RELIABILITY OF ROLLED BARS ULTRASONIC TESNING ON THE AUTOMATED INSTALLATION FOR ULTRASONIC TESTING VOLNA-7

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Operating experience of the automated installation for ultrasonic testing Volna-7 for testing the round rolled bars in diameter from 80 to 190 mm and in length from 4 to 12 m performed at Chelyabinsk Metallurgical Plant is presented. Constructive number of the plant's tuning and reference blocks used when performing the testing technique of internal and surface defects is shown. Surface defects testing technique carried out with the help of the multichannel monitoring system with EMA-transducers has been revised. The analysis of factors and optimization of programmed parameters of installation systems that influence the testing reliability are carried out.

Nowadays the provision of mills with automated systems and quality inspection facilities of the rolled products manufactured becomes increasingly topical. The modern inspection means provide the high level information using different kinds of methods and procedures of inspection integrated into the automated complexes.

Automated installation for ultrasonic testing Volna-7 developed by company Nordinkraft and newly applied at Chelyabinsk Metallurgical Plant (ChMK) complies fully with requirements mentioned above. The installation is intended for inspection of the hot rolled and mechanically treated round steel bars internal and surface defects in diameters from 80 up to 190 mm and length from 4 up to 12 meters using electromagnetic acoustic method (EMA). The inspection of internal defects is carried out in accordance with GOST 21120 and SEP 1920. The inspection of surface defects – in accordance with API 5L.

The installation is a part of straightening equipment line (see figure 1). In accordance with process flow sheet the entirely rolled stock of rolling mill 780 in Rolling Shop No.1 is to be straightened at a skew-roll straightening machine. Simultaneously scale is being removed from the scanned surface. Ultrasonic inspection of the rolled stock make very strict demands to the installation itself. The installation is to work surely under heavy conditions of production department: at under high (up to 50^0C) and relatively low (-30^0C) temperature, dustiness and gas contamination, inspect the products having rough surface or scale, have very high productivity (V=0,5-1,5 m/s) and inspection reliability. The application of the EMA method assures conforming to this conditions of the rolled stock quality conditions.

A part of the installation destined for registrations during the inspection is located on the retractable module (platform). Modular concept of structural arrangement is taken as a basis of this installation based on the experience of similar systems to carry out the inspection system maintenance as well as to adjust testing sensitivity for each surface defects inspection system channel in view of testing technique adjustment. A number of methods aimed at testing reliability enhancement are used in the installation by means of ratio Signal/Noise extension. The installation is program-controlled by means of industrial computer. All systems are connected with a major supervisory computer control system (SCCS), which coordinates their work, operates data flow, collection, processing, presentation and storage of testing results, provides with UST results data through mill informative computer network.

SCCS organizes the inspection in accordance with rejection regulations set by the operator. This norms and regulations may be chosen from the enlarged list of standards or technical specifications titles. Based on the results of testing (in accordance with the specified sensitivity level and testing criteria selected) a defect map of the scanned part of tested unit is displayed on monitor screen. Simultaneously a flaw marker identifies the defected zones on the test unit. After testing completion the bar is classified as a “suitable”, “partially suitable” of the Class 1, “partially suitable” of the Class 2 or “rejected” and separated into 4 pots. Further the bar test reports are created in the computer memory.

The installation includes two conditionally independent systems: internal defects testing system (IDTS) and surface defects testing system (SDTS).

For internal defects system electromagnetic acoustic transducers (EMAT) with transverse wave introduced as per scanned surface normal are used (see Fig. 2,a). During experimental-industrial production of internal defects testing system refinement and optimization of the programmable installation parameters were carried out. Methods of internal defects testing as per degrees of quality specified in SEP 1920 were worked out. Additional reference blocks of OK type with flat-bottomed control deflectors (see Fig. 2, b) were worked out, produced and certified.

Internal defects control system consists of eight channels. The EMATs that excite transverse wave of ultrasonic frequency 2.2 MHz of the type P 411-2,2-Nord-T-(SPr)-160. EMATs are installed in two sections, in fours for each. The angle between acoustic axes of the transducers is 90˚. The angle between the sections is 45˚ (see Fig.2, a). During internal defects testing the EMATs work in turn in simultaneous mode, i.e. the excitation and reception of ultrasonic wave during selected time is fulfilled by means of one transducer.

The identification of DAC form parameters for the correspondent bar diameters range is carried out in static mode using remote EMAT and remote monitor. The checking of the specified sensitivity parameters is fulfilled when reference blocks are tested in dynamic mode. Reference block is a built-up construction. Metrological part is connected to the remaining part of the sample which is necessary for drawing through transport line of the installation. The connection framework provides the turning possibility of metrological part 360˚ relative to the pillar axis and superposition of each EMAT acoustic axis with artificial flat-bottomed deflector axis.

Nowadays the bars are supplied as per 158 metallurgical specifications which makes over 45 steel grades. Maximum testing productivity for rolling-mill shop №1 makes about 8.5 thousand tn per month. Over 300 thousand tn has been scanned at the installation.

Traditional usage of Rayleigh wave by Nordinkraft in installations of the type "Volna" for surface defects testing of hot rolled product with rough surface proved to be uneffective. Therefore Nordinkraft specialists have developed and implemented a multichannel surface defects testing system which includes EMA-transducers radiating transverse waves with specified angle of incident. Surface defects testing system consists of 16 channels (each EMAT has 2 channels). For surface defects testing system the EMATs that excite transverse wave of ultrasonic frequency 1.0 MHz of the type P 421-0, 94-35°-Nord-TSV(SPr) 160. The transducers are installed in two sections, in fours for each. The angle between acoustic axes of the transducers is 90˚. The angle between the sections is 45˚ (see Fig. 3, a). Sonic test direction (angle of incident) is changed for each transducer according to cycle time and makes 35° to normal.

One of the major conditions ensuring reliable performance of testing by the multichannel system is the application of monitoring methods and schemes which provide equal sensitivity into the perimeter of the scanned product. Surface defects testing method developed by Nordinkraft specialists is based on employment of bidirectional reception property of EMA-transducer [1, p. 84-93]. Chordally directed ultrasonic wave ray reflects twice from side cylindrical bar surface and strikes effective surface of the EMAT which ensures bidirectional reception (see Fig. 3, b).

As per these methods twice-reflected wave signal amplitude level is set as a reference one when determining equivalent sizes of surface defects. However, significant design tolerance for EMAT angle of incident deviation ($\pm 3^0$) and ray displacement, when reflected from side surface, the value of which changes against reflective surface curvature causes central ray displacement relative to EMAT effective surface. Marginal rays of different levels strike EMAT effective surface. The automatic gain control system (AGC system) equalizes signal amplitude for the 16 channels to a specified value, noise level increases for particular channels, sensitivity margin decreases considerably. Channels sensitivity values differ significantly which influences the reliability of testing results.

To fulfil SDTS sensitivity adjustment with an allowance to the drawbacks mentioned above adjustment blocks of the type ДП-100 with milled slot (depth 1 mm, stretch 40 mm (see Fig.3, c)) are developed and used. Reference block ДП-100 is attracted by transducer's magnetic system and fixed at the working surface of protective lap, value of the split between EMAT and cylindrical surface of the block remains identical to the conditions of products testing (the split for SDTS equals 0.6 mm). The angle which provides maximum echo signal amplitude of direct ray from milled slot is set by turning of the cylinder. Then the echo signal amplitude is equalized for each channel and set at the given level (-10 dB) which provides equal sensitivity and required sensitivity allowance for all channels.

The scanning scheme is formed by a direct ray and a single-reflected one in order to create thick coverage of ultrasonic wave rays, directivity characteristic as per level – 6 dB (Fig.4, a). Corrective amplification gain AD/AD' is introduced in order to equalize single-reflected ray channel sensitivity and direct ray channel sensitivity (Fig. 4, b).

Products surface defects exposure and their equivalent size evaluation are carried out in gating zone for wave with surface. Gate parameters are counted against bar diameter. Programmed parameters settings and SDTS estimation criteria verification under dynamic regime is carried out using reference blocks of ДН-type with milled slots (depth 0.3; 1.0; 2.0 mm) (Fig. 5). Additional sensitivity setting verification is fulfilled simultaneously for all IDTS channels under dynamic regime using reference blocks of ДН-type with side cylinder reflector, diameter 2 mm.

During experimental-industrial production of the installation SDTS optimal parameters trial was carried out and factors which influence reliability of testing results were studied:

Factors and actions	Factor influence
Exact split verification between EMAT base surface and working surface of protective lap which contacts directly with bar surface. Periodical testing of the split. SDTS split nominal value is 0.6 mm.	The rate of echo-signal amplitude without split to the echo-signal amplitude at split 0.6 mm $AD_{3=0}/AD_{3=0,6}$=9dB The rate of echo-signal amplitude at split 0.8 to the echo-signal amplitude at split 0.6 mm $AD_{3=0,8}/AD_{3=0,6}$= -7dB
EMAT characteristics testing on an input (conventional sensitivity, signal-to-noise ratio)	The rate of echo-signal amplitude of the transducer with maximum sensitivity to echo-signal amplitude with minimum sensitivity $AD_{EMATmax}/AD_{EMATmin}$=7dB

Usage of scanning scheme for direct ray as well as for single-reflected one.	Increases bar perimeter scanning density at testing.
Pressing and steady contact of the monitoring system owing to optimal pressure setting at the operating mechanisms of the installation pneumatic system. Removing of metal dust from EMAT base surface by means of compressed air effective stream.	Operation of the channels is blocked without removing metal dust and scale stuck to EMAT base.
Individual setting of the given sensitivity level for each channel using reference block ДП 100.	Spread of amplification gain values at equalizing the channels sensitivity reaches 6 dB.
Optimal parameters and SDTS evaluation criteria selection (K4, K5 and rate AD/AD') for grade and profile range.	Influences the accuracy of defect equivalent sizes evaluation.
Optimal digitized echo-signal processing parameters which provide resistance to interference and maximum signal-to-noise ratio (selection of amount at averaging the signal, frequency filtering, selection of pulse duration value)	Increases sensitivity allowance and testing results repeatability.
Change in structure of EMAT unit to provide safe fixation and stable split.	Increases sensitivity allowance and testing results repeatability

To calculate probability rate of testing reliability the results of repetitive testing at reference block ДН 140, reference block ДК 152 (with natural defects, equivalent and conventional sizes of which are measured at manual testing by means of remote EMAT) and rolled bars lot in dia. 140 mm, length 11.8 m [2]. At testing the amplitudes of echo-signals of direct and single-reflected rays from defects were measured and testing reliability was calculated accordingly. Data precision is characterized by normal distribution law which is determined by average defect amplitude value $\bar{x}$ and mean-square deviation σ for the amount of runs chosen.

$$\sigma = \sqrt{\frac{\sum (x_i - \bar{x})^2}{N-1}}$$

$$\bar{x} = \frac{\sum x_i}{N}$$

where x_i stands for signal amplitude in resulting channel for each run,

N stands for the amount of runs of the lot.

Distribution characteristics at repetitive run of reference blocks ДН 140 and ДК 152 (on the oblique stroke left and right are data for the first and second lot from respectively, amount of runs per lot is 20) are as follows:

Depth and length of defect, mm	Average echo-signal amplitude value for defect $\bar{x}$, dB	Mean-square deviation σ, dB
СОП ДН-140		
0,3×40	–25,2/–26,3	2,3/2,4
1,0 ×40	–19,3/–20,8	1,8/2,0
СОП ДК-152		
0,4 -0,7×75	–28,09/–27,8	1,9/1,8

Fig.6 shows surface defects testing reliability calculation algorithm [3 -5] and graphic presentation of accumulated distribution.

Fulfilment of all factors mentioned above permits increasing sensitivity allowance as per signal-to-noise ratio and testing reliability. The results of reference block ДН 140 repetitive runs analysis for defect in depth 1mm before consideration of the factors influencing testing reliability (on the oblique stroke left) and after (on the oblique stroke right) are as follows:

Correct detection probability P_{11}	0,6/0,98
Overrejection probability P_{01}	0,2/0,1
Underrejection probability P_{10}	0,4/0,02

Testing reliability calculated as per [4] the formula

$$D = 1-(P_{(10)}+P_{(01)})$$

for two variants studied was

D_1= 0.4; D_2 =0.88

Testing results for products in dia. 140 mm of steel grade 20 are shown at Fig. 7 and 8.

Thus the automated installation Volna-7 provides manufactured products quality monitoring, increases rolled bars competitiveness, ensures guaranteed quality of the products. Necessary conditions of effective ultrasonic testing of internal and surface defects as per methods developed are as follows: qualified maintenance support of all systems of the installation, systematic training and certification of nondestructive testing operators, effective analysis and subsequent correction of bars manufacturing technology according to the results of ultrasonic testing using an integrated information computer network.

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Fig.8 Microstructure according to the defects location at the H1 sample surface, steel grade 20, round, diam.140 mm

Surface Defects Testing Reliability Calculation Algorithm

Parameters	Formula
Determination of characteristics of defects distribution laws	
Average defect amplitude value	$\bar{x} = \frac{1}{n}\sum_{n} x_i$
Mean-square deviation σ for each defect detected	$\sigma = \sqrt{\frac{\sum\left(x_i - \bar{x}\right)^2}{n-1}}$
Distribution laws determination	
Differential law of normal distribution (frequency function)	$D(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-a)^2}{2\sigma^2}}$
Integral law of normal distribution (reliability characteristic of SDTS installation)	$\varphi(x) = \frac{1}{\sigma\sqrt{2\pi}} \int e^{-\frac{(\bar{x}-x_i)^2}{2\sigma^2}} dx$
Normalized distribution of natural defects in a lot of tested products (relation between quantity of defects and their size)	$\mathbf{f}(x) = \left[\left[\frac{1}{(x-5)^{0.3}}\right] - 0.36\right]$
Distribution through composition of integral law of normal distribution and normalized distribution of defects according to size	F(x)=f(x)*φ(x)

Fig.1. Automated installation for rolled bars ultrasonic testing Volna-7

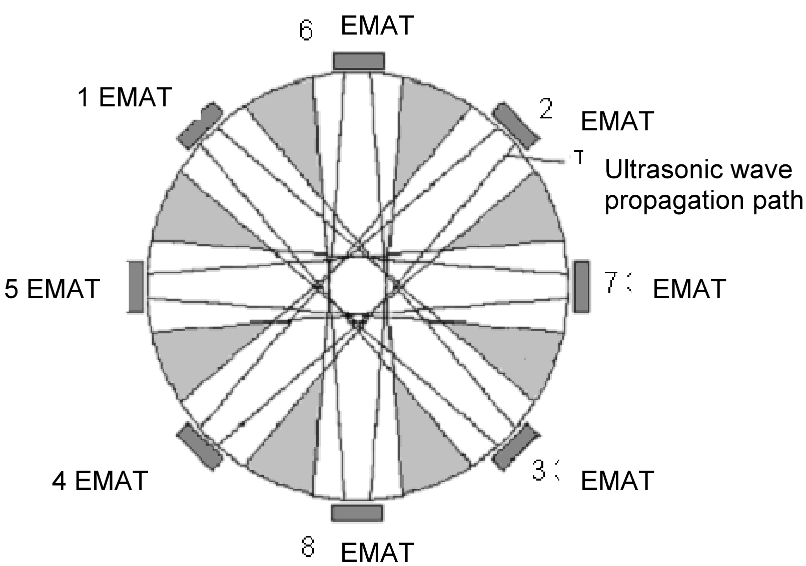

Fig.2a. IDTS transducer position scheme

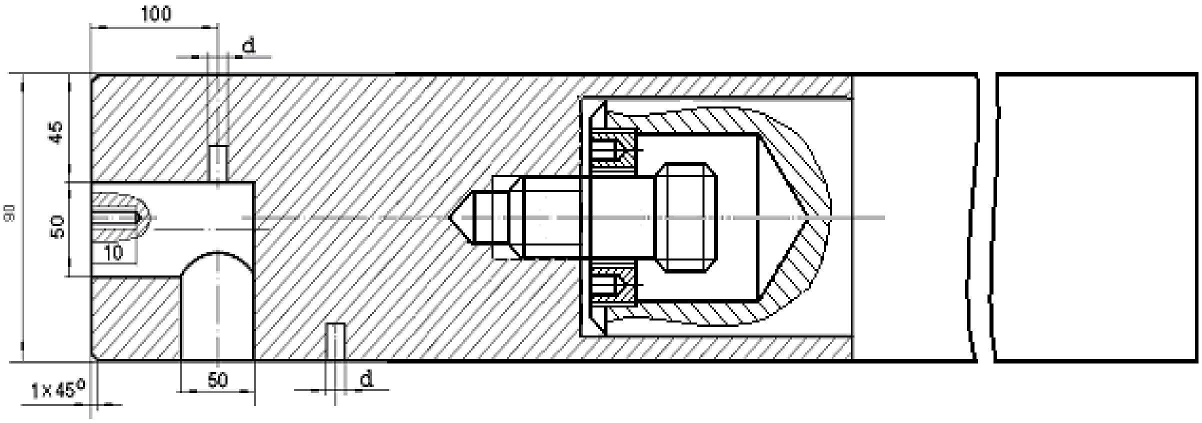

Fig.2b. Reference block draft

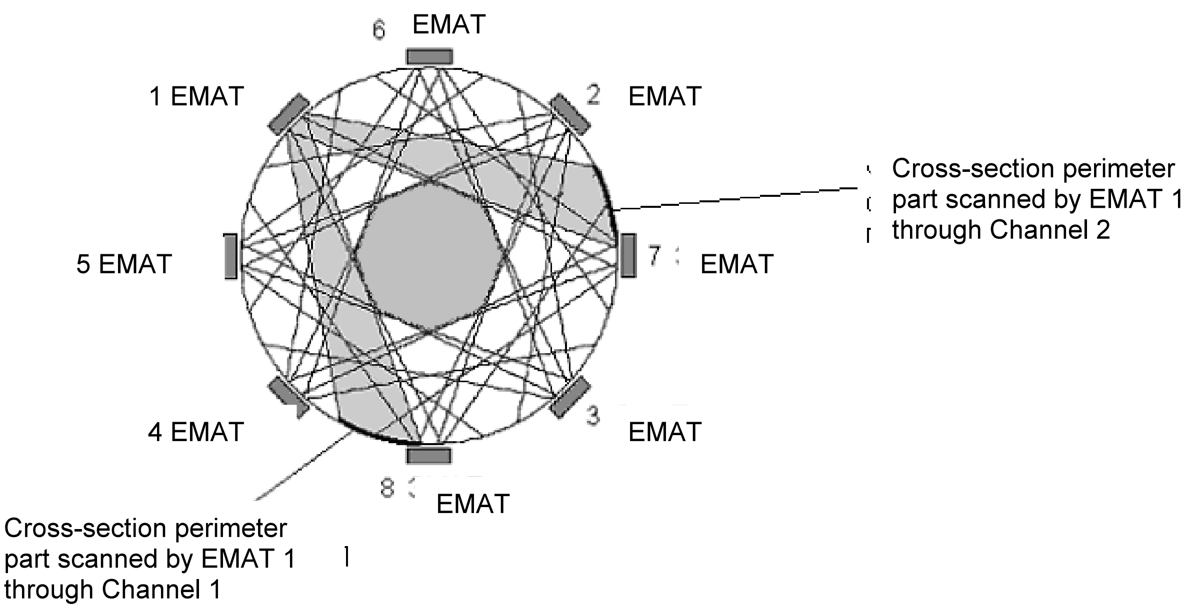

Fig.3a. SDTS transducer position scheme

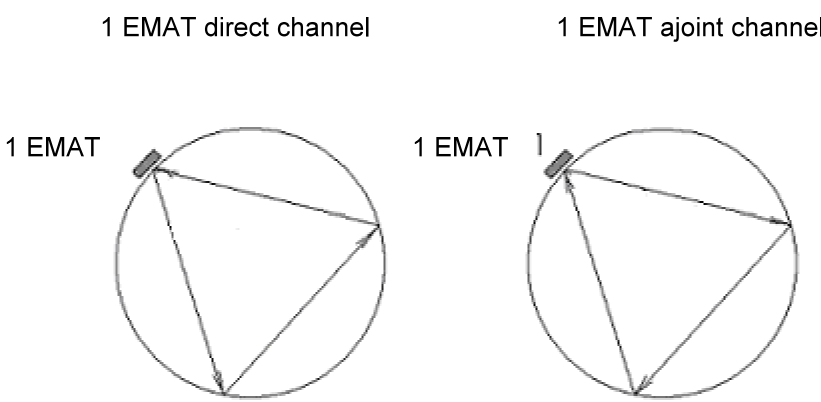

Fig.3b. Sonic test direction of the EMAT №1 for different SDTS cycle times.

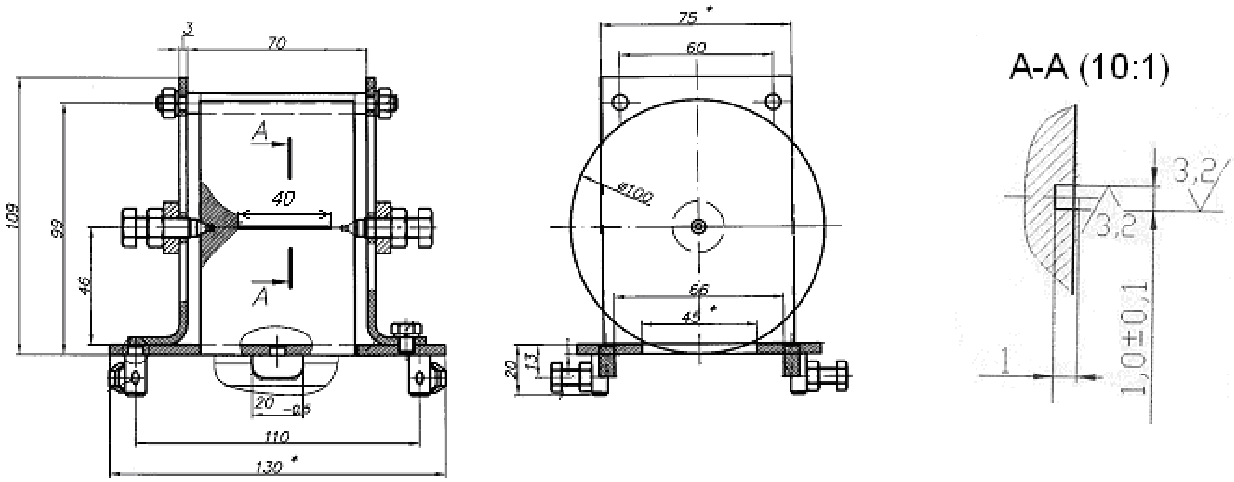

Fig. 3c. Adjustment block of ДП-100-type draft

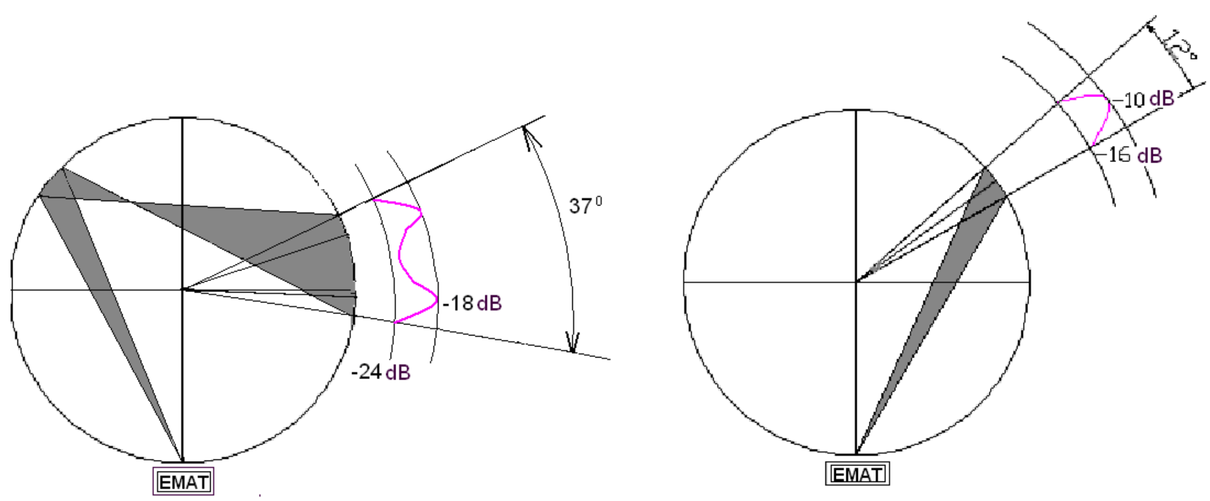

Fig. 4a. Scattering diagram for direct and single-reflected rays from milled slot (depth 1 mm) for different EMAT cycle time before sensitivity correction

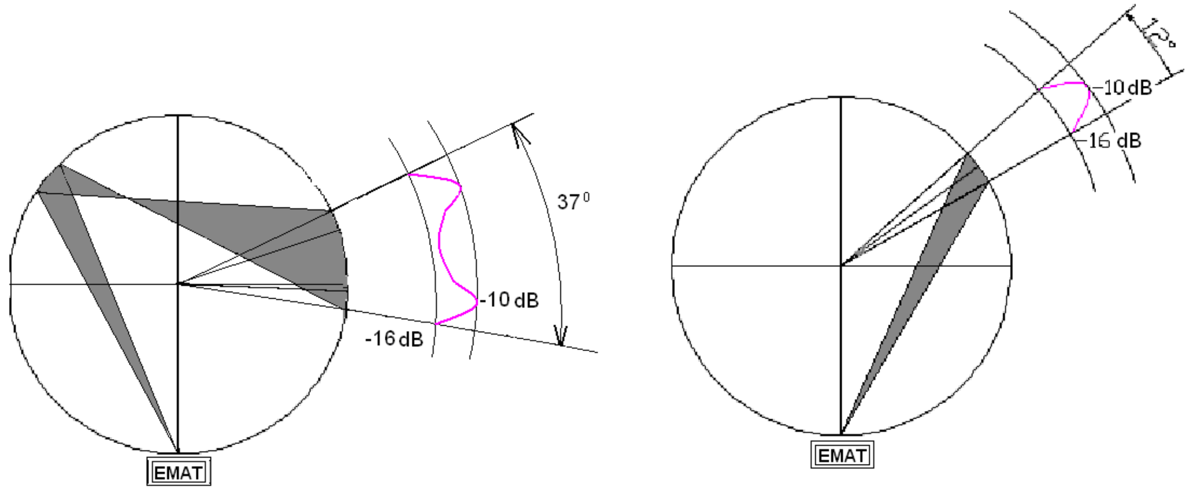

Fig. 4b. Scattering diagram for direct and single-reflected rays from milled slot (depth 1 mm) for different EMAT cycle time after sensitivity correction.

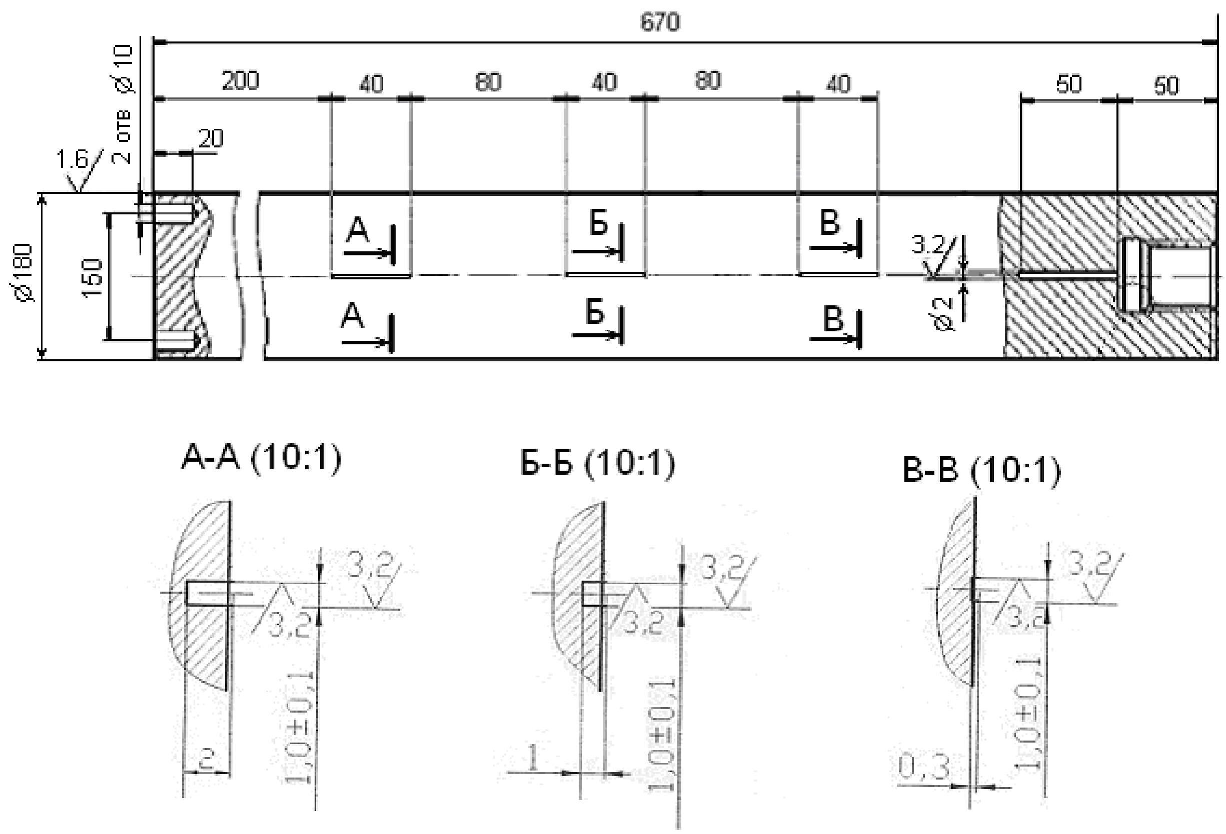

Fig. 5. Dynamic reference block of ДН-180-1-type metrological part draft.

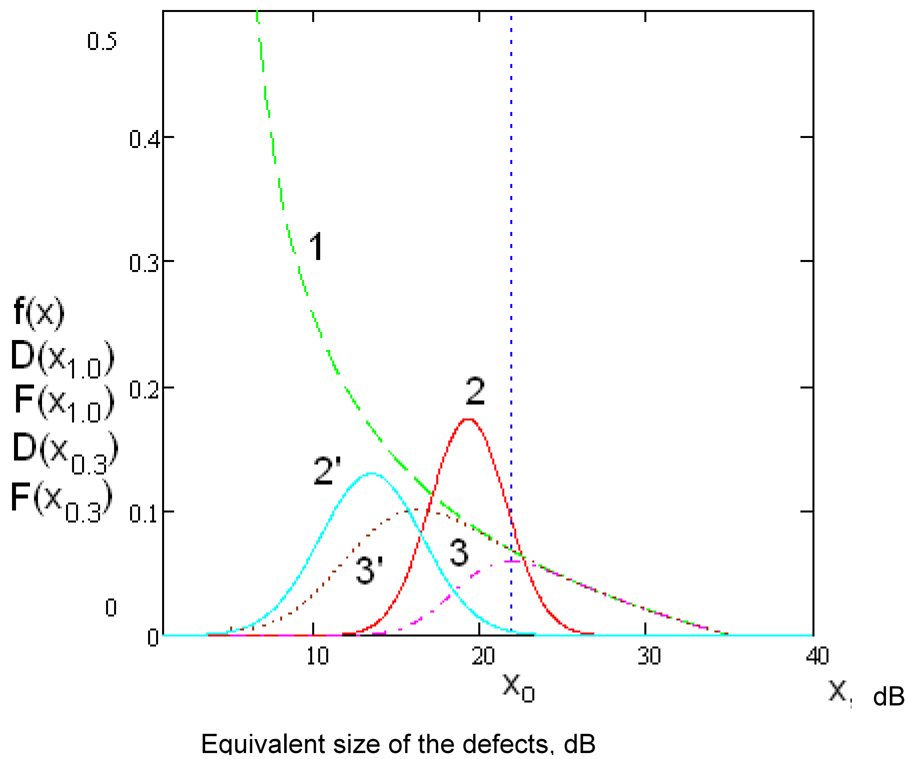

Fig. 6. Accumulated distribution graph

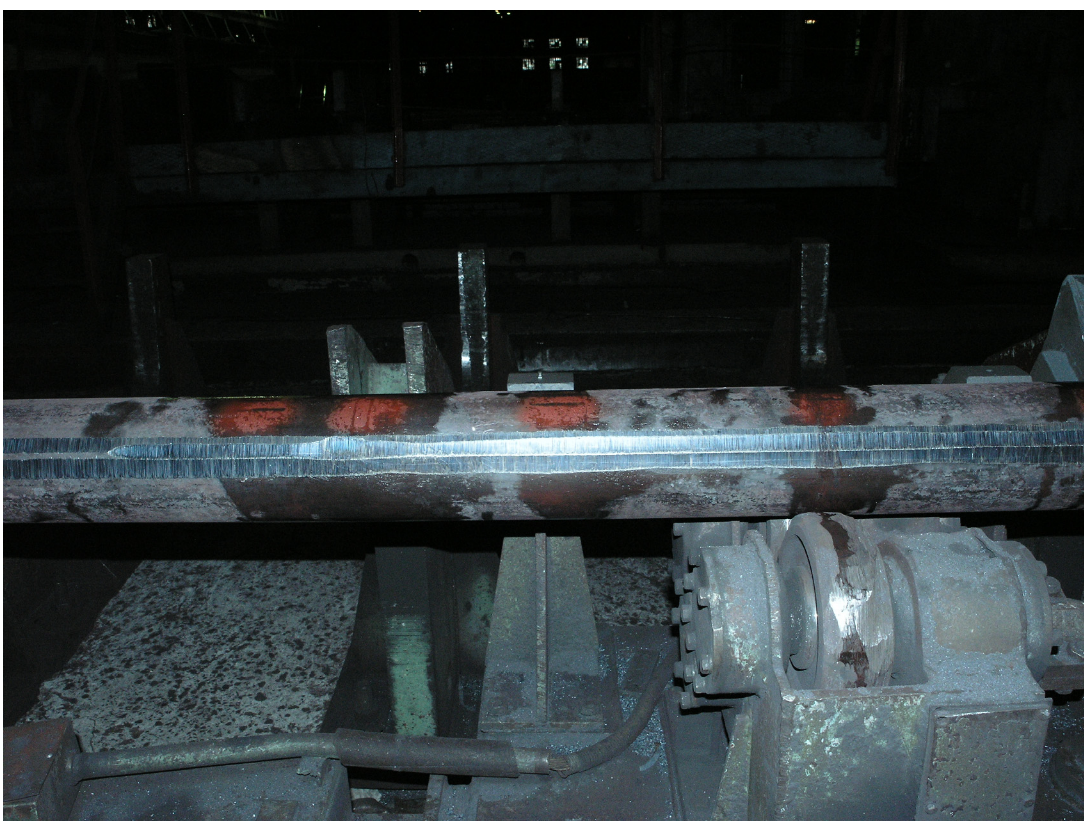

Fig. 7a. Bar with crack defect detected in course of testing at automated installation Volna-7

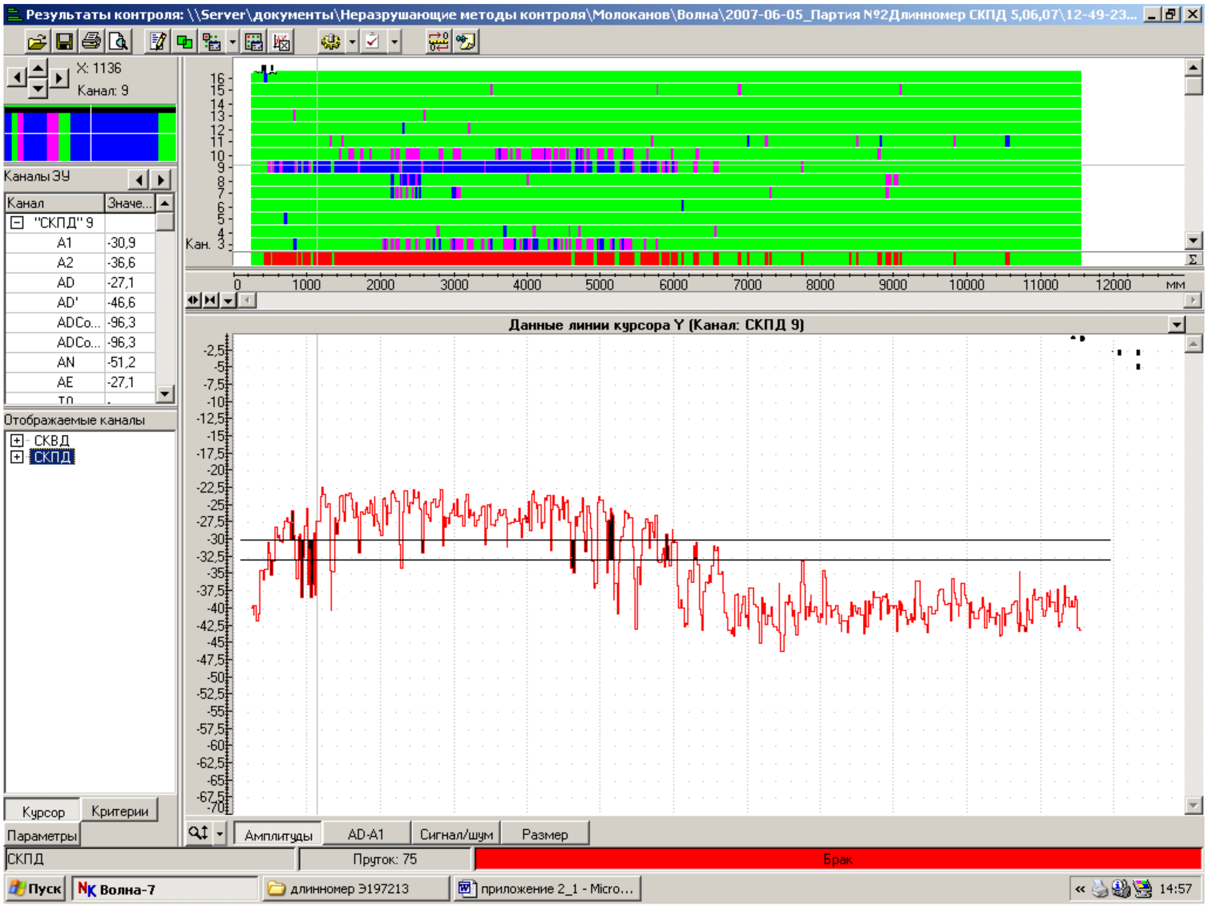

Fig. 7b. Report of SDTS testing results for round bar H1 of steel grade 20, diam.140 mm, with crack defect detected.

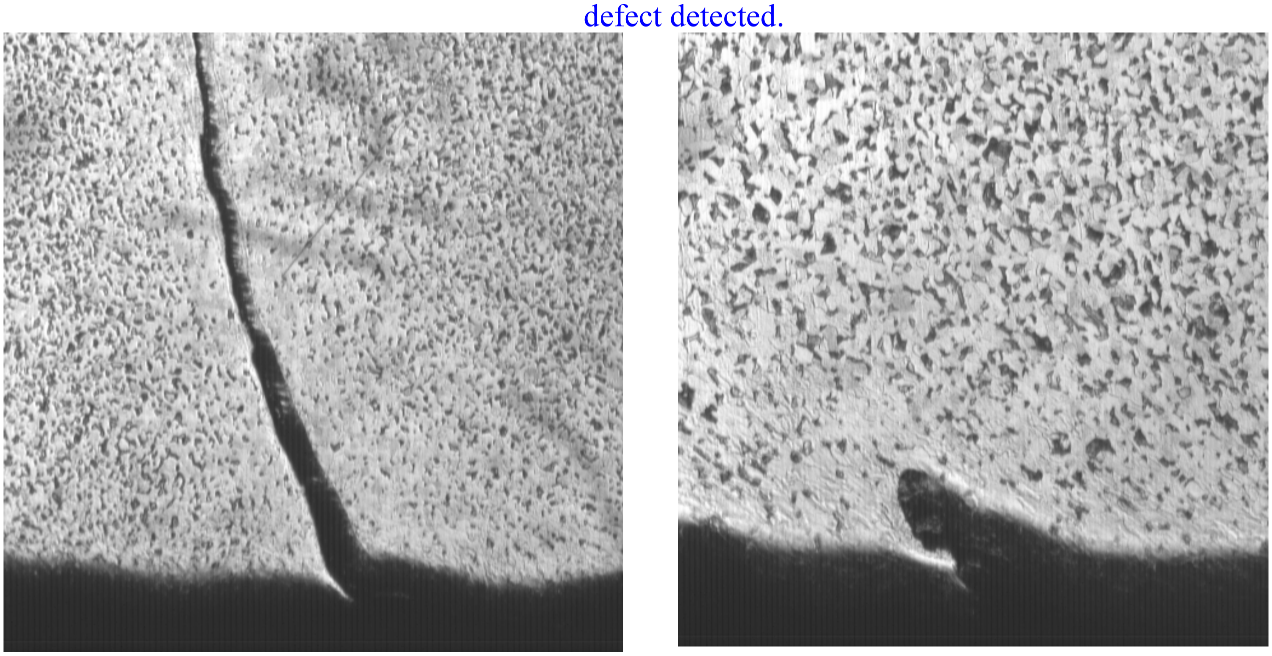

Fig.8. Microstructure according to the defects location at the H1 sample surface, steel grade 20, round, diam.140 mm

a) Defect depth 5.6 mm b) Defect depth 0.7 mm