INCREASE IN SENSITIVITY OF RESIDUAL MAGNETISATION TO STRUCTURE OF PRODUCTS MADE OF FERROMAGNETIC MATERIALS .

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This report concerns the magnetic testing methods in metallurgy. In the paper we present the means to provide a high sensitivity of the residual magnetization to the structure of products.

1. The coercitive force H_C is known to be a magnetic parameter, most sensitive to the structure of constructional materials. The residual magnetization M_d of products with a large demagnetization factor N is proportional to H_C after their magnetization to technical saturation. Using the elaborated [1] methodology for calculating M_d of a product magnetized in an open magnetic circuit, based on N, H_C, magnetization of saturation M_S, residual magnetization M_R of the material, and intensity H_e of the external magnetizing field, it is established theoretically and verified experimentally [2] that for products with $N \geq 0.04$ at magnetization to a condition far from magnetic saturation, one observes an increase of sensitivity of M_d to the tested properties compared to magnetization to saturation (Fig. 1).

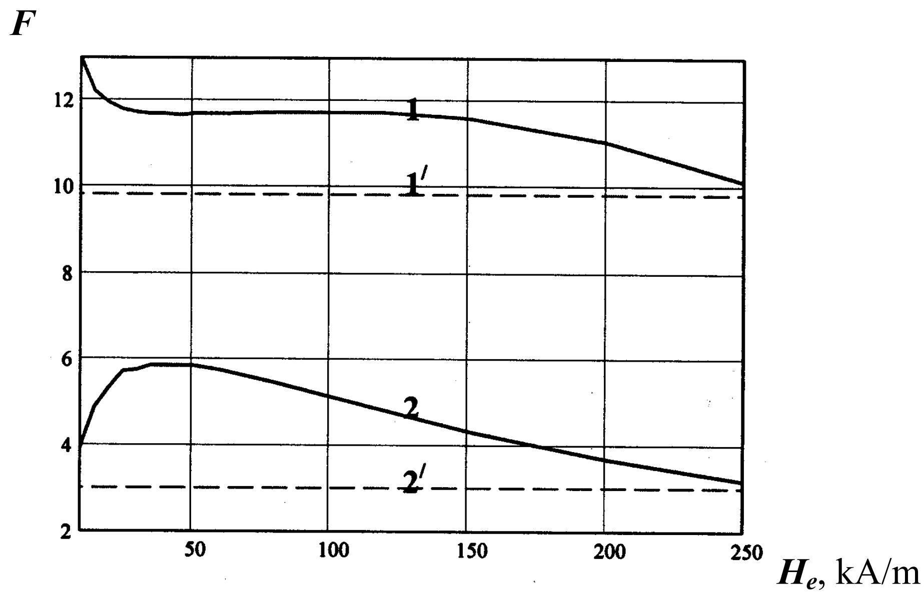


Figure 1. The dependence on the H_e of the ratio F between the residual magnetization M_d of products with $N \approx 0.2$ made of white cast-iron and the M_d of products made of ferrite malleable (1) and gray (2) cast-irons. Calculation. $1^/$, $2^/$ show F after magnetization of products in $H_e = 1000$ kA/m.

In the methodology we use the following formulas, describing magnetization of constructional materials based on parameters of the saturation hysteresis loop.

A formula for normal magnetization curve:

$$M_m = \chi_H \frac{H_C^2 H_m}{H_m^2 + H_C^2} + \frac{M_S}{\pi} \frac{H_m^2}{H_m^2 + kH_C^2} \left[\sum_{n=0}^{1} (-1)^n \, arctg \frac{H_C + (-1)^n H_m}{H_0} \right]. \quad (1)$$

A formula for the descending branch of the saturation hysteresis loop:

$$M = \chi_H \frac{H_C^2 H}{H^2 + H_C^2} + \frac{M_S}{\pi} \frac{H_m^2}{H_m^2 + kH_C^2} \left[2arctg \frac{H_C + H}{H_0} - \sum_{n=0}^{1} arctg \frac{H_C + (-1)^n H_m}{H_0} \right], \quad (2)$$

where M is magnetization of the material in a field H on the descending branch of the saturation hysteresis loop after magnetization in a field H_m to magnetization M_m,

$$H_0 = \frac{H_C}{tg\left[\frac{\pi}{2}\frac{M_R}{M_S}\right]}, \quad k = \frac{M_S}{\pi}\frac{arctg(2H_C / H_0)}{M_C - \chi_n \frac{H_C}{2}} - 1 \quad , \quad M_C \approx 0{,}67(0{,}476 + \beta H_C)M_R \quad ,$$

$$\chi_н \approx 0{,}33(0{,}476 + \beta H_C)\frac{M_R}{H_C} - 1 \quad , \quad \beta = 0{,}0712 \text{ м/кА}.$$

The methodology also employs the formula which links the internal, H_i, and the outer, H_e, magnetic fields in a product:

$$H_i = H_e - NM \ . \quad (3)$$

Methodology consists in the following. The value, H_m, of the maximal internal magnetic field in the product at magnetization with a magnetic field of intensity H_e is determined by simultaneously solving the equations (1) and (3). Whereas in Eq. (3) $H_i = H_m$. Using the obtained value H_m, from the joint solution of Eq. (2) and (3) at $H_e = 0$ the quantity M_d is calculated. At that in Eq. (3) we assume $H_i = H$.

Experimental measurements of variation of the ratio F_1 of remanent flux Φ_d in casts "nippel 1¼" of white cast-iron to Φ_d of casts with varying structure of ferritic-pearlitic malleable cast-irons (Fig.2) were conducted with the device MAQSI [3, 4]. The increase in sensitivity of the parameter M_d to the structure of cast-iron after magnetization of products in a field of 46 kA/m amounted to 20% compared to magnetization in a closed magnetic loop [5].

The discovered effect is proven for materials for which at variation of the tempering temperature after annealing, the H_C decreases, while the M_S increases. This regime is efficient for testing non-magnetized products – after consolidation from a liquid state, annealing, quenching, or tempering. Its efficiency is proven at testing the structure of casting products made of malleable cast-iron at the Minsk factory for heating equipment (Fig. 3).

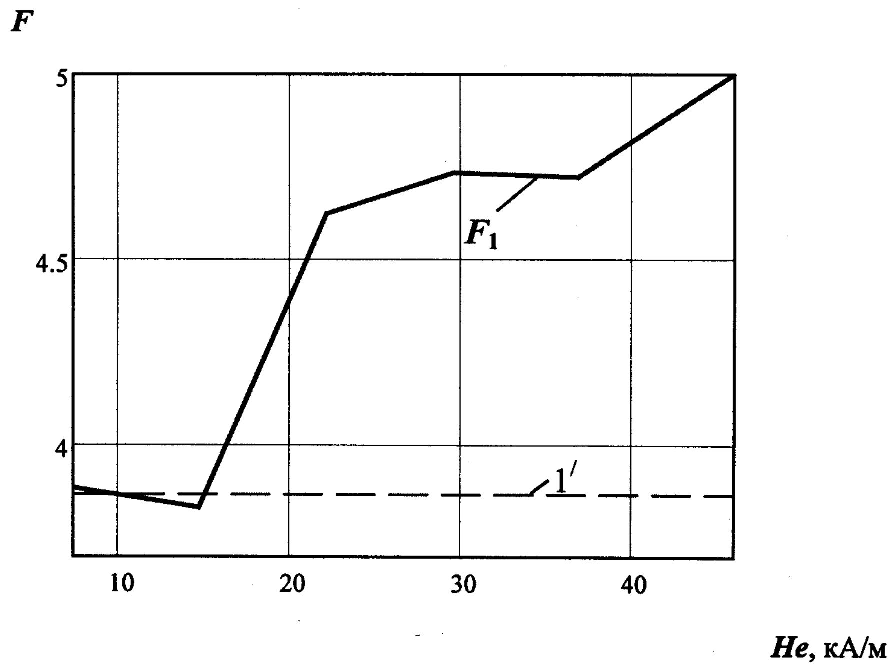
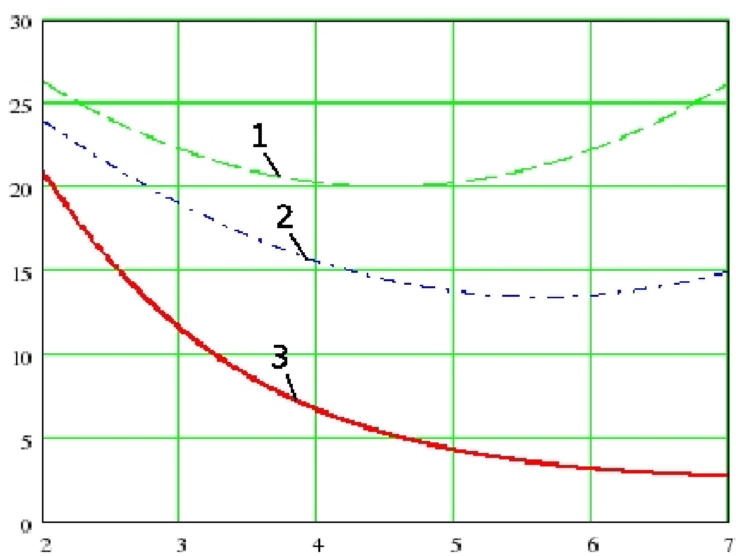


Fig.2 Dependence of ratio F_1 of the remanent flux Φ_d of casts "nippel 1¼" of white cast-iron to Φ_d of casts of ferritic-pearlitic malleable cast-iron on the magnetization field, H_e, at magnetization in an open magnetic circuit. $1^{/} - F_1$ after magnetizing the casts in a closed magnetic circuit.

Fig.3 Line for controlling the structure of the casts "nippel 1¼" of malleable cast-iron after annealing at the Minsk factory for heating equipment.

2. Magnetic testing of mechanical properties of products made of medium-carbon steels is particular: H_C and M_d of these products are ambiguously related to the tempering temperature T_{tem} after annealing. For the quality testing of such products, the following is proposed [3]: to magnetize a product, measure M_d ($M1$) after the product leaves the area with the magnetizing field, create a localized area with a constant demagnetizing field of intensity 2 kA/m on the product's pathway, measure the second value of M_d ($M2$) in the product after its partial demagnetization, and judge on the properties of the product based on the relation $F3$ of the result of this measurement to the difference of the first and the second measurements. The parameter $F3$ has (Fig.4) a high sensitivity to mechanical properties of products made of medium-carbon steels and is independent of variations in sizes of products within technological tolerance.

M1, ***M2***, ***F3*** (rel. units)



$T_{tem}/100, °C$

Figure 4. Diagram of variation of the residual magnetization $M1$ (1), residual magnetization $M2$ (2) after the partial demagnetization, and the informative parameter $F3$ (3) of the elaborated method with T_{tem} of the chilled products made of medium-carbon steels.

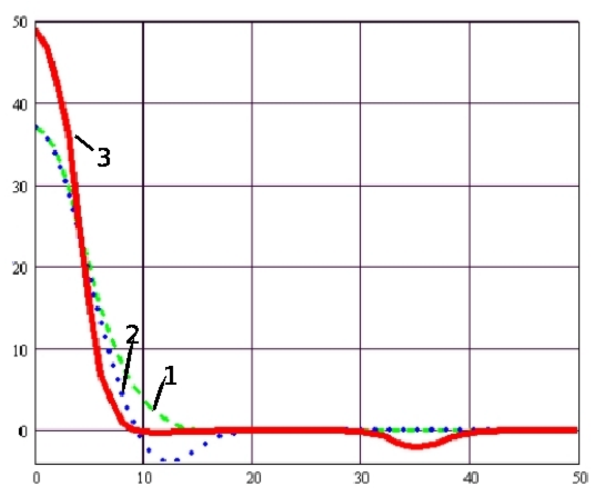
The physical grounding of the efficiency of the method lies in the following. The dependence of M_d ($M1$) of the chilled products made of medium-carbon steels on T_{tem} has an ambiguous character (Fig. 4). The residual magnetization $M2$ of the same products after their partial demagnetization decreases monotonically in the range $0 \leq T_{\mathrm{tem}}°C \leq 600°C$, although at $T_{\mathrm{tem}} \geq 500°C$ the dependence of $M2$ on T_{tem} weakens and is often non-monotonic. Nevertheless, the dependence of the parameter $F3 = M2/(M1–M2)$ of the elaborated method on T_{tem} stays monotonic in the whole range of the T_{tem} variation (Fig.4).

At $T_{tem} \geq 500°C$ monotonicity of the dependence of $F3$ on T_{tem} is provided by the increasing difference $M1 - M2$.

Elaborated methodology is implemented in the device MAQSI – U (universal) [3] (Fig.5) and the transducer device MAQSI–D (diesel) [4], which guarantees establishing on the products' pathway the given (Fig.6) magnetic field configuration and is based on measuring the remanent fluxes, Φ_d (Φ1) and Φ_d ($\Phi 2$), in products at their motion in magnetic field.

Fig.5 Appearance of the device MAQSI -U and the controlled bolts.

H, кА/м



X, см

Fig. 6 Distribution of the magnetic field along the motion axis of products in the transducers devices: 1 – MAQSI (АНБ-692); 2 – MAQSI -2; 3 – MAQSI -D.

The transducer (Fig.7) at length 560 mm guarantees zero influence of magnetizing and demagnetizing magnetic fields on the result of measuring the *Φ1* and *Φ2* of products with length up to 180 mm (Fig.6) and diameter up to 40 мм. Device MAQSI–U achieves productivity of testing of up to two articles per second. In the measurement's range of 0.01 - 99.9 mkWb, the device is certificated to have a major normalized error ≤ 1.5 %.

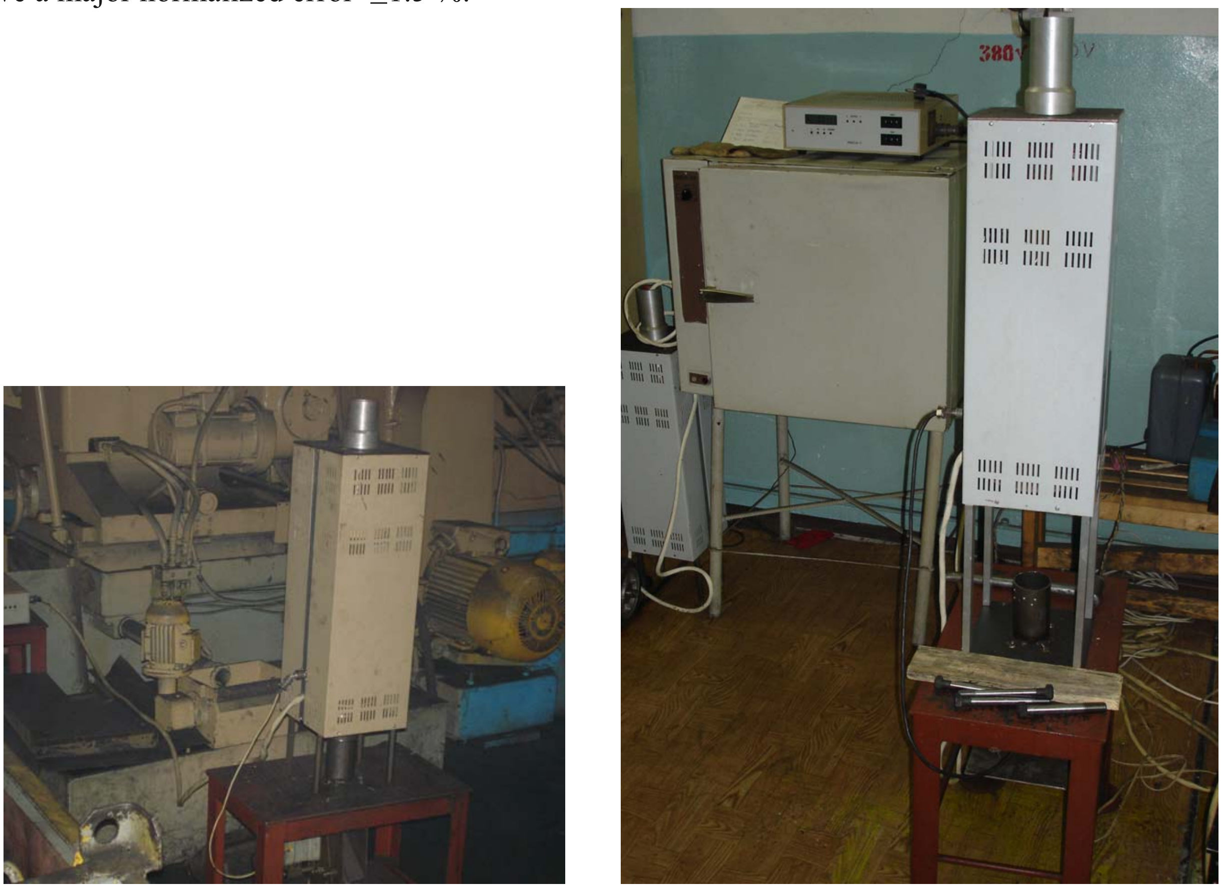
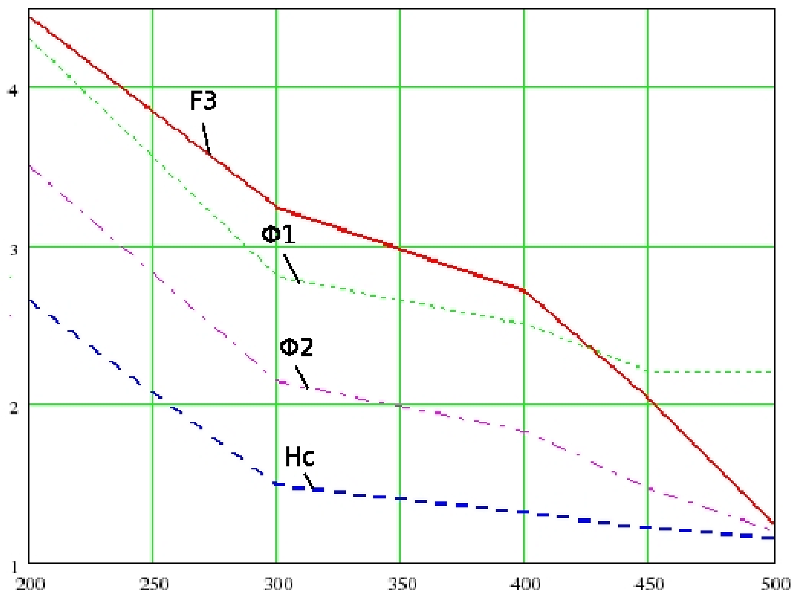


Fig. 7 Device MAQSI-Д on the Minsk motor plant.

On the Fig.8 we compare the dependences of informative parameters of different devices on T_{tem} of the bolts №240–1005018 with length 58 mm and diameter 10 mm of steel 40XH. The products are annealed at temperature 830 C. The results indicate that when T_{tem} changes from 200 to 500C, the parameter *F3* increases by a factor of 3.61, while *Φ1* increases by a factor of 1.95, and *Φ2* - a factor of 2.92 (the parameter H_C of steel 40C increases in the same conditions by a factor of 2.3).

Different testing methodologies are compared on the Fig. 9 for solving the task of testing hardness of the same bolts. To conduct the experiments, the bolts with different properties were obtained by varying their T_{tem} in a range 300 – 600 C. Preliminarily, all bolts were simultaneously annealed at 830 C. The bolts were then exposed to magnetic influence according to the methodology (Fig.6) in the transducer device MAQSI-D (Fig.7). Measuring the parameters *Φ1*, *Φ2* and *F3* of the bolts was conducted with the device MAQSI -U (Fig.5).

F3; $\boldsymbol{\Phi_d}$,мкWb**;** ***Hc***, кА/м.

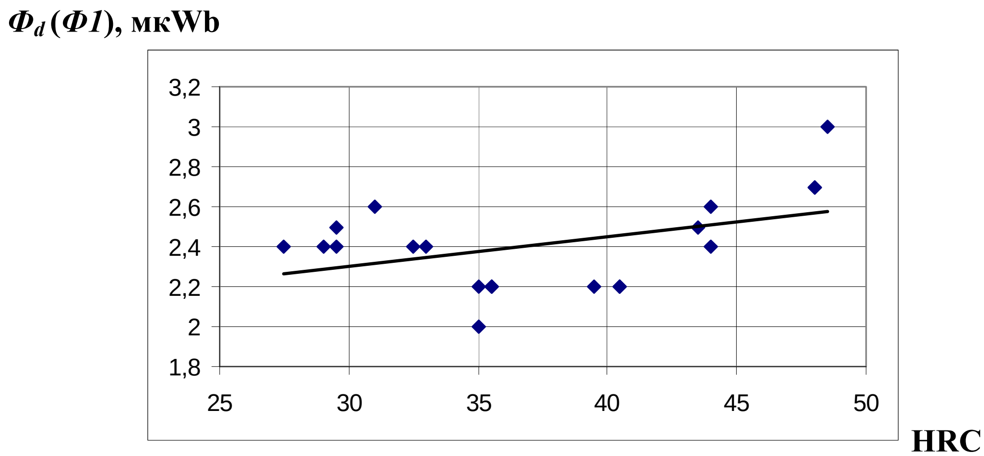


T_{tem} ,C

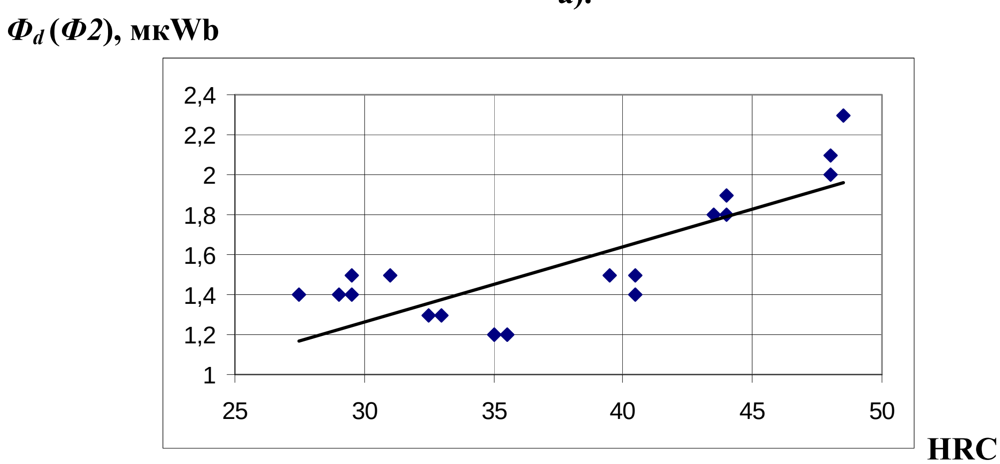
Fig.8 Variation with the tempering temperature T_{tem} of the coercive force *Hc* for steel 40X as in [5] and informative parameters of different devices at testing the bolts Nr240-1005018 of steel 40XH.

The statistical treatment of the results (shown on the Fig.9) for dependences of parameters Φ1, *Φ2* and *F3* on Rockwell C hardness HRC of products delivered the following correlation coefficients R in linear regression equations (correspondingly): 0.44; 0.79 and 0.92. The given range of the Rockwell C hardness HRC of 27 – 36 can be guaranteed only by testing with the elaborated methodology.

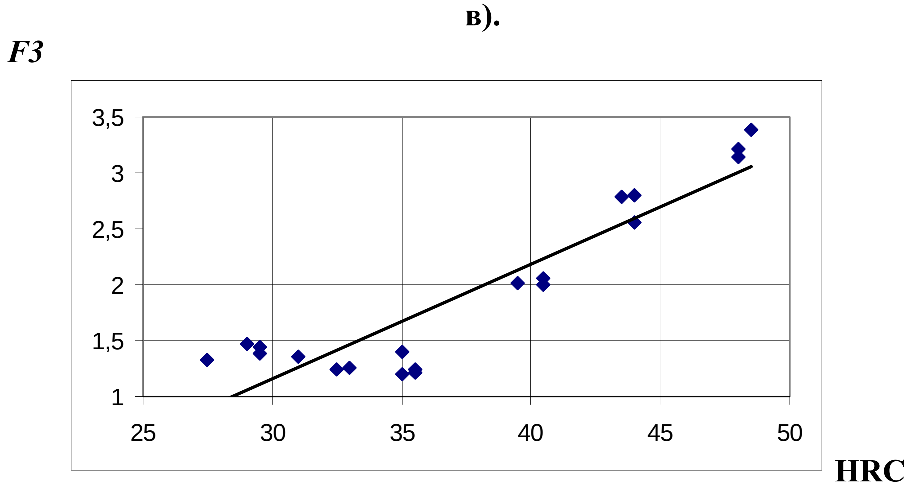
Application of the method enabled a high correlation coefficient R = 0.85 in the regression equation between the breaking point of the bolts made of steels 40X, 40XH, 45X and the display of the device implementing the method (Fig. 10). This guaranteed the required mechanical properties of the bolts. Thousands of expensive bolts were returned to production after the non - destructive testing (Fig. 11). The reliability was increased for all motors produced on the Minsk motor plant [6].



a).



в).



c).

Fig. 9 Dependence of parameters *Φ1* (a), *Φ2* (в) and *F3* (c) on Rockwell C hardness HRC of the bolts №240-1005018 of steel 40ХН.

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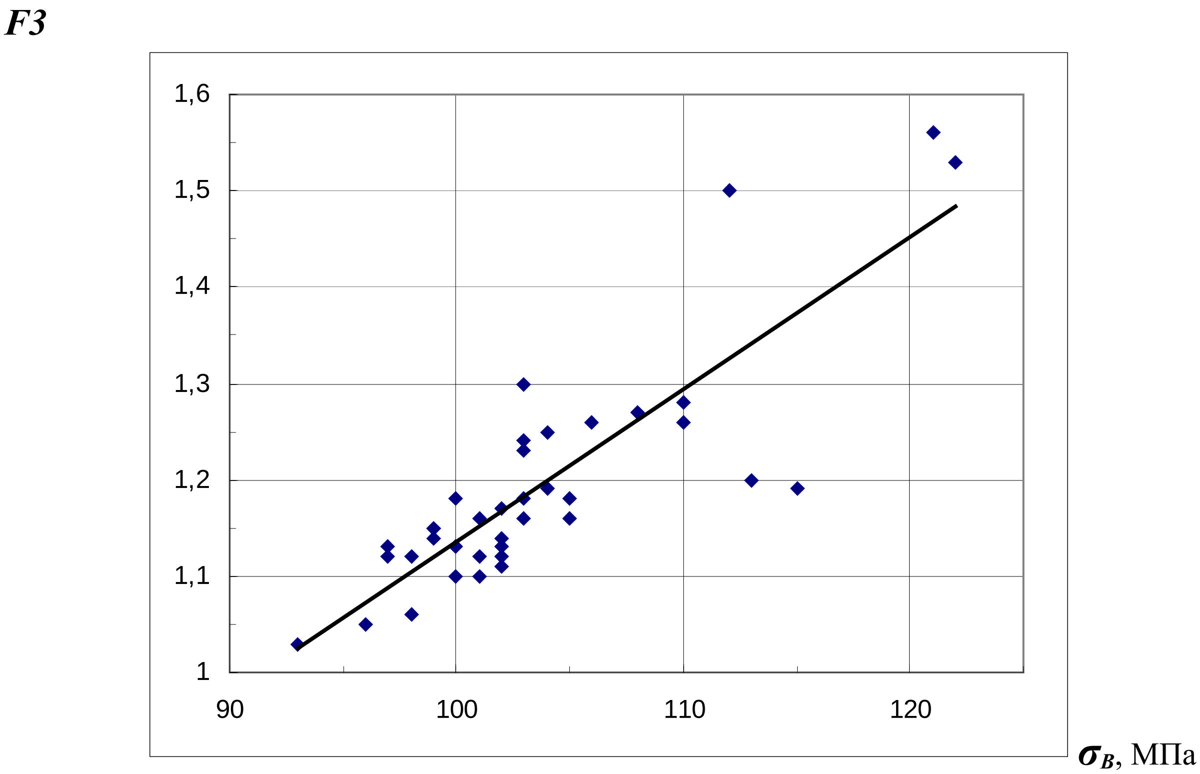
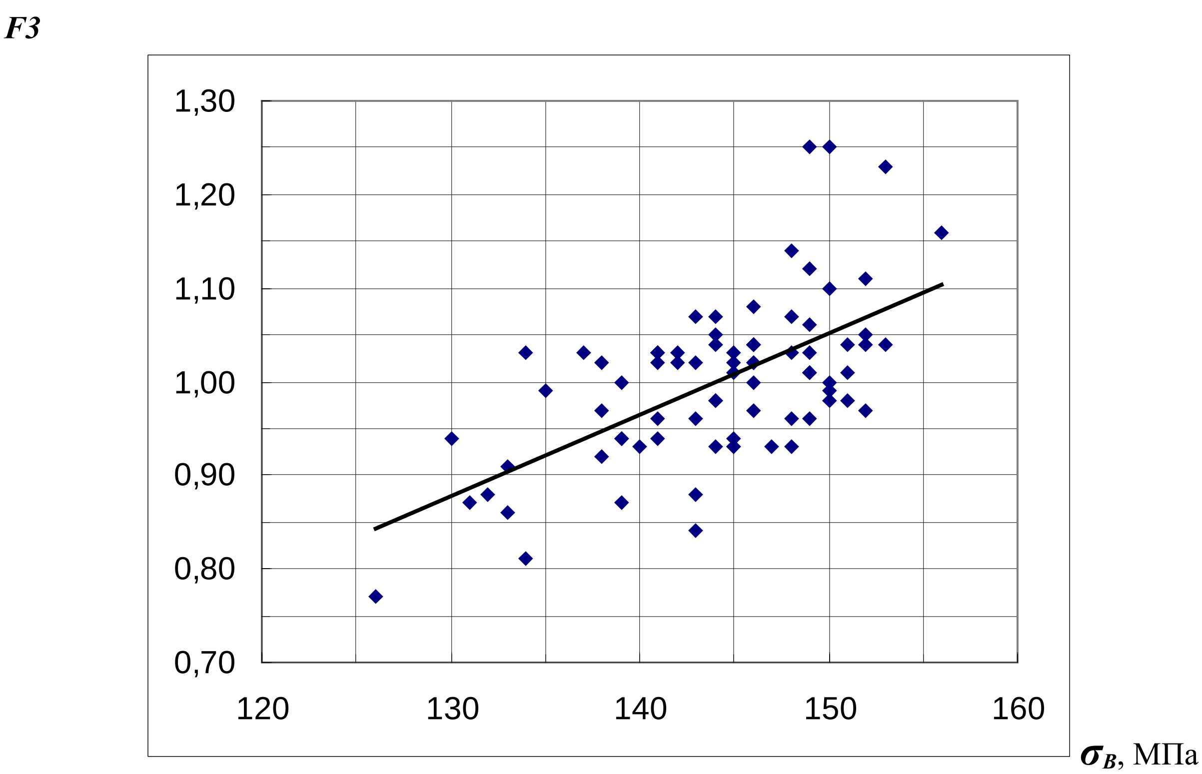


a).



в).

Fig.9 Dependence of parameter *F3* on stress rupture strength σ_B of the bolts №240-1005018 of steel 40XH (a) and of the bolts №240-1002047 of steel 40X (b).

Fig.10 The bolts, tested by the magnetic nondestructive method and returned to production on the Minsk motor plant.

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