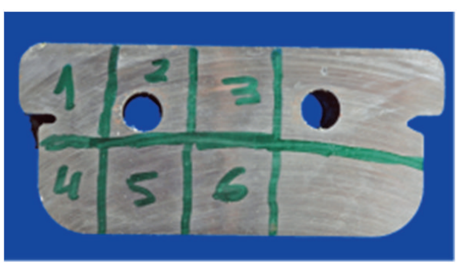


Figure 16: Heat cracks with the internal cooling circuit shape.

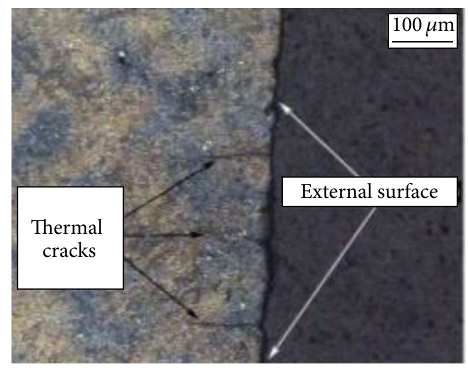


Figure 17: Heat cracks with the internal cooling circuit shape.

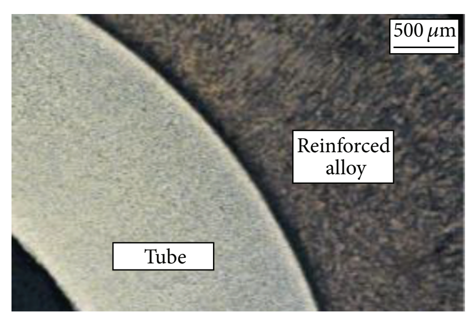


Figure 18: Interphase between tube and reinforced material.

over material in the eroded area, in coincident with the eroded and cracks areas showed in Figures 14 and 15.

5. Conclusion

There are several methods to construct dies, but nowadays it is necessary large machining operations in order to obtain the desired shapes and internal cooling circuits with several constraints in the design. Rapid prototyping process cannot afford by the moment the same results than machining dies from 3D forged hot work steels.

The SHS process allows developing a ceramic Fe(TiMo)C master alloy that is dispersed in the molten steel and after solidification gives a martensitic matrix reinforced with particles of carbides (TiMo)C well distributed.

This composite material allows increasing the UTS, YS, hardness, and wearing, with a decrease in elongation and to impact. Thermal fatigue is also increased with the new reinforced alloy. These properties are obtained producing the near-net shape dies by pouring the liquid material into sand moulds, what permits reducing drastically the machining operations and costs, reducing delivery times in about 2 weeks.

The use of stainless steel tubes filled with zirconia sand allows developing customized cooling circuits, reducing the necessities of machining operations to construct the cooling circuits, given a better thermal control. Also a good continuity between the tube and the reinforced alloy is observed.

Verification tests of new reinforced alloy on casting pieces show an increase on the life time, a decrease in core temperature in working conditions, but also a limit in the distance from the cooling circuits to the surface of the part, due to heat cracking.

(a) (b)

Figure 19: (a) Base alloy cast part, (b) reinforced alloy cast part.

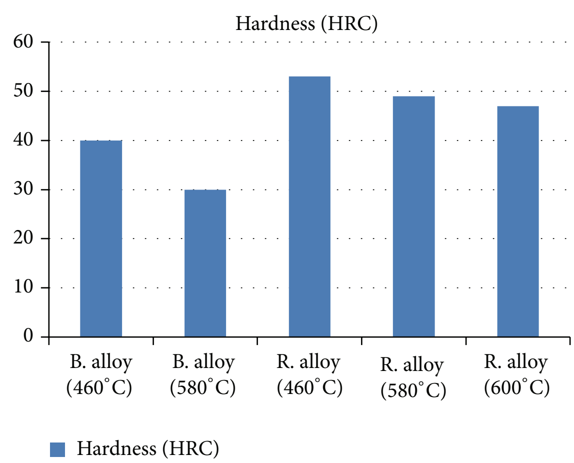


Figure 20: Hardness variation in function of temper temperature.

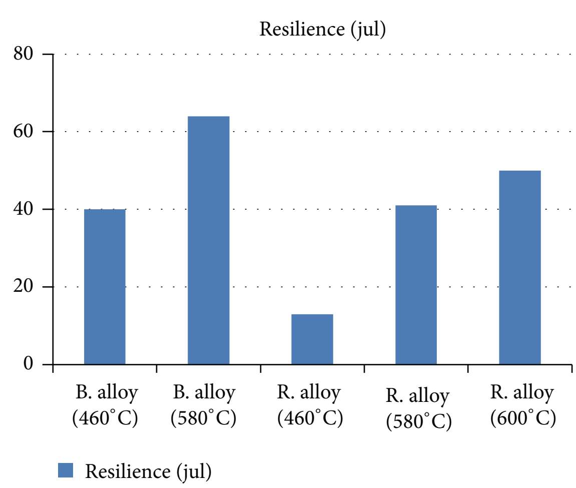


Figure 21: Hardness variations in function of temper temperature.

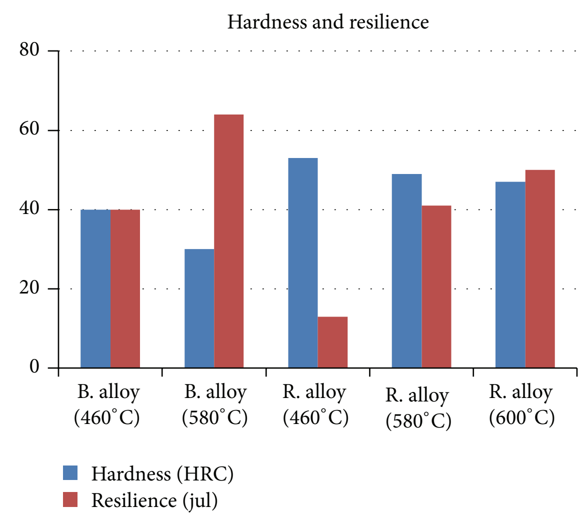


Figure 22: Hardness and resilience variations in function of temper temperature.

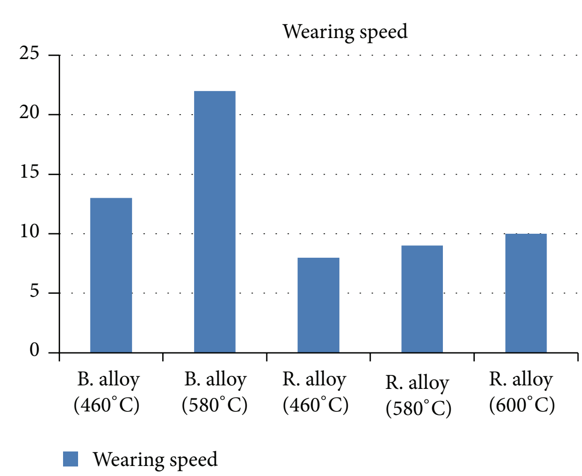


Figure 23: Pin on disk wearing speed comparison.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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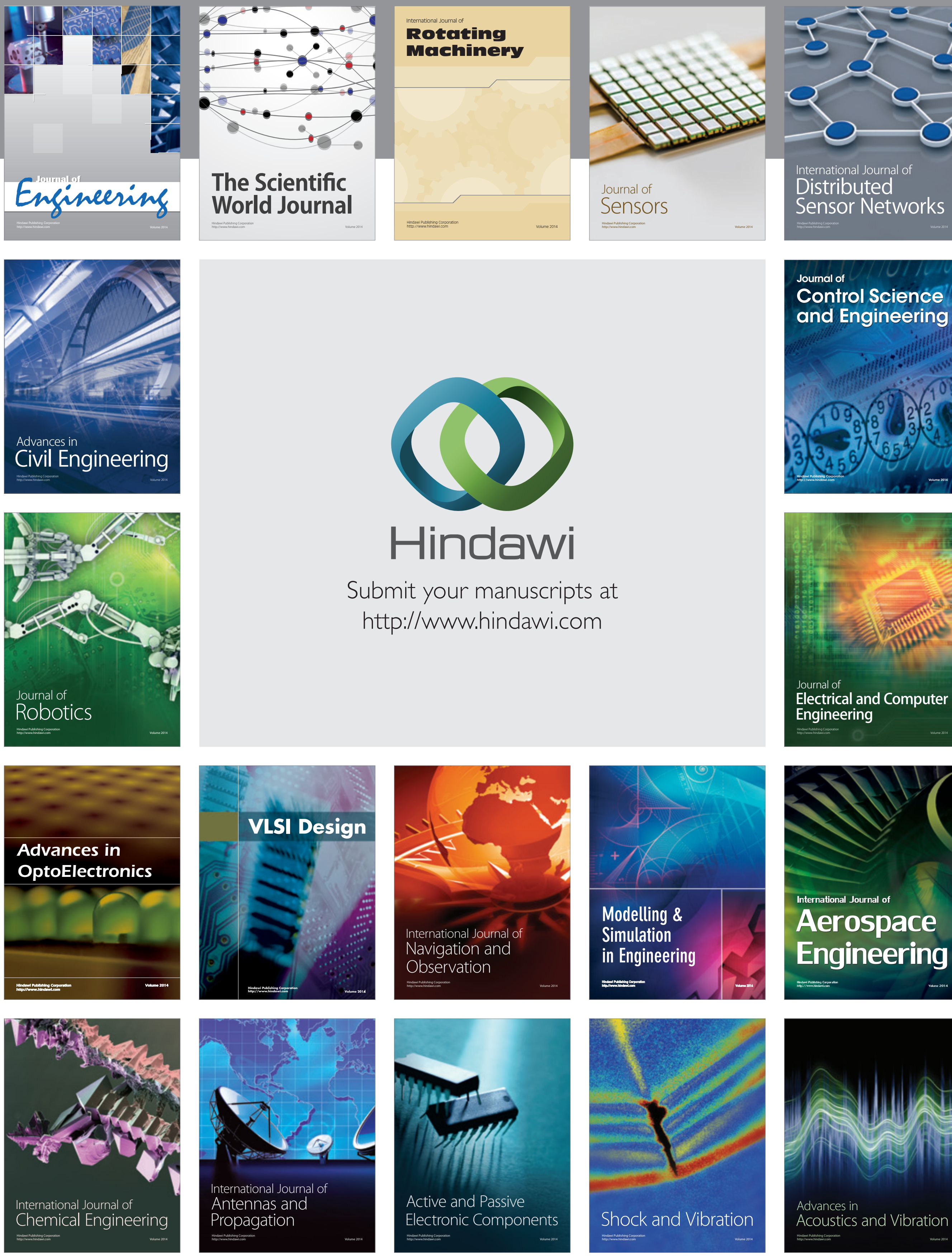
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