

Texture Analyzer for On-Line r_m -Value Estimation

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This article describes the development of an X-ray texture analyzer that can be used for continuous on-line inspection of cold rolled steel.

KEY WORDS: r_m -value, texture analyzer, on-line estimation.

INTRODUCTION

The importance of nondestructive evaluation of characteristic technological values (which provide information concerning properties of materials during processing and service) of materials, particularly steels, has significantly increased in recent years. Estimation of grain size in steel by ultrasonic-wave scattering (Goebbels and Willems, 1982), study of internal stresses by X-ray diffraction (Hauk, 1981) and use of the Barkhausen effect to study structure changes, e.g. during the annealing process (Hoesch Stahl AG and IZfP, 1986) are examples of industrial applications of nondestructive evaluation. The deep drawing properties of cold rolled steel strips, which are correlated with crystallographic microstructure, i.e. texture, are of particular interest. Hoesch Stahl AG has therefore conducted research to develop X-ray texture analysis methods that can be installed in a production line to permit continuous on-line inspection over the entire length of cold rolled steel strip (Maurer, 1982), (Böttcher and Kopineck, 1985).

The resulting measuring technique can be characterized as follows:

- Texture measurement with X-ray diffraction by transmission for steel sheets up to 3 mm thick

- Using 60 keV continuous (“white”) radiation from a *W*-anode
- Use of energy-dispersive detectors for simultaneous measurements of X-rays diffracted by characteristic lattice planes
- Correlation of the intensity diffracted by one or more types of lattice planes with deformation properties of the sheets to be inspected.

The implications of these points are explained as follows:

- In contrast to the reflection method, the transmission method (Figure 1) allows detection of lattice planes whose normals lie in the sheet plane. Lattice planes through the entire sheet are detected in the transmission technique. The results are therefore integrated by the measurement. This method is thus independent of surface condition, and no surface preparation is necessary. From Bragg’s law, we obtain

$$E_{hkl} = hc / (2d_{hkl} \sin \theta), \quad (1)$$

where h = Planck’s constant, c = velocity of light, d_{hkl} = interplanar spacing, θ = Bragg angle and E_{hkl} = energy of radiation associated with θ and d_{hkl} . It follows, that for constant θ , there is a relation between the interplanar spacings, d_{hkl} , and the

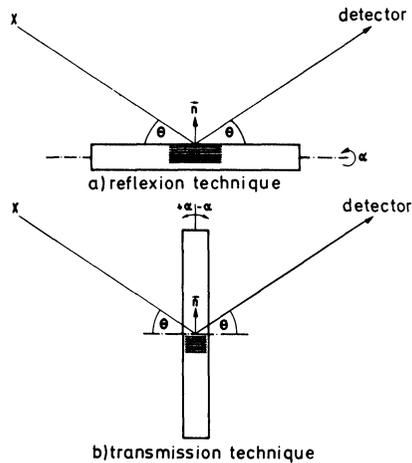


Figure 1 X-ray back-reflection and transmission technique (schematic).

discrete energy values, E_{hkl} . This means that, by using the continuous ("white") radiation of an X-ray tube, it is possible to associate different diffraction lines with different energy values.

- With semiconductor detectors, the energy-dispersive measuring technique permits simultaneous measurement of different energy values. With this technique, it is possible to measure simultaneously several lattice-plane reflections, and thus several complete or partial pole figures.

The resulting laboratory equipment is shown schematically in Figure 2. X-rays from the tube are diffracted by lattice planes in the sheet and reach the semiconductor detector. Variation of angles α and β allows simultaneous measurement of up to 5 partial pole figures. The (211) and (220) reflections seem to correlate well with formability data for cold rolled and annealed steel sheets.

These two reflections are particularly important for the anisotropy coefficient r_m (Lankford-value).

As a result of the laboratory research, a prototype measuring device was installed in the inspection area of the Hoesch cold rolling mill 2 in 1980. This measuring system is schematically illustrated in Figure 3. It agrees in principle with the arrangement in Figure 2,

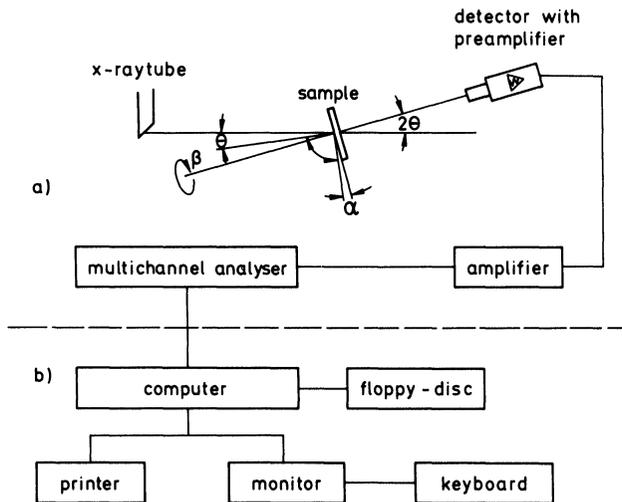


Figure 2 Measuring arrangement in laboratory.

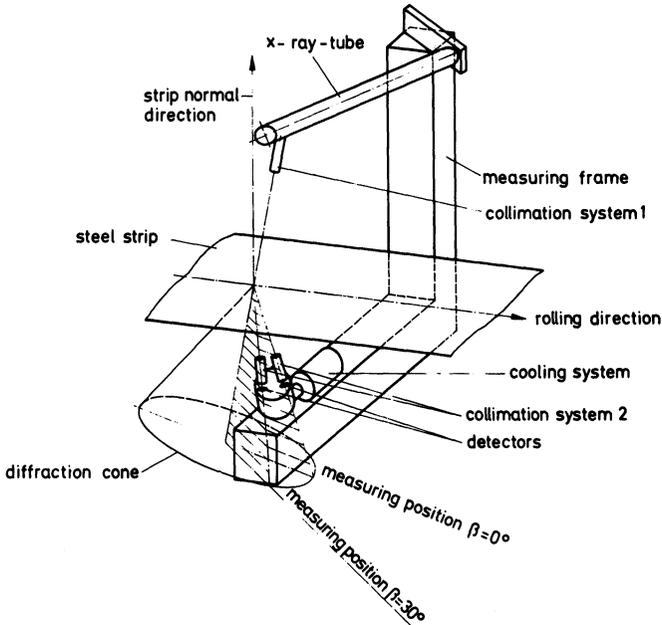


Figure 3 System for r_m -value estimation.

with the exception that the measuring points are now fixed. Figure 3 therefore shows a “fixed-angle texture-analyzer”.

X-rays from the target are collimated at an angle $(90^\circ - \theta)$ with the rolling direction. Detectors are installed at fixed points ($\alpha = 0^\circ$), ($\beta = 0, 30^\circ$) along the diffraction cone.

The diffracted X-rays are also collimated before reaching the detectors. Two detectors are installed in the measuring device shown in Figure 3. The measuring system is supported in a C-frame. The X-ray tube and detectors are housed in the upper and lower portions, respectively. In addition to the above, a microcomputer and multichannel analyzer are also required for automatic measurement. The microcomputer controls the measurement and processes the measured data.

The measuring device is presently still operating in the cold rolling mill and has given extensive information. With the help of measured results, it has been possible to identify the influence of operating variables on r_m -value during production. Because of the

good experience with this measuring device, a second was built in 1985. It operates in the inspection area at the end of the new Continuous-Annealing-Line (CAL) of the cold-rolling mill 2 at Hoesch Stahl AG.

Laboratory work necessary for development of the new measuring system and the device itself will be described in this paper.

LABORATORY RESEARCH

Estimation of r -value by texture measurement.

As is known, the r -value is indicative of the deep drawing quality of a sheet. The r -value is normally determined by a tensile test. It is defined as the ratio of width to thickness strains during a longitudinal extension of about 20%. The r -value is measured as a function of the angle β of the tensile axis from the rolling direction. A mean r_m -value is often specified. It is determined from $r(\beta = 0^\circ)$, $r(\beta = 45^\circ)$ and $r(\beta = 90^\circ)$ according to:

$$r_m = \frac{r(0^\circ) + 2r(45^\circ) + r(90^\circ)}{4} \quad (2)$$

The deep-drawing properties, and thus the r -value, are primarily influenced by the texture of the material. If the mechanics of deformation of a polycrystalline material were sufficiently understood, it should, in principle be possible to calculate the r -value from a knowledge of the texture. X-ray diffraction provides a practical method to determine the texture. To get complete information about texture, it is necessary to measure several pole figures and to treat the results mathematically.

In recent years, the most-frequently used description is the orientation distribution function (ODF) particularly in the form of a series expansion (Bunge, 1969).

Theoretical models, like the Taylor model, have been used to estimate the plastic anisotropy of a polycrystalline material. These models require the ODF of the texture (Bunge and Esling, 1982). It is thus possible to estimate the $r(\beta)$ -values from several pole figures.

This method is too complex for a practical estimation of the r_m -value. It is, moreover, not suitable for an on-line measurement,

because of the measuring and computation time requirements. This is the reason the method described in the introduction was developed at Hoesch Stahl AG. With this method, it is possible to correlate r_m -value with the intensities of some special points of the pole figures for different types of texture. This procedure requires that the type of texture does not change for a given sheet quality.

The prototype device for on-line estimation of the r_m -value of batch-annealed aluminium killed steel was based on this assumption. In general, this sheet quality has the same type of texture.

Introduction of the new Hoesch Continuous Annealing Line (CAL) required construction of a new r_m -value estimating device for different types of texture. The consequently necessary laboratory investigation provided the following results.

MEASURED RESULTS

The measuring arrangement shown in Figure 2 was used for this laboratory investigation. With this arrangement, it is possible to

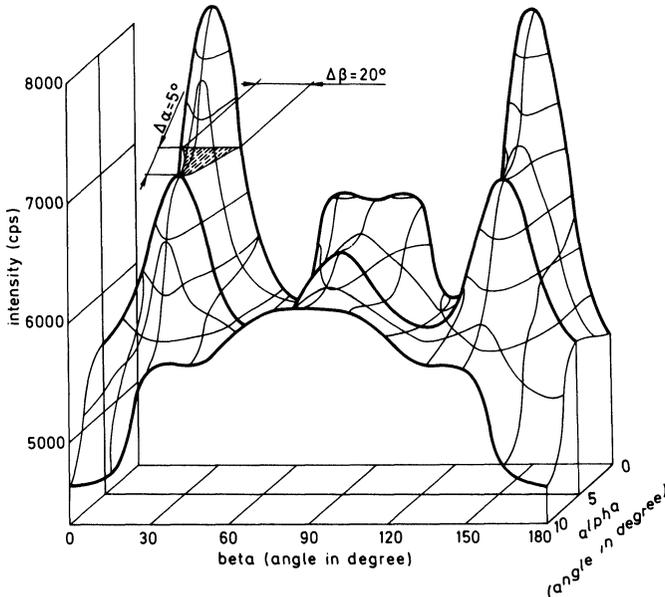


Figure 4 Intensities of (211) pole figures of annealed steel sheet for $0^\circ < \alpha < 10^\circ$, $0^\circ < \beta < 180^\circ$.

simultaneously measure several partial pole figures of different reflections or the intensities of several special points of these pole figures. It is important to know the angular resolution of the measuring apparatus for interpretation of a measured pole figure, particularly with respect to the sharpness of the texture.

It is helpful to use the angular range (half-height width) of a texture peak as a measure of the texture sharpness. The geometric data from the laboratory equipment give an angular resolution of 0.5° for the α -angle and 4° for the β -angle (Bunge, 1962).

The intensity curves for α from 0° to 10° and for β from 0° to 180° for a typical steel sheet texture are given in Figure 4. The curves are assumed symmetric with respect to $\beta = 90^\circ$. It can be seen that the half-height width of the maxima is 20° for the β -direction and 10° for the α -direction. The given angular resolution of 0.5° for α and 4° for β is therefore sufficient for the measurement of steel sheets. In order to improve the statistics for single-point measurements, it would be better to increase the angular divergence for the angle α .

(a) Steel sheets with the orientation (111) [110] as the principal texture component

Aluminium killed, batch-annealed sheets and most continuously-annealed sheets are characterized by the (111) [110] orientation. Figure 5 shows the outer parts of the (211) and (220) pole figures measured on a sample from the CAL (sample 1), using the transmission method. The maxima, particularly in the (211) pole

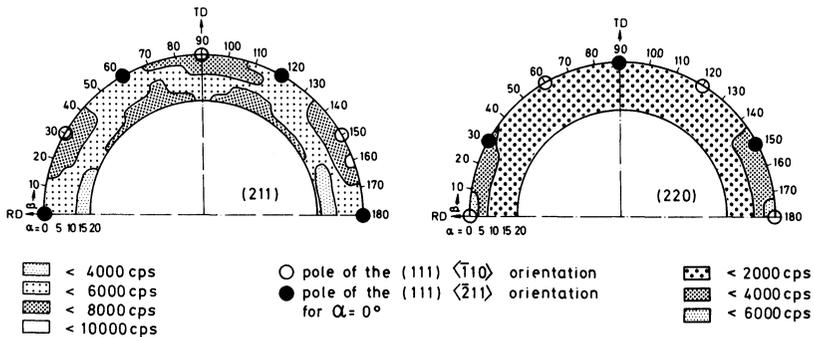


Figure 5 (211) and (220) pole figures of samples.

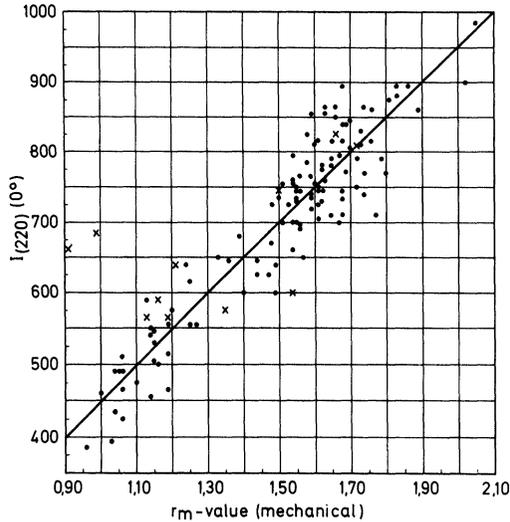


Figure 6 Correlation between X-ray intensity and the mechanically determined r_m -values. Values denoted by x do not fulfil the criterion of selection.

figure, are consistent with the (111) [110] orientation. We shall call this texture type A. Sheets with texture type A show a correlation between, the intensity of the peak at $\alpha = \beta = 0^\circ$ of the (220) pole figure and the r_m -value. This correlation is illustrated in Figure 6 for batch-annealed-sheets. Thereby specific experimental condition, such as sheet thickness, voltage and current of the X-ray tube, size of the collimator slits and others are assumed.

The intensities are plotted versus the mechanically determined r_m -values. The deviation of the measured points from the fitted curve depends on the error in measurement of the mechanical r_m -value and on the statistical error of the X-ray measurement and on deviation from the ideal texture type.

It has already been recognized that sheets with other texture types do not show correlation between the (220) peak and r_m -value. The measured points plotted as crosses in Figure 6 are from sheets with different texture types, which consequently do not fulfil the correlation condition. In the prototype device these measured points are separated by a specific selection criterion.

(b) Steel sheets with different superposition of texture components

Due to many variable production parameters in the continuous annealing procedure, the sheets so annealed can have different texture types. For these groups of sheets new correlations must be determined from the pole figures. These different texture types and thereby different correlation functions must be selected in an on-line measurement by the measuring device itself.

In the following example the main points of the r_m -value estimation of a texture with orientations other than (111) [110] are described and the selection criterion is specified.

Figures 7 and 8 show the (211) and (220) pole figures of two sheets (sample 2 and 3) with texture types other than type A.

Both (211) pole figures shows that the $\beta = 90^\circ$ peak (see Figure 5) is no longer so sharp. There is a shifting of the texture such that the (111) [110] orientation is superposed by others.

Figure 8 shows that, for this texture type, additional peaks, which are consistent with a (111) [211] orientation, appear at the positions $\alpha = 0^\circ$, $\beta = 0^\circ$ and 60° . This texture type will be referred to as texture type B.

Figure 9 provides a better overview of the intensity curves for $\alpha = 0^\circ$ and $\beta = 0^\circ$ to 180° than the (211) pole figures displayed in Figures 5, 7 and 8. It can be seen that, in comparison to texture type A, texture type B does not have such sharp maxima. In accordance with the (211) pole figure (Figure 8), the curve of sample 3 shows a superposition of the (111) [211] orientation with

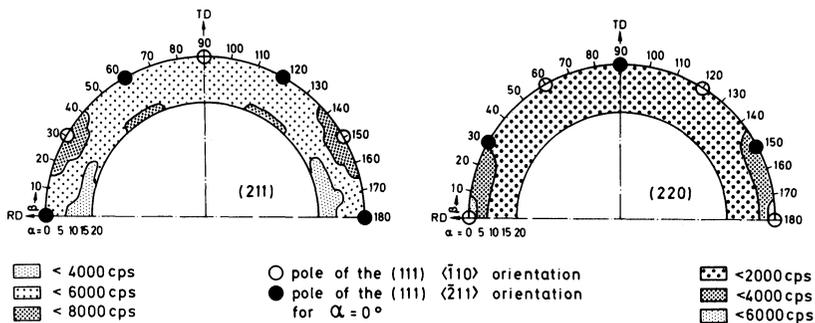


Figure 7 (211) and (220) pole figures of sample 2.

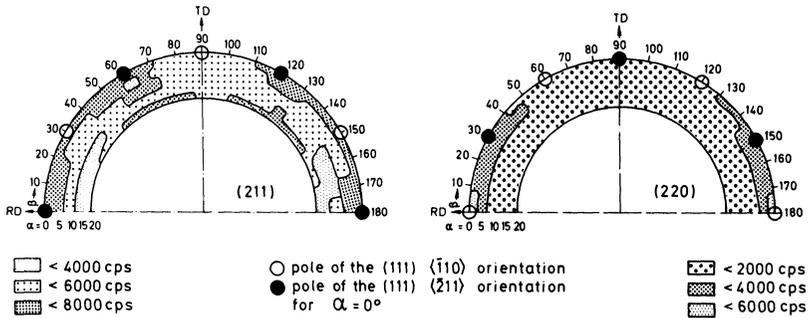


Figure 8 (211) and (220) pole figures of sample 3.

maxima for $\beta = 0^\circ$ and 60° . There is no longer a correlation between the r_m -values and the intensity of the (220) pole for $\alpha = \beta = 0^\circ$, if the sheet has texture type B.

Figure 10 shows this clearly. It illustrates the intensity curves of the samples from the (220) pole figures for types A and B. The intensity of 5500 cps corresponds to a r_m -value of 1.58 for a sheet with texture type A. The curves for texture type B demonstrate that the intensities for $\alpha = \beta = 0^\circ$ can decrease while the r_m -value

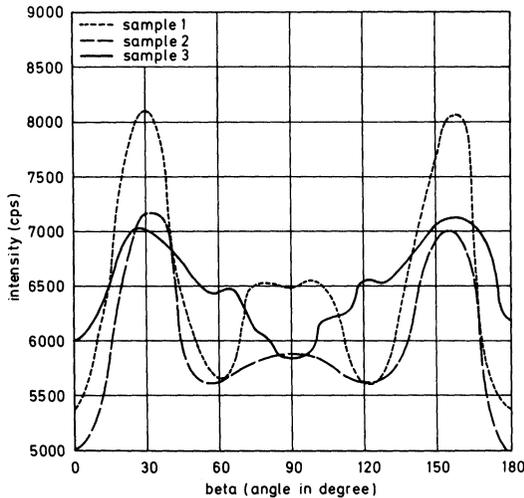


Figure 9 Intensities of (211) pole figures of three different samples of annealed steel sheets for $\alpha = 0^\circ$, $0^\circ < \beta < 180^\circ$.

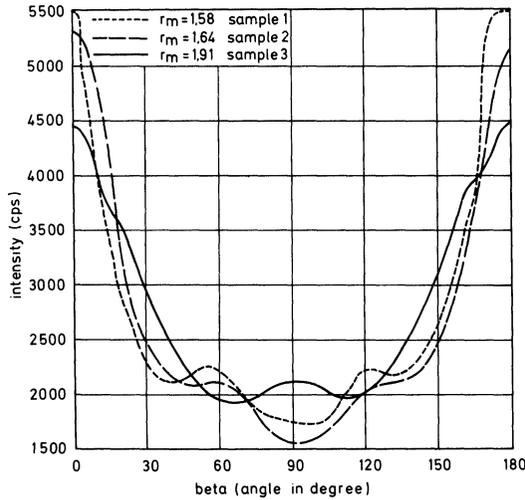


Figure 10 Intensities of (220) pole figures of three different samples of annealed steel sheets for $\alpha = 0^\circ$, $0^\circ < \beta < 180^\circ$.

increases. In particular, the intensity curve of sample 3 shows that it is possible to get high r_m values by superposition of different orientations and not only with a distinct (111) [110] orientation.

A correlation between the intensities of several points of different pole figures and the r_m -value was worked out according to this formula

$$r_m = \sum_i a_i I_i \quad (3)$$

where I_i = intensities of different peaks and a_i = coefficients.

The result is the equation

$$r_m = a_1 * I_{(220)}(30^\circ) + a_2 * I_{(211)}(0^\circ) \quad (4)$$

where $I_{(220)}(30^\circ)$ denotes $\alpha = 0^\circ$ and $\beta = 30^\circ$, $I_{(211)}(0^\circ)$ denotes $\alpha = \beta = 0^\circ$. $a_1 = 1$, $a_2 = 3.5$. I in cps for specific experimental condition.

The correlation function is shown in Figure 11. As with the first correlation function the variation of the measured points depends on the error in measurement of the mechanical r_m -value and on the statistical error of the X-ray-measurement and on deviations from

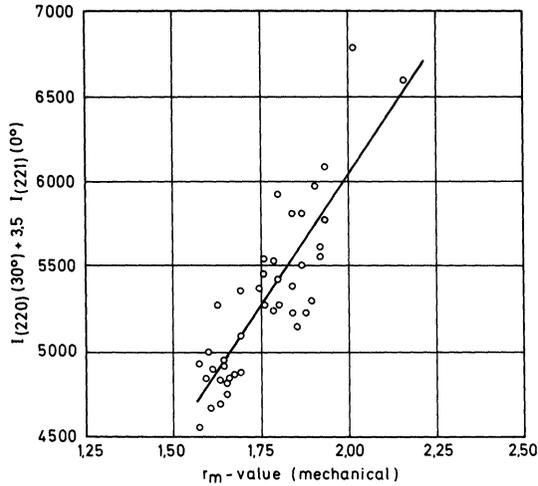


Figure 11 Correlation between measured texture intensities and mechanical Γ_m -values.

the ideal texture type. The measured points in this correlation are from samples which have been treated in a laboratory CAL-simulator (Drewes, 1986) before the new Hoesch Continuous-Annealing-Line was in operation. It was therefore possible to measure the r_m -value on-line in the starting phase of the CAL with the new device, described later. It could be shown that the results of original CAL samples lie in the variation range of Figure 11.

The intensity curves for the pole figures allow development of selection criteria for distinguishing between the texture types A and B.

The selection criteria used for the texture types described above is:

$$\frac{I_{(211)}(30^\circ)}{I_{(220)}(0^\circ)} + \frac{I_{(211)}(30^\circ)}{I_{(220)}(30^\circ)} = D \quad (5)$$

It can be shown, if D is greater than 6.6 the texture is of type A, otherwise B.

These new laboratory results are included in the new measuring device which is working in the Continuous Annealing Line at Hoesch Stahl AG.

ON-LINE MEASURING DEVICE

For the construction of the r_m -value estimation device for the CAL, it was possible to refer to six years experience gained from the prototype measuring device mentioned at the beginning of this paper. Mechanical vibrations (against which the device must be protected), high ambient temperatures and electromagnetic interference were taken into consideration.

The original construction principle was retained as shown in Figure 3. The most important components here are also the X-ray tube above the steel strip, the detection unit below the steel strip and the electrical analysis and control systems which integrate the measuring device in the production process. During the laboratory research an intrinsic-germanium-detector cooled with liquid nitrogen was used. In the prototype device HgJ_2 detectors were used. These detectors have some disadvantages (compared to the germanium detectors), but are generally useable. They were in on-line operation for several years with an agreeable performance, but these detectors are not yet manufactured in a reliable way for on-line application in a production line. Therefore, a detector system with germanium detectors and a closed-loop helium-cooled system were investigated, together with a detector supplier for the measuring device in the CAL. The new detector system can be seen installed in the measuring device in Figure 12. The two secondary collimators, through which the X-rays reach both detectors can be seen in the upper middle of the figure. The equipment for the optical adjustment is on the left-hand side. The cold head of the cooling system is flanged to the detectors. The refrigeration unit is supplied with precooled helium by the flexible copper tubes (upper right hand corner of the figure). Figure 13 shows the new device during the on-line measurement in the inspection area at the end of the CAL. The steel strip runs from left to right between the X-ray tube (above the strip) and the detector group (below the strip) of the measuring device. The strips are stabilized through the inspection area of the CAL due to the roll arrangement.

In addition to the detector system, the most important difference from the prototype device is that the new device can estimate r_m -values of different texture types and identifies these texture types from the measurement itself, using the above-mentioned selection

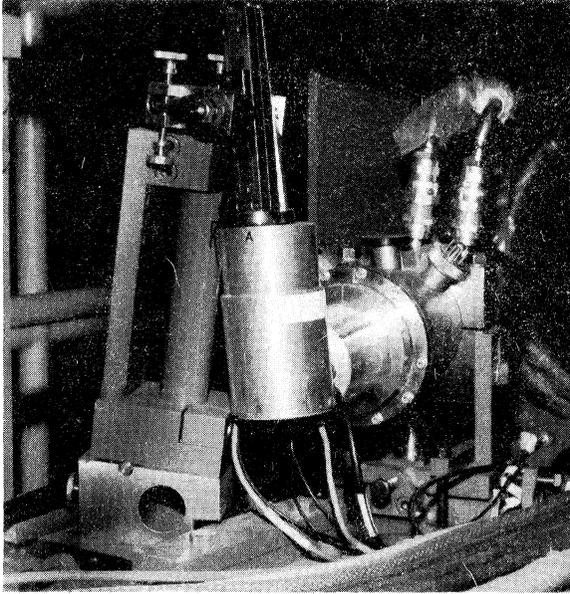


Figure 12 Closed-loop cooled germanium detector system.

criterion. This is necessary, since steel strips with different quality properties can be attached to another quality group. In such cases, the quality group in process control would not agree with the deep-drawing quality, and the measurement would lead to false results. The selection criteria, however, result in a correct r_m value estimate.

The whole measurement is controlled by a microcomputer. With permanent logical controls in the computer program interruptions are registered immediately. There is data transfer, not only to the process-control system but also to the quality-assurance system, so it is ensured that, in addition to the measurement itself, data transfer of measured results to the quality-assurance system is on-line. Estimated r_m -values are recorded over the whole strip length. The lowest and highest estimated r_m -values and the strip length belonging to these values are also shown on a monitor on the control platform. A direct response to the measured results is therefore possible.

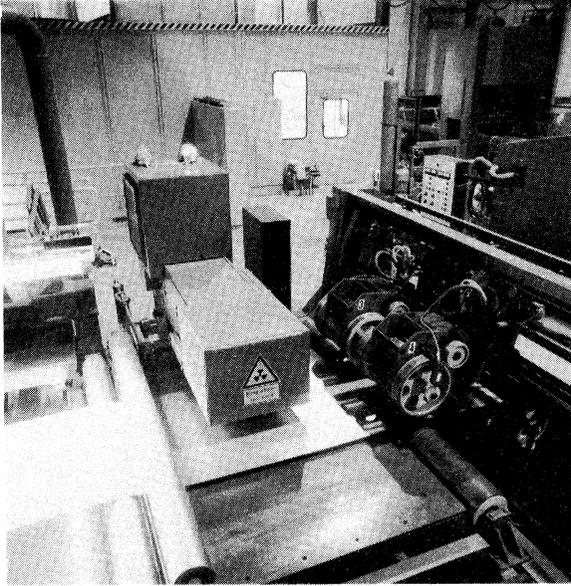


Figure 13 On-line r_m -value estimating device in the production line (CAL).

RESULTS

In the starting period, many samples with different qualities and known data were used for the basic calibration of the nondestructive X-ray method. From these data and many additional measurements, the accuracy of the r_m -data estimated by X-ray diffraction was determined to be ± 0.1 .

On-line measurements in the production line have shown that the complete system works accurately and reliably. The results obtained are plotted versus strip length and given to the quality-assurance department. These plots provide condensed information in a clear form.

Figure 14 gives a example of an estimated Lankford-value recording. The value is plotted versus the strip length. The mean estimated value of r_m over 3 km strip length is 2.09. In this example, the variation σ is ± 0.03 . The maximum value is 2.20 (at strip-length point 973 m) and the minimum value is 2.00 (at the strip-length

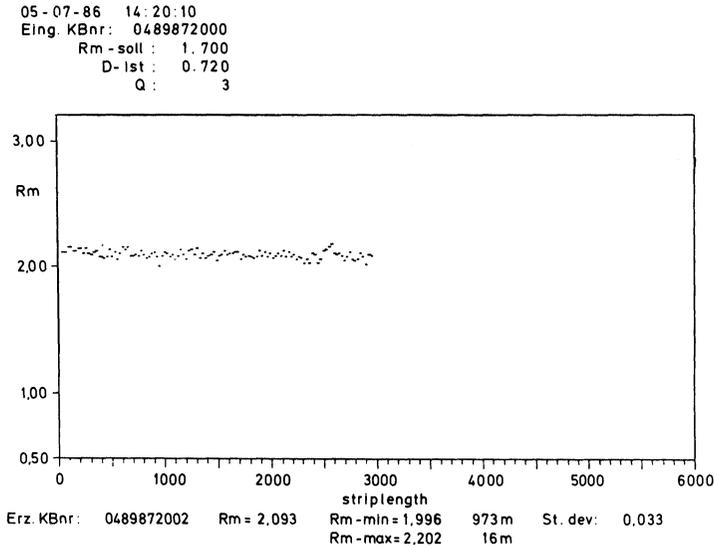


Figure 14 Example of a measured result.

point 16 m). When interpreting the variation σ it has to be taken into consideration that the single measuring points are integral values over nearly 10 sec., i.e. over a strip-length of about 100 meters. But within the range of 100 meters strip-length the r -value of continuously cast material does not change noticeably.

The observation of cold-rolled steel strips shows in general that the standard deviation, σ is between 0.03 and 0.08. These data characterize steel strips with excellent homogeneity and consistent deep-drawing properties.

SUMMARY

Various technological data of cold rolled and annealed steel strips are influenced by the texture of the material. An X-ray technique for texture determination with an on-line measuring system was therefore developed in a research program. This X-ray transmission technique uses the 60 keV-continuous spectrum of a tungsten tube and energy-dispersive detectors. It permits simultaneous detection

of several X-ray reflection. In earlier work it was shown that intensity peaks of the texture are correlated to the r_m -value of cold-rolled and annealed steel strips. Because of this correlation, a prototype device for estimating r_m values of batch-annealed steel strip was constructed.

The new Hoesch-Continuous-Annealing-Line produces steel qualities with different texture types. Different correlation functions and an additional selection criterion therefore proved necessary in the design of a new on-line r_m -value estimating device. Extensive laboratory work was required to find these correlations and selection criterion. From these results, and using experience with the prototype device, a new instrument was constructed for the inspection area at the end of the CAL of Hoesch Stahl AG in Dortmund.

The measured results of this on-line instrument are helpful and important for quality control and quality assurance. Much information for improvement of the cold-rolled and annealed material can furthermore be obtained.

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