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The Effect of the Return Material Implementation into the Production of Silumin Casts on Technological and Economic Indicators of Production Process

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Abstract

The production of high pressure die casts also brings difficulties regarding the processing of the waste material. It is mainly formed by runners, overflows and other foundry supplements used and, in the case of machines using the cold chamber, also the remainder from this chamber. As this material is often returned to the production process, we refer to it as return material. In the production process, it is therefore essential to deal with the proportion issue of return material against primary material that can be added to the melt to maintain the required cast properties. The submitted article monitors the quality properties of the alloy, selected mechanical properties of casts and porosity depending on the proportion of the return material in the melt. At the same time, the material savings are evaluated with regards to the amount of waste and the economic burden of the foundries. To monitor the above-mentioned factors, series of casts were produced from the seven melting process variants with a variable ratio of return to the primary material. The proportion ratio of return material in the primary alloy was adjusted from 100% of the primary alloy to 100% of the return material in the melting process. It has been proven that with the increasing proportion of the return material, the chemical composition of the melt changes, the mechanical properties of the alloy decrease and the porosity of the casts increases. Based on the results of the tests and analyzes, the optimal ratio of return and primary material in the melting process has been determined. Considering the prescribed quality of the alloy and mechanical properties, concerning the economic indicator of the savings, the ratio is set at 70:30 [%] in favor of the primary material.

Keywords: HPDC, Product development, Quality management, Mechanical properties, Castings defects

1. Introduction

The solid cast removed from the die is referred to in foundry practice as raw. Rough cast is defined as a raw cast free from leaks, runners, auxiliary overflows, fine-grained burrs and other foundry supplements. The rough cast corresponds to the cast drawing [1,2]. The mass difference between the raw and rough cast can be defined and subsequently considered as waste material. In the case of its reimplementation into the production process, it is referred to as a return material. The returned material also includes mass-significant residues from the cold chamber [3]. The proportion ratio of return material in the rough cast is dependent on the size of the rough cast. According to its size, the proportion ratio of return material varies from 20% for large casts to 75% for small casts. For machines with a cold chamber, it is up to 65% of the liquid metal mass, for machines with hot chamber it is up to 50% [4].

Due to the large proportion ratio of return material that needs to be re-melted, it is necessary to pay attention to some principles, by which we will ensure that the alloy maintains the prescribed properties. Above all, the return material must be carefully sorted. A distinction must be made between pure and contaminated return material. Only scrap casts should be fundamentally considered as pure return material. In some cases, gating systems can also be considered as pure material. In cold chamber machines, the contaminated material consists mainly of oil-contaminated filling chamber residues, alloy splash and oil-contaminated scrap casts [5-7].

The implementation of return material into the production process entails increased demands on the purification treatment and refining of the alloy. Impurities entering the process during the re-melting and casting are one of the primary roots of foundry defects and have a negative impact on the mechanical properties of the Al-Si components [8].

Solid impurities and various oxide inclusions are one of the primary impurities present in the process of return material implementation into the melt. Return material has a higher specific surface area and may have higher inner inclusion content than primary alloy blocks, which increases the total inclusion content of the casts [9,10].

The proportion ratio of return material implementation is also reflected in the change in the chemical composition of the alloy and the microstructure change, which has a consequent effect on the mechanical properties of the casts. The microstructure is mostly affected by the presence of iron, which can originate from tools and return material and tends to be deposited on the bottoms of melting furnaces, where it can accumulate to high levels [11,12].

Trace amounts of iron Fe, in an amount of 0.3% - 0.5% in Al-Si alloys is generally desirable. The presence of a small portion of iron has a positive effect on the running property of the alloy, prevents the alloy from attaching to the mold walls, increases the strength and, in larger quantities, the heat resistance [13,14].

On the other hand, the increased proportion of Fe particles in Al-Si alloys impairs the mechanical properties of the casts. Iron with other elements present in Al-Si-Cu-Fe alloys forms intermetallic phases, such as Al3Fe, Al7FeCu2, Al8Fe2Si, Al5FeSi. The Al5FeSi phase, also known as the β-phase, has a greater effect on the structure and mechanical properties than the α-phase. It has a shape of a block and, when observing the microstructure, represents the shape of a needle. The occurrence of long blocks of this phase promotes the start of fatigue fractures and increases the porosity, as it interferes with the flowing melt during solidification [15].

The submitted article addresses the issue of return material implementation into the production process of silumin-based casts. The percentage of primary and return material and its effect on the chemical composition of the alloy and the mechanical properties represented by the permanent deformation and surface hardness of the casts are investigated. Simultaneously, economic indicators are analyzed concerning the savings of primary material. The results of individual measurements are based on mutual correlation, based on which a recommendation is established for the maximum proportion ratio of return and primary material and concerning the prescribed properties of casts.

2. Experimental procedure

The analysis of the effect of return material proportion on the technological and economic aspects of the production process was performed on the casts of the pump flange shown in Figure 1.

Fig. 1. Location of monitoring points

The permanent deformation examination "s" was performed on the TIRAtest 28200. The permanent deformation values in the area of the cast mounting hole labelled as the critical point of the cast were monitored (Figure 1). This area is labelled as critical due to the force load after the assembly. Simultaneously, respecting the melt flow around the core, it is possible to assume an increased proportion of pores in this area.

Since the melt flow around the cores, the splitting and subsequent joining to the melt stream during circumfluence of the cores provide the preconditions for an increased porosity, the porosity analysis was performed in the area around the mounting holes. Macroscopic analysis of porosity is performed using OLYMPUS GX 51 microscope, and subsequently, the percentage of porosity in the area of metallographic cuts is evaluated using ImageJ software.

The surface hardness measurement of the casts was performed according to Brinell on an HPO 250 device. The hardness measurement conditions were in accordance with standard EN

6506-1 (ball diameter D = 2.5 mm, stress force F = 613 N, stress time t = 10 s).

Chemical analysis of the composition of experimental melts with variable proportion rate of return material in the batch was performed with a Q4 TASMAN optical emission spectrometer.

The casts were produced of alloy EN AC 47 100 (AlSi12Cu1(Fe)). The prescribed chemical composition of the alloy in accordance with EN 1706 (STN 42 4310) is presented in Table 1.

Table 1.
Chemical composition of the alloy in accordance with EN 1706

Al	residue
Si	10.5 – 13.5
Fe	max. 1.5
Cu	0.7 – 1.2
Mn	max. 0.55
Mg	max. 0.35
Cr	max. 0.1
Ni	max. 0.3
Zn	max. 0.55
Pb	max. 0.2
Sn	max. 0.1
Ti	max. 0.2

The mechanical properties of the alloy EN AC 47 100 in accordance to the standard EN 1706 are given in Table 2.

Table 2.
Prescribed mechanical properties of the EN AC 47 100 alloy

Property	Value
Tensile strength R_m, MPa	240
Tensile yield strength $R_{P0.2}$, MPa	140
Elongation A_5, %	1
Hardness, HB	70

The cast was produced in series of seven melting processes, with a variable proportion ratio of primary and return material, according to Table 3. From each melting process, 5 experimental casts were selected by random sampling, on which the qualitative production indicators were monitored, represented by mechanical properties dependent on the proportion of return material in the batch.

Table 3.
Composition of experimental melting processes

Melting process number	Proportion of primary material	Proportion of return material
MP 1	100%	0%
MP 2	90%	10%
MP 3	80%	20%
MP 4	70%	30%
MP 5	50%	50%
MP 6	30%	70%
MP 7	0%	100%

A semi-automatic horizontal cold chamber casting machine with the type designation Müller Weingarten 600 was used to produce the casts. The setting of technological casting factors was constant for all melting process variants and is presented in Table 4.

Table 4.
Setting of casting cycle technological parameters

Parameter	Value
Piston velocity in 1st phase, $m.s^{-1}$	0.3
Piston velocity in 2nd phase, $m.s^{-1}$	2.6
Holding pressure, MPa	25
Melt temperature, °C	705
Mold temperature, °C	200
Piston diameter, mm	80
Length of the filling chamber, mm	350
Biscuit height, mm	25

3. Achieved results

The results achieved by the experiments can be divided into three parts. The first part describes the change in the chemical composition of the melt induced by the implementation of return material to the melting process. The second part describes the modification of selected quality properties of casts. The third part describes the economic aspects of return material implementation into the batch.

3.1. Melting process chemical composition analysis

Table 5 documents the results of the spectral analysis of chemical composition of individual melting processes depending on the percentage proportion change of return material in the batch.

Table 5.
Experimental melting processes chemical composition

	MP 1	MP 2	MP 3	MP 4	MP 5	MP 6	MP 7
Al	85.72	85.37	84.61	84.16	83.79	83.13	82.50
Si	11.56	11.78	12.43	12.59	12.87	13.15	13.38
Fe	0.75	0.89	0.94	1.18	1.26	1.53	1.63
Cu	0.89	0.94	1.05	1.15	1.19	1.34	1.65
Mn	0.29	0.24	0.23	0.21	0.20	0.18	0.17
Mg	0.32	0.31	0.26	0.23	0.22	0.20	0.19
Cr	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Ni	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Zn	0.35	0.35	0.36	0.36	0.35	0.35	0.36
Pb	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Sn	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Ti	0.03	0.03	0.03	0.03	0.03	0.03	0.03

From Table 5, it is apparent that with the proportion of return material exceeding 50%, the volume of the element Fe and Cu exceeds the prescribed chemical composition of the EN AC 47 100 alloy.

3.2. Analysis of qualitative properties

Permanent deformation, surface hardness and porosity at the critical point of cast are chosen among the selected qualitative indicators of the cast quality.

3.2.1. Assessment of casts' permanent deformation

According to the GME 06007 standard, depending on the geometry of the experimental samples, the technological parameters of the samples were determined: Fa = 16 kN, Fm = 8 kN, pressing velocity v = 10 mm.s^{-1}. According to the prescribed values in compliance with the GME 06007 standard, the maximum value of permanent deformation for a given experimental sample can reach the level s = 0.025 mm, which represents 0.5 % of the mounting hole length l = 5 mm.

Table 6 presents the measured values of permanent deformation depending on the return material percentage implemented to the batch.

Table 6.
Measured values of the permanent deformation depending on the return material percentage

Sample No.	Proportion of return and primary material	Permanent deformation s, mm	Arithmetic mean
Sample 1-1		0.013	
Sample 1-2	MP 1	0.011	
Sample 1-3	primary 100%	0.014	0.013
Sample 1-4	return 0%	0.016	
Sample 1-5		0.012	
Sample 2-1		0.018	
Sample 2-2	MP 2	0.014	
Sample 2-3	primary 90%	0.019	0.016
Sample 2-4	return 10%	0.014	
Sample 2-5		0.015	
Sample 3-1		0.020	
Sample 3-2	MP 3	0.019	
Sample 3-3	primary 80%	0.022	0.020
Sample 3-4	return 20%	0.019	
Sample 3-5		0.018	
Sample 4-1		0.024	
Sample 4-2	MP 4	0.026	
Sample 4-3	primary 70%	0.021	0.023
Sample 4-4	return 30%	0.023	
Sample 4-5		0.023	
Sample 5-1		0.033	
Sample 5-2	MP 5	0.036	
Sample 5-3	primary 50%	0.035	0.036
Sample 5-4	return 50%	0.038	
Sample 5-5		0.037	
Sample 6-1		0.039	
Sample 6-2	MP 6	0.041	
Sample 6-3	primary 30%	0.045	0.043
Sample 6-4	return 70%	0.042	
Sample 6-5		0.044	
Sample 7-1		0.057	
Sample 7-2	MP 7	0.046	
Sample 7-3	primary 0%	0.048	0.052
Sample 7-4	return 100%	0.051	
Sample 7-5		0.058	

Based on Table 6, a dependency graph of the average values of permanent deformation s on the proportion ratio of return material in the melting process was constructed, shown in Figure 2. As mentioned above, according to GME 06007 standard, the maximum allowed value of permanent deformation for a given experimental sample is 0.025 mm. No sample from the series of melting processes MP 1 – MP 3 – blue color exceeded this value. In MP 4 – orange, one value was above the critical one. The arithmetic mean of the measured values of permanent deformations falls under the critical value. Permanent deformation of the samples from MP 5 – MP 7 is above the critical value, thus the higher proportion ratio of return and primary material than 50:50 can be determined as unsatisfactory.

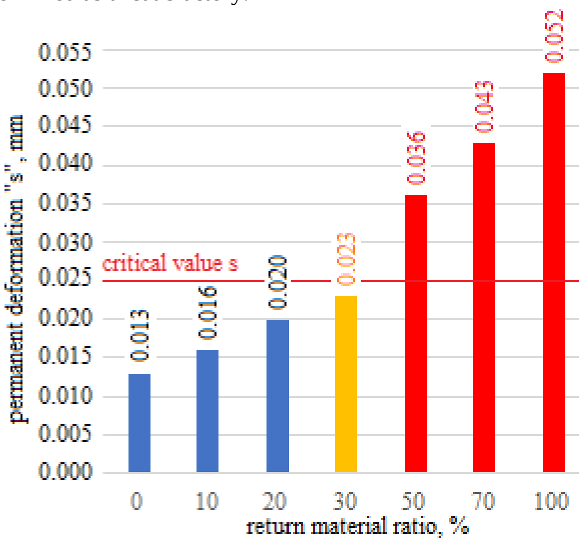

Fig. 2. Average values of permanent deformation in compliance with the return material proportion ratio

3.2.2. Surface hardness assessment of casts

The Brinell HB surface hardness of casts produced from the series of melting processes with variable proportion ratio of return and primary material was monitored at five areas of the casts. The assessment of the surface hardness was performed on the casts that with the values of permanent deformation were approximating the values of permanent deformation arithmetic mean in series, from which they were selected according to Table 6. The results of measurements are stated in Table 7.

Table 7
Surface hardness values of casts dependent on the proportion ratio change of return and primary material

	Measurement of hardness, HB					
Sample No.	No. 1	No. 2	No. 3	No. 4	No. 5	Average
1-1	98	97	98	97	97	97.4
2-5	96	98	95	96	96	96.2
3-1	97	98	97	96	97	97.0
4-4	97	98	98	96	98	97.4
5-2	98	96	95	96	96	96.2
6-4	96	98	97	97	97	97.0
7-4	96	98	97	97	96	96.8

Based on the measured values presented in Table 7, a graphical dependence of hardness on the proportion ratio of return material in the batch depending on the casts´ average surface hardness values HB is constructed, shown in Figure 3. As can be seen, HB surface hardness value oscillates around 97 HB. It can be stated that the implementation of return material to the batch does not have a significant effect on the surface hardness of the casts.

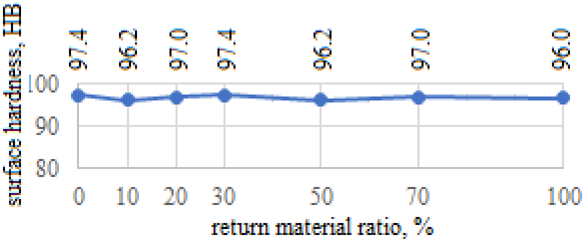

Fig. 3. Average values of surface hardness of casts depending on the proportion ratio of return material

3.2.3. Assessment of casts’ porosity

To examine the homogeneity of the experimental samples, macroscopic analysis of the longitudinal sections at the location of mounting holes was performed. These homogeneity monitoring locations were also selected concerning the possibility of investigating the correlations of porosity and permanent deformation, according to Figure 1.

The assessment of the porosity “f” of the experimental samples was performed as the assessment of surface hardness on casts which permanent deformation values approximated the arithmetic means of permanent deformation in the series from which they were selected according to Table 6. The measurement results are shown in Table 8. Subsequently, a graph of the cast porosity dependence on the proportion ratio of return material in the batch was constructed and is presented in Figure 4.

Table 8.
Porosity values depending on the change of proportion ration of return and primary material.

Sample No.	MP	Porosity „f“, %
1-1	MP 1	0.23
2-5	MP 2	0.64
3-1	MP 3	0.85
4-4	MP 4	1.86
5-2	MP 5	3.58
6-4	MP 6	5.12
7-4	MP 7	16.24

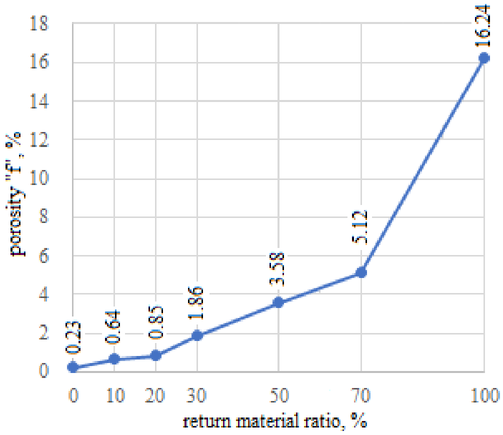

Fig. 4. Porosity change depending on the ratio of return material

It is obvious, that the homogeneity of the casts decreases with the increasing proportion ratio of return material in the batch. Figure 5 shows macroscopic representations of metallographic cuts of the samples with the lowest and highest porosity values.

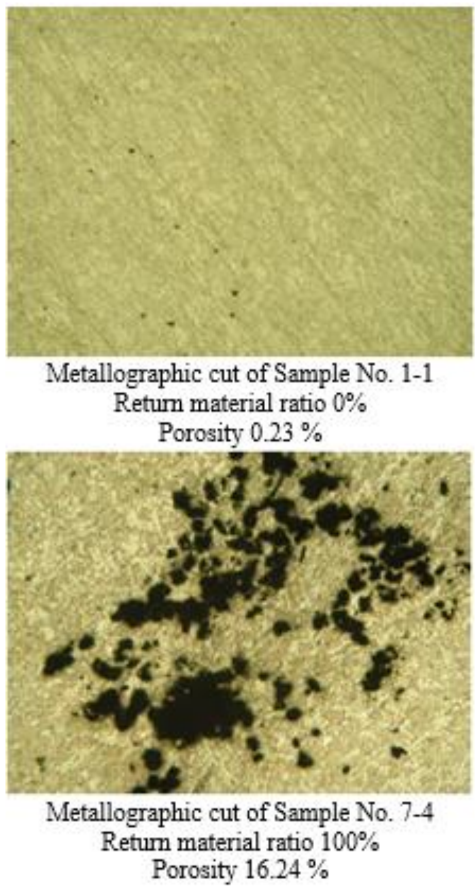

Fig. 5. Macroscopic images of samples 1-1 and 7-4 /x50/

3.3. Economic aspects of return material implementation into the batch

The economic analysis of costs associated with the production waste was performed in terms of the production of 40 pieces of casts. With regard to the monitoring of return material implementation impact on the production process, it is obvious that the return material implementation to the batch reduces the volume of waste material in the production process. Respecting the mechanical properties of the casts, when the values within the permissible range determined by the GM 06007 standard evinced by the casts from series with 0%, 10%, 20% and 30% proportion of return material (see Figure 2), the calculation was performed on the extreme values. The production process used the molds and 4 samples were cast from each of the molds. The mass of the aluminum alloy for the whole system was 3.26 kg. During the melting process from 100% pure primary material, the weight of the waste material was determined for the series of 40 cast samples at 27.08 kg. After the implementation of 30% of return material into the production process, the weight of the waste material was reduced to 20.234 kg, which is a waste material reduction by 25.27%. Table 9 presents the conversions of the total weight of the waste material according to the proportion ratio of return material.

Table 9.
Comparison of waste material accumulation during the production process of 40 pieces of casts for the extreme values of the return material proportion ratio

	Return material ratio 30:70		Return material ratio 0:100	
Casts, Ks	Use of primary alloy, kg	Waste accumulation, kg	Use of primary alloy, kg	Waste accumulation, kg
4	3.260	2.708	3.260	2.708
8	5.542	4.438	6.520	5.416
12	7.824	6.186	9.780	8.124
16	10.106	7.898	13.040	10.832
20	12.388	9.628	16.300	13.540
24	14.670	11.358	19.560	16.248
28	16.952	13.088	22.820	18.956
32	19.234	14.818	26.080	21.664
36	21.516	17.526	29.340	24.372
40	**23.798**	**20.234**	**32.600**	**27.080**

In a specific numerical evaluation of the costs reduction for the production of 40 pieces of casts, the decrease in consumption of primary material by 6.846 kg means the reduction in costs by 19.24 EUR Excl. VAT, considering the purchase price of EN AC 47100 alloy at 2.81 EUR Excl. VAT per kilogram. In terms of 1 ton of saved material, the saving and cost reduction considering the 30% return material implementation to the batch equals 2810 EUR Excl. VAT.

4. Discussion

Based on the achieved results of the chemical composition of individual experimental remelting processes of the alloy, depending on the percentage of the return material in the batch, it arises that for alloys with a 70% up to 100% proportion ratio of return material the chemical composition of the alloy does not meet the prescribed values given in EN 1706 standard. The results also emerge that with the increasing proportion rate of the return material in the batch a decrease in the volume percentage of Al, Mg, Mn elements and an increase of the Fe, Cu, Si elements are recorded.

The increased volume of the Fe element has a negative impact on the values of mechanical properties – permanent deformation, as documented in Figure 2. In a small percentage, up to 0.5%, iron is considered a positive element in Al-Si alloys, as it not only increases the strength but the running property of the alloy as well. However, further increase in Fe volume is causing a decrease of plastic properties and at the same time increases the brittleness of the material. Simultaneously, a higher volume of Fe increases the extent of the porosity and fissure predisposition of the material. The occurrence of the Fe also causes the decrease in the solubility of Si in Al.

The increased volume of Copper reduces the material shrinkage during solidification, increases the ductility, but significantly reduces the corrosion resistance of the casts.

The reduction in the volume of Al is caused by the burn of the return material and the reduction of Mg is caused by the oxidation. The increased volume of Si complicates the machinability but has a positive impact on the running property of the melt.

Following the monitoring of the permanent deformation values depending on the proportion ratio of return material in the batch, the high-quality casts in terms of the monitored parameter were achieved at 0% proportion of return material in the batch, when the permanent deformation value s = 0.013 mm. With the increasing proportion ratio of return material in the batch, an increase in permanent deformation values and thus a decrease in mechanical properties is detected, as documented in Figure 2. Based on the above mentioned, we can state that the measured values confirmed the negative impact of return material on the quality of the cast, which is conditioned by its amount in the melt.

The measured values of permanent deformation further imply that the values of permanent deformation according to the GM 06007 (s = 0.025 mm) achieved at 10% and 20% proportion of return material in the batch were satisfactory. The 30% proportion of return material can be referred to as borderline and critical. In the series of results obtained from the casts produced using a 30% proportion of return material in the batch, a value exceeding the permissible value of permanent deformation occurred locally (Table 4, Sample 4-2).

When assessing individual casts produced depending on the percentage of return material in the batch, it arises that the HB hardness values do not depend on the monitored parameters. HB hardness values vary from 96 to 98 HB. These slight differences in hardness confirm that the determining factor influencing the value of the casts´ hardness is the sub-cooling degree in the contact area of melt with the face of the mold.

Evaluating the homogeneity of individual experimental samples, the impact of the return material proportion on the resulting porosity is evident. This difference can be observed by analyzing the samples in Figure 5. Simultaneously, in comparison with the graphs in Figure 4 and Figure 2, a close correlation of the cast homogeneity with its surface hardness is demonstrated.

Concerning the monitoring of the economic evaluation of the return material proportion impact on the die casting technology, it arises that with the increasing percentage of the return material in the batch, the waste material weight in the production process decreases. With an increase of the return material percentage in the batch in the melting process (MP) 1 (100/0) to the melting process (MP) 4 (70/30), a decrease in total waste material in the production process of 40 pieces of a specific type of cast was recorded from 27.08 kg to 20.234 kg, which is about 25.27%. In a specific numerical evaluation, the costs reduction for the production of 40 pieces of monitored die casts, the decrease in primary material consumption by 6.846 kg (27.08 kg – 20.234 kg = 6.846 kg) means the reduction in costs by 19.24 EUR Excl. VAT (6.846 x 2.81 EUR Excl. VAT = 19.24 EUR Excl. VAT). The melting process in percentage ratio 70/30 of return material in the batch, therefore, appears to be the most admissible with regards to the technological and economic aspects of the production process of a specific type of the die cast.

5. Conclusions

Recognition of the dependence between the return material proportion ratio in the batch, the values of mechanical properties of the casts and the expenses of the melt preparation is an important aspect influencing the quality and efficiency of the production process in the high pressure die casting technology.

Experimental results confirmed the negative impact of increasing the return material proportion in the batch on the values of the quality composition of the melt and mechanical and structural properties of the casts.

The following conclusions can be stated based on the experimental results:

- Increasing the return material proportion in the melting process significantly changes the chemical composition of the alloy. With the proportion of the return material higher than 70%, the standardized values of Fe and Cu are exceeded;
- A higher proportion of return material in the batch has an adverse impact on the permanent deformation of the casts. With return material proportion higher than 30% in the batch, the values of permanent deformation exceed the prescribed standard value;
- As the return material proportion in the batch increases, a decrease in the homogeneity of the casts can be observed. Clusters of impermissible pore size can be observed in metallographic cut samples when using 100% proportion of return material;
- A close correlation between the permanent deformation values and porosity in the monitored area of casts is demonstrated;
- The return material implementation does not affect the surface hardness of the casts;
- Only economic indicators of the return material implementation in the batch are beneficial.

In practice, it is not possible to rely solely on economic indicators and cost savings. It is necessary to find a suitable intersection between the permissible chemical composition of the alloy, the required qualitative properties of the casts and economic efficiency.

Based on the performed experiments and technological and economic indicators of the production process, we recommend not to exceed the 30% return material proportion in the batch during the production process of low-weight silumin-based casts.

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