Analysis of the properties of castings obtained by direct synthesis based on iron-containing industrial waste engineering

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Abstract. The production activity of large machine-building enterprises is associated with the formation of quite large quantities and a diverse range of waste, including a dispersed type, which pose a great problem for their involvement in the technological process, both because of their dispersion, and the presence of non-metallic inclusions and an oxidized form of existence of metal elements. The functioning of large metallurgical and machine-building companies leads to the formation of a large number of different man-made waste, which can be either in a coarse or fine state [1-7]. Processing of such man-made waste is quite difficult, since they are in an oxidized state. The technological process for utilization of iron-containing dispersed waste of mechanical engineering is proposed.

1. Introduction
The production of castings from melts prepared in a melting unit for melting iron-containing particulate wastes of mechanical engineering (ICDMEW) (Figures 1) is combined with the economic effect expressed in Figures 2 and 3.

Figure 1. Technological scheme of ICDWME utilization in specialized processes of casting production of materials based on Fe-C-Si systems [8].
According to the proposed technology, materials based on the Fe-C-Si system for obtaining castings of oil-removing piston rings were melted in a specialized melting unit (figure 1).

The following materials were used in the charge using this technology: bighouse dust, blacksmith scale, iron waste when cleaning castings with shot, FeCl₃ based etchant for copper boards. The chemical composition of the charge is shown in table 1[9,10].

Table 1. Chemical composition of granule composition elements.

| Chemical component formula | Bighouse dust | Blacksmith scale | Powdered Iron Waste |
|----------------------------|---------------|------------------|---------------------|
| FeO                        | 11.9          | 12.1             | -                   |
| Fe₂O₃                      | 59.7          | 87.1             | -                   |
| Fe total                   | 51.1          | 70.4             | 98.86               |
| MnO                        | 1.4           | 0.6              | -                   |
| Cr₂O₃                      | 0.2           | -                | -                   |
| SiO₂                       | 21.7          | 0.2              | -                   |
| CaO                        | 1.5           | -                | -                   |
| MgO                        | 0.9           | -                | -                   |
| Al₂O₃                      | 1.1           | -                | -                   |
| C                          | 1.6           | -                | 0.16                |
| Si                         | -             | -                | 0.04                |
| Mn                         | -             | -                | 0.17                |
| Cr                         | -             | -                | 0.21                |
| Ni                         | -             | -                | 0.45                |
| S                          | -             | -                | 0.02                |
| P                          | -             | -                | 0.01                |
| Al                         | -             | -                | 0.02                |
| Ti                         | -             | -                | 0.06                |

Graphite in the form of chips and CaO in the form of powder were introduced into the granule composition. The weight of these components per 1 kg of the mixture is 0.014 kg and 0.065 kg, respectively. The mass of liquid components in the total mass of the mixture was 35%.

Melting of materials based on the Fe-C-Si system was performed on a special unit, using graphite electrodes as a reducing agent. The consumption of pellets in a special unit is set at 7 kg of iron per min, the temperature of metal and liquid slag in the melting bath is 1873 K, the temperature in the counter-current reactor is 1173 K.

The liquid metal was released into 150 kg ladles as it accumulated in the melting bath. The average chemical composition of materials based on the Fe-C-Si system selected from 10 buckets had a content of % (wt): C-3.67; Si-2.58; Mn-0.71; S-0.009; P - 0.03; Cr -0.08; Cu - 0.25. The required content of elements in the smelted material based on the Fe-C-Si system was guaranteed due to the presence of these elements in the pellets and the organization of metallization processes. The molten material based on the Fe-C-Si system was poured into molds at a temperature of 1713 K.

The specified economic effect from the application of the developed technological solutions for the use of iron containing dispersed waste of mechanical engineering will be obtained provided that high quality castings are manufactured. In the work on the example of specific responsible castings of KAMAZ PJSC, the results of a study of their quality upon receipt according to two options are presented: basic and proposed.
Figure 2. Costs for the production of 1 ton of cast iron based on the Fe-C-Si and Fe-C-Al systems in the "Kama Foundry" in the basic and proposed versions.

Figure 3. Starting materials for the production of castings according to the proposed and basic options: a - dispersed iron-containing engineering waste; b - metal furnace charge.

2. Piston oil collection ring for KAMAZ car
Casting a piston oil scraper ring (Figure 4) for a KAMAZ automobile is made of gray cast iron of the following composition, % (wt): C - 3.6 ... 4.0; Si - 2.4 ... 3.0; Mn - 0.5 ... 0.8; Cr - <0.3; S is <0.12; P - 0.4 ... 0.6. Mechanical properties: HB hardness 210 ... 280, flexural strength σ> 35 × 107 Pa, elastic modulus E> 81 × 109 Pa. Microstructure: the form of graphite inclusions is lamellar and nest-shaped, the metal base is perlite.

According to the basic version of the preparation of gray cast iron melt, an induction furnace IST-2.5 with a quartzite lining was used. Cast iron was smelted from a charge consisting of pig iron and its own production in the ratio of 120:100. Adjustment of the chemical composition of cast iron before production was carried out by feeding the following ferroalloys into the liquid metal: ferromanganese FMn75, ferrosilicon FS45, ferrophosphor FF14, copper cathode, ferrochrome FH65. Casting of the alloy was carried out at a temperature of 1783 K.
The liquid metal was modified in a ladle with ferrosilicon FS75 (0.5 % of the metal weight) and poured into molds at a temperature of 1703 K. The chemical composition of the metal was characterized by the following data, % (wt): C-3.82; Si-2.6; Mn-0.62; S-0.024; P-0.44; Cr-0.29; Cu-0.21

Production of sand-clay foundries molds is carried out by the method of stack forming. The molding mixture was made from the following components: Montenegrin bentonite (0.4...0.6 %), recycled mixture (97%), quartz sand, grades OB 1K01 (1.5...2.5%).

The quality of the metal castings of the oil-removing piston ring according to the basic version was characterized by the following data: mechanical properties: hardness NRB 99, modulus of elasticity 97.4×10⁹ PA, bending strength 41.2×10⁹ PA; microstructure:

- a) the Metal matrix as a whole consists of plate perlite PT1 with a small amount of ferrite P96(F 4). The dispersion of perlite varies within P 0,3...P 0,5. The area of the phosphide eutectic corresponds to FEP2000, distributed evenly in the form of a torn grid of FER1, 2.

- b) Graphite inclusions have a nest-like and plate-like swirled shape of Pg4, 2. The size of inclusions varies within 25 ... 45nm, Pgd25 Pgd45, they are distributed: unevenly, colonies of plate graphite, colonies of inter-dendritic graphite, rosette PGR2, 3, 4, 7. The Number of graphite inclusions, characterized by the occupied area, is 10 % PG10.

The quality of the metal castings of the oil-removing piston ring according to the proposed variant was characterized by the following data: mechanical properties: hardness NRB 100, modulus of elasticity 123×10⁹ PA, bending strength 53.8×10⁹ PA; microstructure:

- a) the metal matrix as a whole consists of granular PT1 perlite with a small amount of ferrite(2...5 %) P96 (F4).

- b) graphite inclusions have a worm-like sinuous shape VGf2 with a uniform distribution VGR1, their length is estimated at an average of 90 microns VGD90. The total area of graphite inclusions is 10 %. Along with vermicular graphite, there is also spherical graphite, the proportion of which is estimated at 8 % in VG 92.

3. Piston compression ring for KAMAZ car

Casting of the piston compression ring for the KAMAZ car is made of high-strength cast iron of the following composition, % (wt): C - 3,5...4; Si - 2,1...2,9; Mn -0,2...0,5; P<0,3; S<0,05; Cr<0,2; Ni<1. Mechanical properties: hardness NRB < 90, modulus of elasticity 150÷170×10⁷ Pa, bending strength > 130× 10⁷ Pa. The microstructure is represented by spherical graphite with uniform distribution, the metal base is ferrite.

Melting of cast iron for castings of compression piston ring and oil-removing piston ring was carried out in the same melting unit as for the basic version, but with an increase in the temperature of liquid cast iron by 10 degrees.

Graphitizing and spheroidizing modification was carried out in buckets with a capacity of 150 kg. The bottom of the ladle was initially loaded with ferrosilicon magnesium ligature FeSiMg5K2 in an amount of 1.7 %, then ferrosilicon FeSi75L-6 in an amount of 0.7. 8 %, then the molten metal was poured.

The furnace was filled with pig iron and returned to its own production in a ratio of 170: 50 to each other. The chemical composition of cast iron was corrected by ferroalloys: ferrosilicon FeSi45 and ferromanganese FeMn75. The liquid metal was poured into a bucket at a temperature of 1783 K.

The molds were filled at a metal temperature of 1723 K. Analysis of the chemical composition of the metal gave the following results, % (wt): C - 3.98; Si - 2.72; Mn - 0.34; S - 0.013; P - 0.07; Cr - 0.02.

Casting molds for producing compression piston ring castings are similar to those for producing oil-removing piston ring castings. However, the percentage of bentonite and quartz sand in the
molding mixture is increased. Castings of the compression piston ring were annealed in a 3-zone furnace with temperatures of: 1 zone - 1223 K, 2 zone -1123 K and 3 zone-983 K. In the first and second annealing zones of the furnace, the castings were 4.65 hours each and 9.3 hours in total. The cooling of the castings is carried out in the chamber with water cooling for 9.3 hours. The heat treatment process takes 18.6 hours.

The technological process of manufacturing compression piston ring castings from a special material based on the Fe-C-Si system is similar to the process of manufacturing oil-removing piston ring castings in a specialized electrothermal melting unit. The charge materials were pellets made from the same iron-containing dispersed waste of mechanical engineering and in the same proportion as was used in the production of oil-removing piston rings. However, the composition of the granule composition was additionally introduced pulverized waste of ferrosilicomagnesium ligature FeSiMg5K2 in the amount of 0.012 kg per 1 kg of the mixture and increased the amount of powdered lime to 0.108 kg. In addition, the liquid component was replaced with an aqueous NaCl solution.

The average composition of the experimental high-strength special material based on the Fe-C-Si system for 10 spilled buckets is characterized by the following element content, % (wt): C-3.64; Si-2.54; Mn-0.32; S-0.008; P-0.07, Cr-0.09. The Liquid metal was poured at a temperature of 1723 K into molds without preliminary modifying treatment in the bucket.

The quality of the metal castings of the compression piston ring according to the basic version was characterized by the following data: mechanical properties: hardness NRB 107, modulus of elasticity 162×10^7 Pa, bending strength 155×10^7 Pa; microstructure:

- a) Graphite is represented by a spherical shape ShGf4, 5, inclusions have a regular and irregular appearance with dimensions ShGD15, 45, 25. The degree of spheroidization of graphite SSG 95 ... 97 %. The number of graphite inclusions is 10 % ShG10, and they are distributed unevenly SHGR2.
- b) the Metal matrix of castings in the cast state is characterized by perlite and ferrite in the ratio of P 80(F 20). The dispersion of perlite corresponds to a Pd 0.5.
- c) after heat treatment, there was a change in the metal matrix of the piston ring casting. It became ferrite with a small amount of P2 perlite (F98).

The quality of the metal castings of the compression piston ring according to the proposed variant was characterized by the following data: mechanical properties: hardness NRB 109, modulus of elasticity 167×10^7 Pa, bending strength 158×10^7 Pa; microstructure:

- a) Graphite is represented by a spherical shape ShGf4, 5, inclusions are correct and incorrect with the dimensions ShGd15, 25, there are single graphite inclusions with the size ShGd45. The degree of spheroidization of SSG graphite is 98...99 %. The number of graphite inclusions is 10 % ShG10, and they are distributed unevenly ShGR2.
- b) the Metal matrix of castings in the cast state is characterized by perlite and ferrite in the ratio of P 85(F 15). The dispersion of perlite corresponds to a Pd 0.5.
- c) after heat treatment, there was a change in the metal matrix of the compression piston ring castings, which became ferrite P0(F100).

The above mentioned data make it possible to conclude that material of castings produced from melt prepared from iron-containing dispersed wastes of machine building by method of direct synthesis is not inferior in mechanical properties to material of castings produced from melt prepared according to basic technological version. Note that these mechanical properties of the test piston rings were obtained without treating the liquid metal in the ladle with graphitizing and spheroidizing modifiers. Their role was played by the complex inside the furnace measures, as well as by the organization of the process of melting granule compositions from iron-containing dispersed wastes of mechanical engineering in a specialized electrothermal unit, which ensured the production of a melt of the specified chemical composition, including Mg at the level of 0.04%, with low content of surfactants and the required microstructure during crystallization. Inside furnace technological procedures involve direct synthesis of metal components by method of rain melting when metal phase passes through slag phase. This allows to eliminate "bad" inheritance of charge materials. The
measures also include high overheating of the melt with simultaneous thermo-slag-electric arc and electric current treatment.

The analysis of quality of responsible castings of piston rings of the KAMAZ vehicle engine has shown that the proposed variant of melt preparation for obtaining the mentioned castings provides a sufficient level of mechanical properties and metal structure comparable to the basic variant of melt preparation, and in the case of the oil-lifting piston ring the quality indicators are higher.

The piston rings are paired with valves and are subjected to impact loads (2000 strokes per minute) in an aggressive exhaust gas environment with temperatures up to 523 K.

To check the specified properties of the casting material ensuring the parts serviceability, comparative long-term reliability tests of KAMAZ-740.11-240 engines were carried out in PJSC "KAMA3-Diesel" together with the reliability department of this enterprise. The tests were carried out at the AVL stand of Austrian manufacture.

The engines were equipped with valve seats and piston rings made of experimental cast irons based on the Fe-C-Si system. Piston rings and valves were made of cast irons, both according to the basic technological version of KAMAZ Foundry and proposed using iron-containing dispersed wastes of mechanical engineering in a specialized electrothermal melting unit. Engine tests showed the following results. After the second stage of parts testing, their suitability for further operation was revealed. The results of control after the third stage of engine tests are given in Tables 2 - 5.

| Table 2. Values of compression ring measurements (basic version of technology). |
|-------------------|-------------------|-------------------|-------------------|
| Clearance in lock, micron | E, $10^3$ MPa | Wear, micron On radial thickness | Wear, micron On height |
| 537 | 163 | 80 | 43 |
| 449 | 160 | 63 | 50 |
| 568 | 166 | 90 | 48 |
| 797 | 158 | 146 | 61 |
| 647 | 169 | 73 | 62 |
| 539 | 153 | 118 | 68 |
| 602 | 167 | 95 | 79 |
| 721 | 161 | 121 | 66 |
| 597 | 153 | 98 | 46 |
| $\bar{A}_1$ mean value 606 | $\bar{A}_2$ mean value 152 | $\bar{A}_3$ mean value 98 | $\bar{A}_4$ mean value 58 |
| $S^2{\{\bar{A}_1}\}}$ 10853,25 | $S^2{\{\bar{A}_2}\}}$ 33,36 | $S^2{\{\bar{A}_3}\}}$ 684,9 | $S^2{\{\bar{A}_4}\}}$ 145,4 |
| Standard deviation 104,18 | Standard deviation 5,77 | Standard deviation 26,17 | Standard deviation 12,05 |
| Confidence interval Confidence interval | Confidence interval Confidence interval |
| 75,36 | 4,17 | 18,93 | 8,71 |

| Table 3. Values of oil collection rings measurements (basic version of procedure). |
|-------------------|-------------------|-------------------|-------------------|
| Clearance in lock, micron | E, $10^3$ MPa | Wear, micron On radial thickness | Wear, micron On height |
| 806 | 93 | 96 | 66 |
| 757 | 88 | 94 | 62 |
| 722 | 86 | 102 | 43 |
| 506 | 96 | 102 | 78 |
| 623 | 94 | 91 | 60 |
| 752 | 112 | 102 | 69 |
| 793 | 86 | 79 | 55 |
| 705 | 104 | 108 | 66 |
Table 3 continuation

|    | 1     | 2     | 3     | 4     |
|----|-------|-------|-------|-------|
| 751| 96    | 98    | 71    |
| $\overline{A_1}$ mean value 712,77 | $\overline{A_2}$ mean value 95 | $\overline{A_3}$ mean value 96,8 | $\overline{A_4}$ mean value 63,3 |
| $S^2\{\overline{A_1}\}$ 8880,44 | $S^2\{\overline{A_2}\}$ 73,5 | $S^2\{\overline{A_3}\}$ 70,86 | $S^2\{\overline{A_4}\}$ 102 |
| Standard deviation | Standard deviation | Standard deviation | Standard deviation |
| 94,23 | 8,57  | 8,41  | 10,09 |
| Confidence interval | Confidence interval | Confidence interval | Confidence interval |
| 68,16 | 6,19  | 6,08  | 7,29  |

Table 4. Values of compression ring measurements (proposed technology version).

| Clearance in lock, micron | E, $10^7$ MPa | Wear, micron |
|---------------------------|---------------|--------------|
|                           | On radial thickness | On height    |
| 659                       | 168           | 91           | 77           |
| 668                       | 158           | 75           | 48           |
| 449                       | 159           | 54           | 67           |
| 558                       | 161           | 89           | 38           |
| 548                       | 167           | 97           | 69           |
| 677                       | 156           | 96           | 43           |
| 623                       | 165           | 54           | 51           |
| 448                       | 160           | 76           | 75           |
| 872                       | 156           | 91           | 71           |
| $\overline{A_1}$ mean value 611,33 | $\overline{A_2}$ mean value 161,1 | $\overline{A_3}$ mean value 80,33 | $\overline{A_4}$ mean value 59,88 |
| $S^2\{\overline{A_1}\}$ 17220,5 | $S^2\{\overline{A_2}\}$ 20,61 | $S^2\{\overline{A_3}\}$ 282,5 | $S^2\{\overline{A_4}\}$ 220,36 |
| Standard deviation | Standard deviation | Standard deviation | Standard deviation |
| 131,2 | 4,54  | 16,8  | 14,84 |
| Confidence interval | Confidence interval | Confidence interval | Confidence interval |
| 94,9 | 3,28  | 12,15 | 10,73 |

Table 5. Values of oil collection rings measurements (proposed technology version).

| Clearance in lock, micron | E, $10^7$ MPa | Wear, micron |
|---------------------------|---------------|--------------|
|                           | On radial thickness | On height    |
| 405                       | 116           | 68           | 44           |
| 524                       | 123           | 92           | 61           |
| 605                       | 126           | 92           | 41           |
| 641                       | 111           | 75           | 51           |
| 571                       | 117           | 86           | 49           |
| 447                       | 124           | 81           | 63           |
| 615                       | 125           | 94           | 48           |
| 510                       | 114           | 95           | 45           |
| 587                       | 118           | 91           | 52           |
| $\overline{A_1}$ mean value 545 | $\overline{A_2}$ mean value 119,3 | $\overline{A_3}$ mean value 86  | $\overline{A_4}$ mean value 50,44 |
| $S^2\{\overline{A_1}\}$ 6378,25 | $S^2\{\overline{A_2}\}$ 28,5 | $S^2\{\overline{A_3}\}$ 89 | $S^2\{\overline{A_4}\}$ 55,03 |
| Standard deviation | Standard deviation | Standard deviation | Standard deviation |
| 79,8 | 5,34  | 9,43  | 7,42 |
| Confidence interval | Confidence interval | Confidence interval | Confidence interval |
| 57,7 | 3,86  | 6,82  | 5,37 |
It follows from these tables that the operability of articles made from castings for which melt preparation was carried out according to different technological variants is the same for compression and oil-collecting piston rings (proposed version of melt preparation) according to all control parameters. The latter is obviously due to the increasing compactness of graphite inclusions in Fe-C-Si materials. Long-term tests of diesel engines of KAMAZ vehicle equipped with valves made of experimental materials based on Fe-C-Si system showed that there was no leakage of gas distribution mechanisms.

4. Conclusions
1. Technology has been developed and experimental-industrial version of melting unit for preparation of molten iron on the basis of Fe-C-Si and Fe-C-Al systems from iron-containing dispersed wastes of machine building has been created. Technological process includes production of composite material in the form of granules from dispersed wastes of different composition and synthesis of melt in melting unit. Due to refined effect of slag phase, combination of protective reducing atmosphere and effect of electric field on metal phase, obtaining of molten materials based on Fe-C-Si and Fe-C-Al systems of required composition is provided.
2. Quality of castings produced from melt prepared from iron-containing dispersed wastes of machine building according to developed technology is at the level of castings produced according to basic version.

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