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Improved Mechanical Properties of Casting Made by New LPIC Technology

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Abstract

Nowadays, the emphasis is on improving the integrity of precision castings of Fe, Ni and Co alloys (improving the mechanical properties of the material and increasing process efficiency) more than ever before. For this reason, a technology has been developed which is a combination of low-pressure casting and investment casting. The premise of the combination of these technologies is that a high degree of automation should be achieved, based on low-pressure casting, while bottom filling will reduce reoxidation phenomena during filling. Mainly due to the higher purity of the melt, higher values of mechanical properties in conjunction with shape and geometric accuracy are expected, which guarantees the investment casting. For this purpose, an experimental casting machine has been designed, which is a combination of these two technologies, where we are able to eliminate the disadvantages of low-pressure casting, which include, for example, the low variability of the usable materials, as well as the disadvantages of investment casting, which include the low automation of the process. Using an experimental machine, tensile and impact test samples were cast and subsequently tested. From the initial experiments, it can be said that using this technology we are able to cast materials based on Fe alloys, Ni alloys and Co alloys with mechanical property values that are even close to or within the range of mechanical properties of the formed materials. As a result, the mechanical properties of castings cast by the LPIC method are shown to be tougher and stronger.

Keywords: Innovative Foundry Technologies and Materials, Mechanical Properties, Low Pressure Investment Casting (LPIC) Technology, Casting Integrity, Steel Casting

1. Introduction

Nowadays, the demands on the quality and integrity of castings are constantly increasing. Especially for castings made of steel and special alloys (based on Ni and Co), the shape granularity of castings is increasing at the expense of reducing wall thicknesses and reducing casting weights.

In terms of casting requirements, we are already encountering the limits of foundry technology - both in terms of technology and metallurgical processing.

It is important to mention here that both steels and Ni and Co alloys have significantly poorer foundry properties than, for example, cast irons. [1, 4]

There are several ways in which higher part integrity, more complex shape complexity can be achieved. One technology that allows this increase is casting on a meltable model in shell molds. This technology uses preheated shells up to temperatures of 1100°C, which will greatly help to offset the disadvantages of the poor foundry properties of Ni steels and Co alloys. [2, 5] Unfortunately, even this technology itself is not all-powerful and is subject to a number of foundry defects (especially in terms of reoxidation phenomena - formation of inclusions). There is a way to use vacuum casting, but due to higher costs it is mainly used for special castings of special alloys. [3, 6]

However, there are several possible technological and metallurgical solutions:

- Tree and sprue design,

- Metallurgical route in the form of ultra-fine structure,
- Development of a new technology.

1.1. Design of inlet systems

There are a number of papers dealing with the design and solution of optimal inlet systems for various materials, however steels are a relatively unexplored area. In general, the following assumptions have been confirmed within the research:

- The filling of the mould with alloys susceptible to reoxidation should be continuous to ensure laminar flow. Elimination of oxide inclusions and trapped air in the mould is an important prerequisite.
- The inlet system also acts as a pour, therefore it is necessary to ensure a directed solidification towards the inlet system. This eliminates the occurrence of stagnation.
- The inlet system must have sufficient stiffness. The wax tree must not deform during the production of the ceramic packaging.
- The shell shall be made so that it is easily removable after casting and solidification of the casting.
- The sprue system for precision casting should be simple to manufacture, both in terms of the preparation itself and in terms of ensuring a quiet filling of the mould.
- The design of the sprue system must, on the one hand, ensure the quality of the casting and, on the other hand, reduce the cost of the casting, since materials cast by the precision casting method are incomparably more expensive compared with conventional castings.

By optimizing the sprue systems through simulations, it was concluded that the shape of the impact well has a great influence on achieving a quiet filling. Essentially, this is the area of the mould that comes into contact with the melt first and is therefore potentially the most important element to ensure a calm flow of melt from the casting basin. This finding should provide foundries with a significant reduction in scrap and improved casting integrity.

1.2. Secondary metallurgical processing

However, the solution of simulations in simulation software wants to know the exact thermomechanical and physical data for each material. Among other input data, such as ambient and casting temperatures or filling speeds, it is essential to know the physical parameters of the cast materials. However, these parameters are very difficult to determine, especially as a function of temperature up to temperatures above liquidus. These are properties such as thermal conductivity, density, heat capacity, enthalpy, latent heat, liquid and solidus temperature, viscosity, surface tension and permeability. For this, thermal analysis methods can be used.

Influencing crystallization and thus refining the grain to an ultrafine structure can be achieved by alloying elements such as bismuth and mischmetal and monitoring the mechanical properties and chemical composition in cast samples. [8]

Alloying with mischmetal has demonstrated the following:

- Reduction of the number of inclusions in the material structure,
- Change in the shape of the inclusions to rounded
- Increase in microhardness values,
- Reduction of Charpy impact test values [9-12].

1.3. Change of technology

Gravity die casting technology has its limits. These limits in terms of achieving an intrinsically high quality homogeneous casting can be overcome, but at an associated cost, which is a critical criterion for any change in production. For this reason, the direction of the research focused on changing the production technology. A low pressure shell moulding technology was proposed for castings that require a significant increase in integrity. There are records of experiments that address this issue of increasing the integrity of castings, however, firstly none have been applied in practice and secondly they deal with materials with significantly lower casting temperatures such as aluminium or magnesium alloys. [7, 13]

In cooperation with the IEG precision casting foundry in Jihlava, an experimental facility for low-pressure casting of shell moulds for materials with higher melting temperatures, i.e., hot-rolled steels, cast irons, and nickel and cobalt superalloys) has been designed for the time being. The entire process of the proposed casting technology is still being optimised. Simulating the casting process in NovaFlow&Solid software has proven to be a very effective tool. In this way, time and especially material savings can be achieved. The preparation of the tree and the preheating of the mould is estimated to take two to three days and in case of failure the whole preparation is invalidated within a few seconds of filling.

2. Description of the approach, work methodology, materials for research, assumptions, experiments etc.

For this experiment, the casting device shown in Fig. 1 was used, capable of filling a shell mould by low pressure casting. This technology is still an unexplored area in the world. That is why the research was focused on the technology of low-pressure casting in shell moulds. On the basis of physical principles, it is possible to increase the integrity of the casting up to a region that cannot be achieved by conventional gravity casting into a shell mould and the mechanical properties of the cast materials are close to those of moulded materials. The experimental low-pressure machine has been developed with a view to casting materials normally cast from 1300 °C upwards. Every design detail of the newly developed machine had to be adapted to these elevated temperatures. In particular, the following components:

- The melting furnace for a 20 kg steel charge had to be designed in such a way that a pressure-tight lid could be fitted and with regard to melting temperatures – in order to be able to melt alloys with a melting temperature above 1200 °C, the induction,

- The riser tube through which the melt is pushed into the mould space had to withstand high temperatures and cyclic loading (material resistance up to 1800 °C),
- The melt chamber pressure control system was designed with a series of high temperature sensors and controllers,
- The system for regulating the filling and speed of shell filling was one of the most important issues to achieve quality mould filling,
- The closing of the moulds after filling has been solved so far by retracting a disposable sheet metal gate.

So far, the system of clamping the shell to the casting machine before filling has been implemented using mechanically operated clamps. Compared to conventional gravity casting technology, the meltable model is a prerequisite:

- Increasing the surface quality of the casting,
- Increased internal integrity of the material – manifested in increased values of mechanical properties and specific gravity of the material,
- Possibility of casting more complex castings – at the same time the possibility of increasing the number of castings on the tree,
- Possibility of process automation – after optimization of input parameters (pressure and filling speed), likely increase in productivity,
- Stabilization of the production process – achieving similar quality castings.

Fig. 1 Experimental NTL device (a) and assembly of the ceramic mould on the device (b)

2.1. Tensile test

Tensile testing of samples cast by gravity casting and low-pressure casting is used to determine the values of mechanical properties. The test consists in deforming the test body by tensile loading according to EN ISO 6892-1.

The test specimens for the tensile test had a circular cross-section with a diameter of 8 mm and an initial length of 40 mm. The tensile test was carried out on a LabTest 5.100SP1 tearing machine, which is shown in Fig. 2.

Fig. 2. Tensile test on the machine LabTest 5,100SP1 (a) and a view of the specimen mounted in the machine chuck (b)

Samples were cut from the tree using an angle grinder with a cutting wheel designed to cut stainless steel. Subsequently, the samples were described (Fig. 4).

Trees were cast by gravity from the materials:

- AISI 304L (chemical composition see in Table 1),
- 1.0558 (ČSN 422650) (chemical composition see in Table 2).

Table 1.
Chemical composition of AISI 304L

Element	C	Cr	Ni	Fe
Element content, wt.%	0.02	18.1	8.1	rest

For comparison with gravity casting, the same trees were cast from AISI 304 and 1.0558 material in a low-pressure casting process.

Table 2.
Standardized Chemical Composition of Steel 1.0558 According to EN 10293 [20] (ČSN 422650)

Element	Chemical composition, wt.%					
	C	Mn	Si	P_{max}	S_{max}	P+S $_{max}$*
Range	0.40–0.5	0.4–0.8	0.2-0.5	0.05	0.05	0.09

**Maximum content of unspecified elements Cr+Mo+Ni+V+Cu <1%*

Fig. 3. Low pressure die-cast tree (a) and gravity cast tree with shell (b)


Fig. 4: Separated samples from trees for tensile test

Fig. 5 shows the trend of neck formation at the edge of the measuring area. This is probably due to the small radius between the functional (test) part and the end adapted to the jaws of the testing machine. This is probably due to inhomogeneity throughout the sample volume.


Fig. 5: Tensile test samples after test implementation

2.2. Bending impact test

The test consists of breaking a test specimen with a notch with a single impact of a pendulum hammer under precisely defined conditions. According to EN ISO 148-1, the test bar has the prescribed dimensions: length 55 mm, square cross-section with 10 mm side length, V-shaped notch. The notch has an opening angle of 45°, a depth of 2 mm and a radius at the root of 0,25 mm (see Fig. 6 for samples).

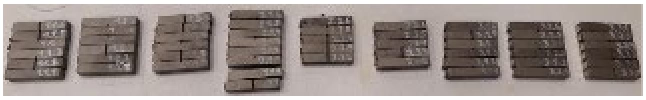
Fig. 6: Specimens for flexural impact test

The bending impact test is a standardised mechanical test used to assess the toughness of a material, i.e. its ability to absorb energy during plastic deformation. This test is particularly important for materials that are subjected to sudden loads or impacts. A 300 J and a 150 J pendulum were used. The measurements were carried out on specimens made by gravity casting and specimens made by low pressure casting, again in AISI 304L and 1.0558 materials. The measurements were carried out at an ambient temperature of 22 °C.

3. Description of achieved results of own researches

Within the expected results, it was assumed that there would be an improvement in mechanical properties of at least 5%. The following Table 3 compares the average tensile test results and the basic mechanical property values for AISI 304 material. Specimens that came out with a crack in the neck or showed a very significant statistical deviation from the results were excluded from the tests. Among the most important ones is the value of $R_{p0,2}/R_m$, which represents in a way the stock of plasticity of the material. Comparing the two ratios of the average values measured for GIC and LPIC results in a 14% increase in favour of LPIC, however, homogeneous ductility must also be taken into account. The plasticity stock is expressed as the area under the curve of the tensile diagram. The homogeneous ductility measured to the ultimate strength represents the area of neck formation and therefore the ability of the material to resist failure propagation to the ultimate strength. If we compare the average values of the homogeneous ductility of A_g, we find an increase of 125% in the case of LPIC, a value very different from gravity casting. This clearly indicates a significant increase in the plasticity stock in the case of LPIC compared to GIC. It is also interesting to compare the overall ductility (value measured up to the absolute separation of the broken sample – A in %) and the value of the homogeneous ductility (A_g in %) already mentioned. The difference between these values indicates the internal homogeneity of the material. The experimental results show almost no difference between A_g and A values in the case of gravity casting and a slight increase (about 8%) in the case of low-pressure casting. Again, an increase in material integrity is demonstrated in the LPIC case.

Table 3.
Comparison of average mechanical properties of AISI 304L for GIC and LPIC

	$R_{p0,2,}$ N/mm^2	Fm, N	$R_{m,}$ N/mm^2	Ag, %	A, %	$R_{p0,2}$ / R_m
GIC	233	37204	478	16	16	0,49
LPIC	231	42146	550	36	39	0,42
Percent. LPIC/GIC ratio, %	99	113	115	225	244	86

By comparing the absolute values, we conclude that there is a clear benefit of low-pressure casting technology in terms of increasing mechanical properties. The average values of the contractual yield strength are practically identical, there is also a 15% increase in the ultimate strength Rm and the aforementioned huge increase in toughness values of up to 144% in the case of overall toughness.

In the following Table 4 it is possible to see the comparison of the average values of the results from the bending impact test for gravity casting and low pressure casting for AISI 304L material.

Table 4.
Comparison of the average values of the bending impact test results for GIC and LPIC

	KCV, J/mm^2
LPIC	3,07
GIC	2,33
LPIC/GIC ratio, %	132

The KCV value J/mm^2 is the resultant value for comparing the results of individual notched specimens and represents the ratio of the energy required to notch the specimen divided by the real cross-sectional area under the notch. From the experimental measurements performed, it was concluded that the average notch toughness increased by 32% in the case of LPIC compared to GIC.

For material 1.0558, the following Table 5 compares the average tensile test results and the basic mechanical property values. In addition to the absolute values of the individual properties, their interpretation is very important. Among the most important ones is the value of $R_{p0,2}/R_m$, which represents in a way the stock of plasticity of the material. When comparing the two ratios of the average values measured for GIC and LPIC, the result is a 9% decrease for the LPIC method. Comparing the average values of the homogeneous ductility of Ag, we find a 19% decrease in the LPIC case, which is a different value from gravity casting. Thus, a significant decrease in plasticity stock can be observed in the case of LPIC compared to GIC. It should be noted that in the case of 1.0558, the material integrity decreases. Therefore, it would be a good idea to repeat the casting, perform mechanical property tests and re-evaluate the experiment from completely identical melts.

Table 5.
Comparison of average values of mechanical properties of material 1.0558 for GIC and LPIC

	$R_{p0,2}$, N/mm^2	Fm, N	$R_{m,}$ N/mm^2	Ag, %	A, %	$R_{p0,2}/R_m$
GIC	310	39547	513	4,32	4,42	0,60
LPIC	342	40171	519	3,48	3,57	0,66
Percent. LPIC/GIC ratio, %	110	102	101	81	81	109

However, comparing absolute values, we conclude that the low-pressure casting technology has significantly increased the contractual yield strength by 10%. Furthermore, the strength limit Rm increased by 1%, but the toughness decreased.

As in the previous measurement, the average values of the results from the bending impact tests are compared. Again, the measured energy required to break the specimen had to be divided by the real cross-section under the notch. A hammer of 150 J was used to break the test bodies. Table 4 shows that in the case of material 1.0558, there was a significant decrease in the average notch toughness for LPIC compared to GIC, by 49%. This decrease may be due to non-compliance with some metallurgical parameters – in particular, different chemical compositions, which were within the range allowed by the standard for both tests but were realized from different melts. Thus, for the LPIC technology, the Mn and Si contents were at the lower limit of the standard, while for gravity casting these values were in the middle of the range. Another reason for the drop in ductility may be the foundry's habit of casting carbon steels by gravity casting into buried shells where there is differential solidification which will affect impact toughness significantly.

Table 6.
Comparison of the average values of the bending impact test results for GIC and LPIC for 1.0558

	KCV, J/mm2
LPIC	0,100
Gravity investment casting technology	0,195
Percentage LPIC/GIC ratio	51 %

4. Discussion

Experiments at this unique workplace have shown the relatively high potential of the newly developed technology. In the examples of two materials, the values of mechanical properties are significantly better than those of gravity casting. Moreover, the results are highly statistically supported and the variance of the values is relatively small.

No one has published on these topics and it is not possible to make comparisons with the results of other authors.

The samples after tensile testing showed breaches in the neck area (Fig. 5). This could be due to micro-shrinkages, which were not confirmed on the metallographic scrapings. The fracture surfaces were also free of visible porosity. The problem here is more likely to be the small radius of the test body to the gripping parts, which was done according to EN ISO 6892-1, where the small test body diameters tend to create an indentation in the radius.

The simulations were carried out in NovaFlow&Solid software. The authors' team has previously published results where simulations were performed on multiple software. Based on these results, we can conclude that in the basic criteria (liquid phase fraction, porosity, shrinkage, solidification time), the NovaFlow&Solid, Magmasoft or Procast simulations are almost identical in their results with the same specified boundary and initial conditions. In this case, the implemented simulations showed a directed solidification for both LPIC and GIC, without any signs of porosity and micro-shrinkage.

Even when the test samples did not fracture in the expected area, the results are notable for steel castings, as they demonstrate higher strengths. This allows designers to reduce wall thickness and produce lighter castings, which is particularly beneficial for automotive applications.

5. Conclusions

An experimental study of low-pressure casting versus gravity casting was carried out on two different materials. Specifically, the materials were AISI 304L and 1.0558. Several trees with test bodies were cast from these materials. It was found that low pressure casting in the case of the AISI 304L material greatly increases the mechanical properties compared to gravity casting. There was a 15% increase in ultimate strength and also a huge increase in toughness of 144%. In the case of material 1.0558, there was an increase in the contractual yield strength but also a decrease in the toughness of the material. This clearly shows the potential of this low pressure casting technology. The other Ni and Co based alloys investigated show a trend of improvement in mechanical properties also in the range of 10 – 15%.

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