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APPLICATION OF I / MR AND CUSUM CONTROL CHARTS TO EVALUATE THE QUALITY OF CAST STEEL IN INDUCTION FURNACES

This article is a result of research carried out in foundry casting steel castings for the railway industry. The smelting process (smelting) in induction furnaces, in terms of the compatibility of the actual chemical elements in the metal with the composition laid down in the technological instructions, was included in the study program. In practice, the actual content of elements is determined by the static spectral analysis method and recorded in the documentation created by the traditional record. Entries are evaluated only in terms of compliance with technological instructions, which does not translate into improvement in the quality of the melt as a function of the duration of the production process.

The introduction of time analysis in the melting range allows to take into account the variability of a number of factors affecting the actual (final) content of the elements and thus the quality of the cast. An example of time analysis presented in the article is the ability to use I / MR control cards for individual (single) observations composed of smelting processes and CUSUM cards that enable the detection of factor variability based on cumulative sums. Cards of this type can be helpful in achieving the quality of alloys in real time of the melting process.

Keywords: cast steel, quality management of castings, Statistic Process Control, control charts

1. Introduction

In the era of the fourth technological revolution, quality is one of the main criteria for evaluating processes and products. The concept of quality is related to the development of material engineering and manufacturing systems characterized by an increasing degree of complexity. These developmental changes involve moving to scientific methods of work organization, increase of efficiency and productivity of production lines, seeking minimization of costs in the entire life cycle of products and mechanization and automation of processes [1,6,10].

In the available literature, quality is identified with the receiver – the customer, and its significance depends on the context of the subject matter. The most common definitions are:

- "quality is the extent to which a set of inherent properties meets requirements", Polish Standard PN-EN ISO 9000-2005 [9],
- "Quality is the overall quality of a product or service that determines the ability of a product or service to meet identified or anticipated needs" – ISO 8402 standard [9].

The quality of the product in terms of SPC (Statistical Process Control) is inseparable from variability. The rule in improving quality is to create conditions to control and reduce the volatility of factors affecting the characteristics of products and processes. This means that quality is inversely proportional to variability.

With respect to the process of melting cast steel in an induction furnace, the quality concerns the variability (accuracy) of the content of the elements from which the final quality of the finished alloy depends, and in the final casting stage as the finished product. Since melting is a thermal process with a certain dynamics as a function of time, it is striven for to use scientific methods that can facilitate the control of process variability. Among the types of methods to be considered are the control charts used to analyze and evaluate data from static spectral analysis.

2. The essence of control charts

Controls that are part of the SPC (Statistic Process Control) system are a commonly used tool for quality assurance [7]. They were introduced by Shewhart for quality management in industrial plants. They allow analysis of data from tests of products' samples taken in a systematic manner. In addition, they allow you to evaluate the stability of the monitored process with information about the need to intervene in the process. This evaluation is facilitated by the graphical presentation of results on the control card's chart. It is composed of four main components: the upper

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and lower control limits, calculated based on equations characteristic for the given card, the central line being the average value of all measurements and the course of the average values of the individual samples. Additional elements are the alert limits that are contained within the control limits. In the case of numerical data, the most commonly used variants of the cards are X-Rr (mean-range) or Xr-S (mean-standard deviation). Their use leads to information about the stability of the process or its lack. It is necessary to have a certain amount of data that must meet the criterion of normal distribution [7].

Often times, the above conditions are not assured. This is due to the following reasons: low-volume production, data do not meet the normal distribution, or a tool is needed to detect small shifts in process mean values [11,12]. The solution to this problem are cards with special purpose. Cards of this type include individual measurement and moving range (I / MR) cards, moving average (MA) cards, exponentially weighted moving average (EWMA) and cumulated sum card (CUSUM). The common feature of these cards is the detection of small process shifts, and more specifically, the shifts in the mean value of the process. The implementation of the cards should be preceded by a thorough analysis of the production process, since inadequate use may result in misinterpretation of the results and erroneous actions that may harm the production process [2,4,5].

The majority of control cards base on taking several samples, which is not always technically or economically justified. In situations where multiple measurements cannot be performed, single measurements are carried out and the data from these measurements are entered into I / MR and CUSUM control cards [3].

The Individual Measurement and Moving Range (I / MR) card monitors the position measure and the variability measure. The measure of the position is the results of individual measurements of the selected product characterizing the product (card I), while the measure of variability is the so-called-moving range (MR – Moving Range). Because the sample consists of one measurement, it is not possible to use as a variation gauge, a traditional range, or a standard deviation. In such situations, the so-called-moving range, which is the absolute value of the difference between two consecutive values (measurements in neighboring samples) [8].

Another card for statistical processing of data derived from spectral analysis is the cumulative sums control card. Its layout differs significantly from the standard cards, and the control boundaries do not have the form of two parallel horizontal lines. This is because the resulting graph represents the sum of the deviations of the measured value of the property from the assumed nominal value (using the numerical evaluation).

In the CUSUM record, the horizontal axis is the sample number and the vertical axis represents the cumulative sum of deviations from the nominal value. The central line is located at zero values of cumulative deviation [10]. If the created graph would overlap with the central line, this would mean that all the results are identical with the calculated nominal values.

3. The method of using control cards in the analyzed example (cast steel foundry)

Cast stell foundry, which has attempted to use control cards, is currently using traditional casting control methods. This method is based on static spectral analysis, and the results are recorded on paper cards. The results are compared for compliance with the standard or technological instructions and then archived. In the foundry, no electronic data archiving system is used, which makes it impossible to analyze the content of elements in molten metal.

The method by which the cards will be used includes those parts of the technological process that affect the quality of the melted metal. The beginning of every smelting is to measure out the load. It consists in compiling metal materials with a certain content of elements. The measured out load is fed to the induction furnace through the loading systems. During the melting process two samples are taken for spectral analysis. The first sample is used to pre-determine the percentage composition of the elements, which allows to adjust the chemical composition of the metal to that laid down in the instructions. The second sample is used to perform the final spectral analysis. After the second test, the actual composition of the elements is expected to be in accordance with the standard and the technical conditions of reception. A general outline of the quality control methodology using I / MR and CUSUM control cards is shown in Figure 1.

4. Research program

The research program was divided into two phases. In the first stage, melting cards related to the most commonly used cast iron alloys in the foundry were arranged. According to this criteria, 160 cards were selected for further analysis in which data from standards and spectral analysis were correctly recorded. Two types of cast steel were analyzed: 230-450W (carbon structural cast steel) and L30GS (alloy structural cast steel). The chemical composition of the tested alloys according to the

TABLE 1

Chemical composition of tested alloys according to standards: 230-450W – PN-ISO 3755; L30GS – PN-ISO 3755 (1994) [13]

Steel	**230-450W**		**L30GS**	
Element/Criteria	**Min %**	**Max %**	**Min %**	**Max %**
C	—	0,25	0,25	0,35
Mn	—	1,2	1,1	1,4
P	—	0,035	—	0,04
S	—	0,035	—	0,04
Si	—	0,6	0,6	0,8
Ni	—	0,4	—	0,3
Cr	—	0,35	—	0,3
Mo	—	0,15	—	—
Cu	—	0,4	—	0,3
V	—	0,05	—	—

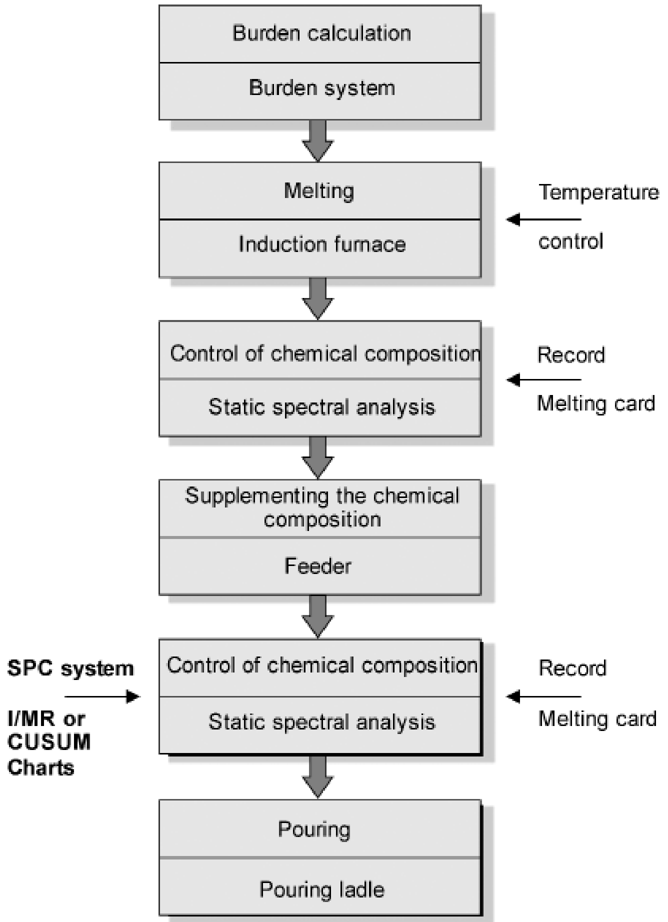


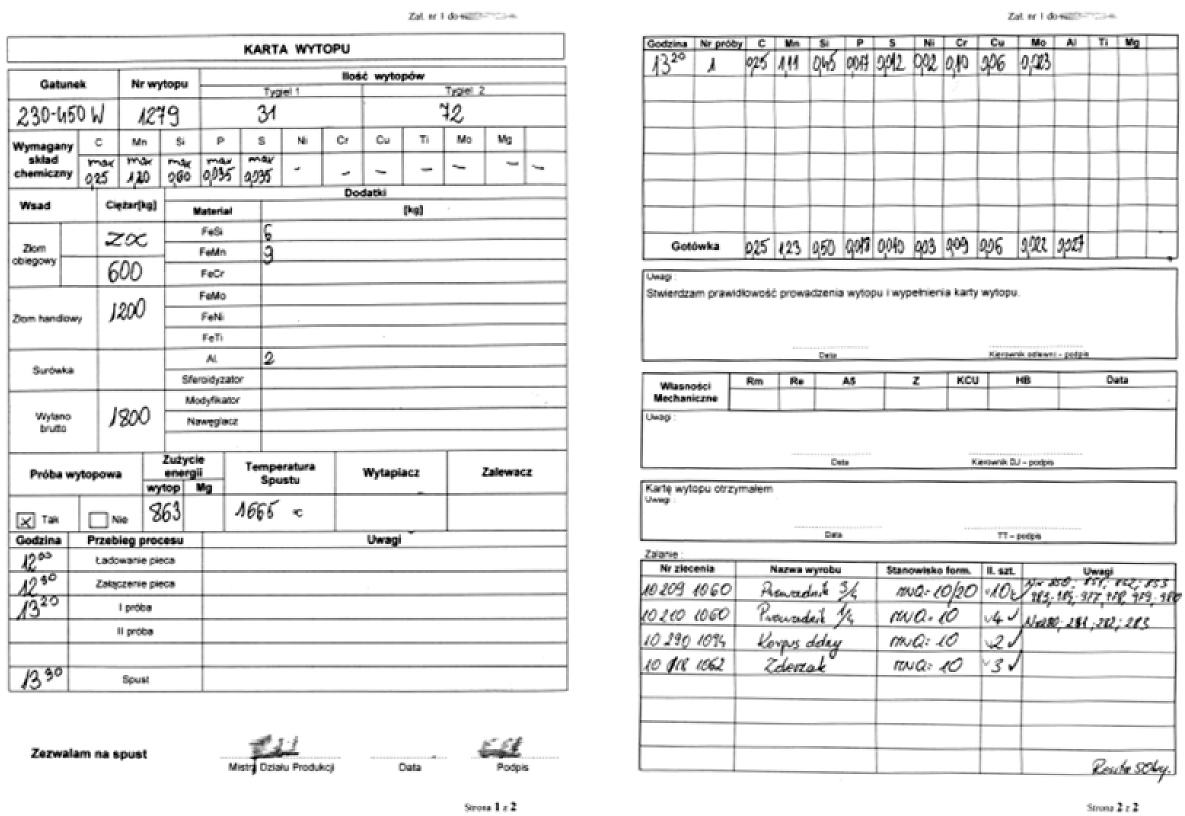
Fig. 1. Methodology of quality control using I / MR and CUSUM control cards

standards PN-ISO 3755 (1994) and PN-H-83156 is presented in Table 1. The results of spectral analysis are presented in the melting card (Fig. 2).

The essence of the quality control process is the ability to quantitatively analyze the data set from the melting cards. For this purpose, a helpful tool is Statistica, which allows to quickly save data in tabular form and present the results in graphical form. The undeniable advantage of this program is the ability to automatically update control cards, thus eliminating the need to manually modify the obtained charts. On the basis of these results an analysis of the change in the percentage of elements in the examined period of time was performed. From the group of important elements influencing alloy quality, the following elements can be distinguished: carbon, manganese, phosphorus, sulfur, silicon, nickel, chromium, molybdenum, copper and vanadium. For methodological reasons, calculations were limited to one element in the first position in the norms. The results are shown in Figs. 3-4 (cast steel L30GS) and Figs. 5-6 (cast steel 230-450W).

5. Analysis of the results

The results should be analyzed according to the type of card. The first group is the I / MR control cards. Their analysis indicates a statistically stabilized process. With few exceptions it can be assumed that none of the melt does not exceed the upper limit of control and only a few are below the lower limit. It is very likely that this is an error when rewriting the results



KARTA WYTOPU

Gatunek	Nr wytopu	Ilość wytopów – Tygiel 1	Ilość wytopów – Tygiel 2
230-450 W	1279	31	72

Wymagany skład chemiczny	C	Mn	Si	P	S	Ni	Cr	Cu	Ti	Mo	Mg	
	max 0,25	max 1,20	max 2,00	max 0,035	max 0,035	-	-	-	-	-	-	-

Wsad		Ciężar [kg]	Dodatki – Materiał	[kg]
Złom obiegowy		200	FeSi	6
		600	FeMn	3
			FeCr	
Złom handlowy		1200	FeMo	
			FeNi	
			FeTi	
Surówka			Al	2
			Sferoidyzator	
Wylano brutto		1800	Modyfikator	
			Nawęglacz	

Próba wytopowa		Zużycie energii – wytop	Zużycie energii – Mg	Temperatura Spustu	Wytapiacz	Zalewacz
[x] Tak	[ ] Nie	863		1665 °C		

Godzina	Przebieg procesu	Uwagi
12.05	Ładowanie pieca	
12.50	Załączenie pieca	
13.20	I próba	
	II próba	
13.50	Spust	

Zezwalam na spust — Mistrz Działu Produkcji — Data — Podpis

Strona 1 z 2

Godzina	Nr próby	C	Mn	Si	P	S	Ni	Cr	Cu	Mo	Al	Ti	Mg
13.20	1	0,25	1,11	0,45	0,017	0,012	0,02	0,10	0,06	0,023			
Gotówka		0,25	1,23	0,50	0,017	0,010	0,03	0,09	0,06	0,022	0,027		

Uwagi:
Stwierdzam prawidłowość prowadzenia wytopu i wypełnienia karty wytopu.
Data — Kierownik odlewni - podpis

Własności Mechaniczne	Rm	Re	A5	Z	KCU	HB	Data

Uwagi:
Data — Kierownik DJ - podpis

Kartę wytopu otrzymałem
Uwagi:
Data — TT - podpis

Zalanie:

Nr zlecenia	Nazwa wyrobu	Stanowisko form.	Il. szt.	Uwagi
10209 1060	Prowadnik 3/4	MNQ-10/20	10	[illegible]
10210 1060	Prowadnik 1/4	MNQ-10	4	[illegible]
10290 1094	Korpus dolny	MNQ: 10	2	
10 [illegible] 1062	Zderzak	MNQ: 10	3	

Strona 2 z 2

Fig. 2. Example of melting card

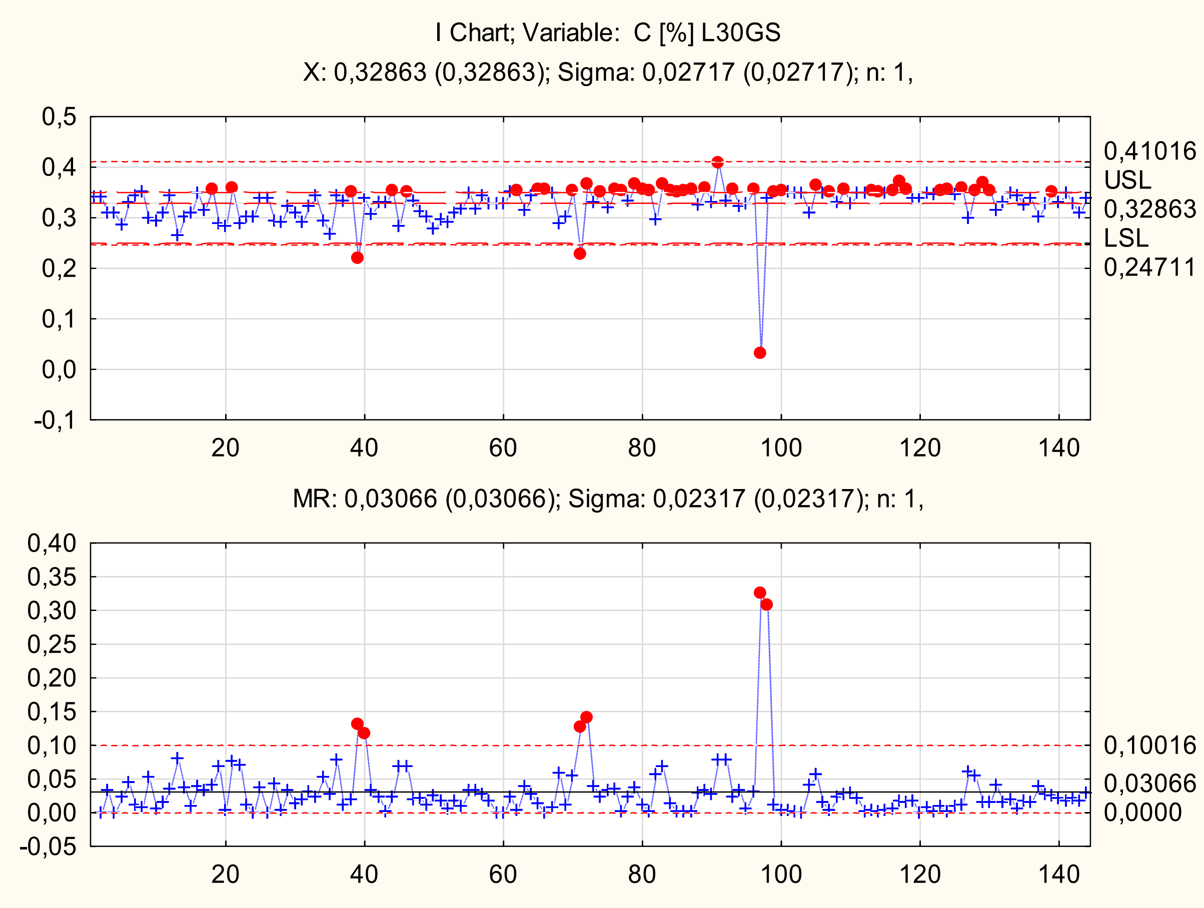


Fig. 3. I / MR card for carbon percentage. L30GS. USL and LSL – upper and lower tolerance limits

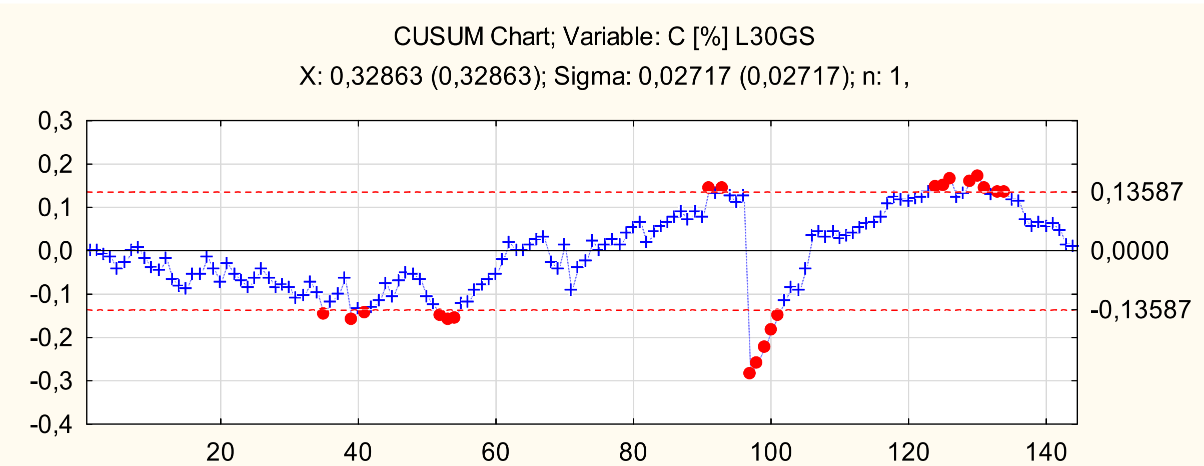


Fig. 4. CUSUM card for carbon percentage. L30GS

from the spectrophotometer. The argument for this error is the understated percentage of the element. An additional cause may be a temporary lack of control of the collected scrap metal or a lack of staff response to the results obtained from the first sample of the chemical composition test. The problem arises when setting the tolerance limits entered for each element on the basis of norms. Both alloys tend to exceed the upper permissible carbon content. In such situations, an analysis of the causes and corrective actions should be undertaken.

In the second group, CUSUM cards were analyzed for the tested alloys. As mentioned above, cards of this type are intended to capture small, but long-lasting shifts in mean values. The graphs clearly show a tendency to change the preset chemical composition and its accumulation over time. Large fluctuations in average over the time period may be due to various problems. One of them may be the wear of the induction furnace lining, another cause is the problem with the stability of the metal load.

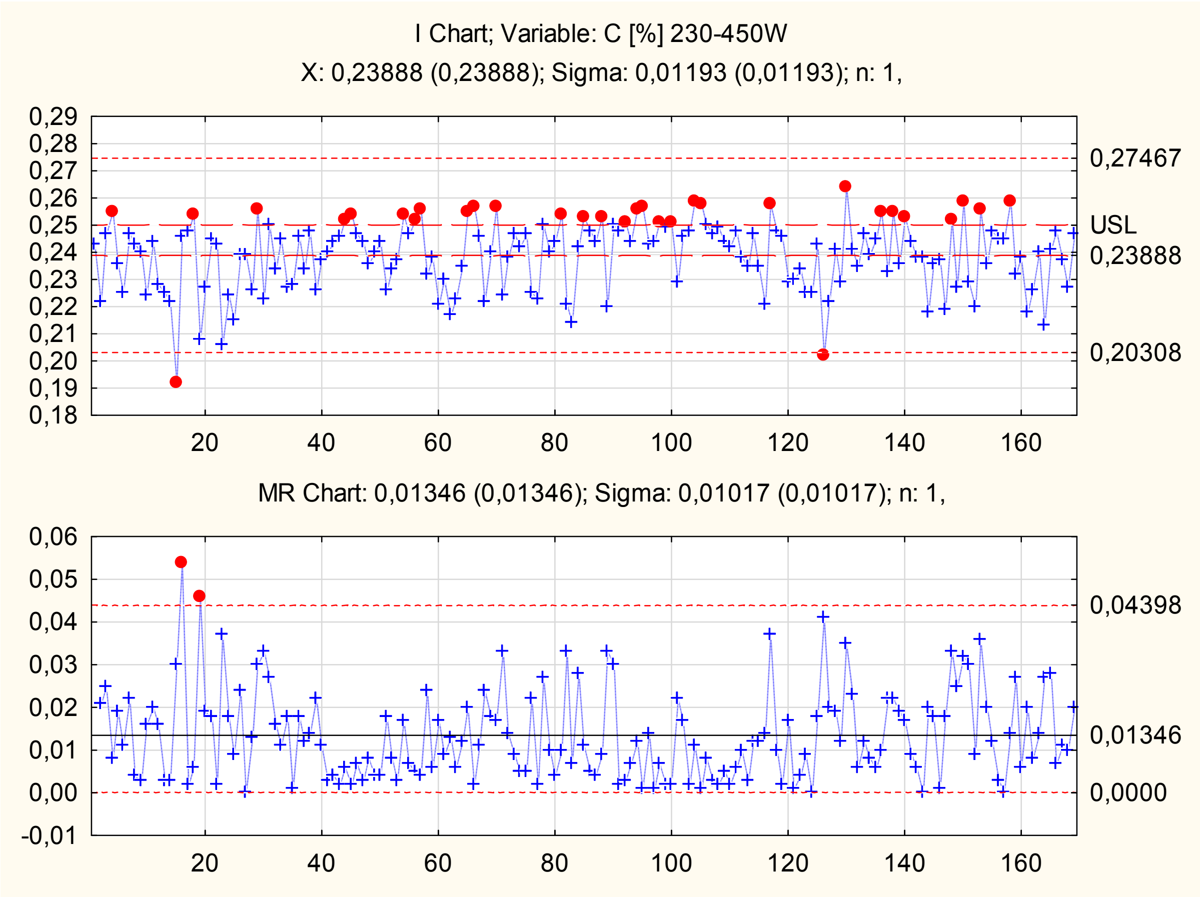


Fig. 5. I / MR card for carbon percentage. Solid 230-450W. USL – upper limit of tolerance

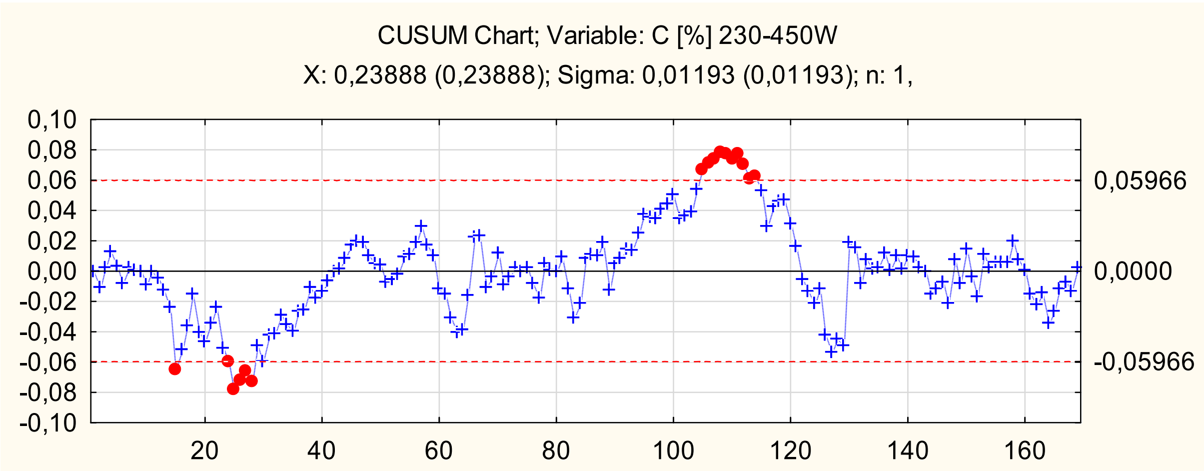


Fig. 6. CUSUM card for carbon percentage. Steel 230-450W

Summary

The method of quality assurance of steel castings in terms of their chemical composition compliance with the standards presented in the article is a tool enabling full control of the elements in alloys. The used control card method is novel in the foundry and also in the foundry processes on a national scale.

In the present case, the results show that the I / MR and CUSUM cards are very useful for the analysis of the content of elements in the tested theses. However, it should be emphasized that the information from each card is complementary, giving a full picture of the process in the investigated foundry. The full use of cards and adaptation of decision related to the process requires creating a system of information flow from sampling, spectral analysis, statistical processing of data to operator position responsible for the smelting process.

Applying the card method together with the information flow system creates the conditions for reacting in case of detection of irregularities and confirming that all means used to control the process ensure its stability. If a signal of dysregulation is recorded on the card, the operator will be able to take corrective action at the appropriate time.

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