Online laser measurement technology for rolled products

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Geometric quantities of rolled products can be measured online in the manufacturing process using laser measurement technology. Examples of laser inspection systems, which are in routine use in rolling mills, their performance, and the operational experience will be discussed. One to three-dimensional geometric quantities are measured, such as the thickness of cold rolled sheets, the cross-sectional profile of rails and flatness defects of heavy plates. The features of the laser method will be compared to those of conventional measuring methods. Precision and measurement capability achieved under production conditions will be described.

Keywords: Laser measurement, Flatness, Thickness, Profile, Rolled products

Introduction

The inspection of geometrical properties of rolled products in a production line is a critical requirement for an efficient process control and quality assurance. Flatness, straightness, profile, thickness and width are typical test parameters which ideally must be measured in the flow of production. In recent years, a number of innovative measurement systems, which are based on laser measurement methods, were introduced into industrial practice. Compared to conventional procedures, laser measurement technology introduces a new potential of applications for online inspection of rolled products with regard to flexibility, measurement speed, measurement accuracy and degree of automation. The progress already achieved and the speed of development of this technology give rise to the expectation, that medium term laser measurement technology will revolutionise the online inspection of geometrical properties of rolled products.

In this article, laser measurement systems for the inspection of flatness of rolled sheet metal, thickness measurement of cold rolled sheet metals and profile measurement of train tracks are presented as examples and experiences gained during operations is reported on.

Flatness measurement of heavy plates

The requirements for the flatness of heavy plates are defined according to DIN EN 10 029.[1] The rolling mill must document to the customer its compliance of the standard. In the case of the example introduced here, the flatness of the rolled sheets is measured immediately following the cold levelling machine. The data recorded online serve as proof for the compliance with the tolerances and form the basis for an automation of the levelling process.

So far, the flatness was determined manually by a ruler measurement. The disadvantage of this measurement method is the restricted reproducibility, the high worker influence and the manual documentation. The traceability of the utilised means of measurement was not assured.

Flatness measurement using optical methods can be carried out by using white light fringe projection and the laser light section method. Both approaches are based on the illumination of the sheet metal surface with lines of light and the observation of the illumination patterns by cameras; these cameras in turn are positioned in a direction of observation which does not coincide with the direction of illumination. By means of triangulation the topography of the sheet metal surface is determined from the measured position and shape of the mapped lines of light on the camera detector.[2]

Table 1 gives a comparison of the properties of flatness measurement systems with white light fringe projection and laser light section methods. For the white light fringe projection method, thermal light sources with rated powers of several kilowatts are used to illuminate the sheet metals from a great height. However, due to the wide optical spectrum of such radiation sources, the radiance, which specifies the radiated power in relation to the irradiated surface element, the wavelength interval and the solid angle, is smaller by many orders of magnitude, compared to laser light sources. Owing to the high spectral radiance of the laser radiation, the influence of stray light on the measurements can be suppressed almost entirely. The suppression of stray light during white light illumination is not possible.

The high lifetime of the laser light sources minimises maintenance expenditures, whereas the lamps of the white light sources must be replaced every three to five months.

Owing to the high spectral radiance of the laser radiation, the exposure time per measurement can be

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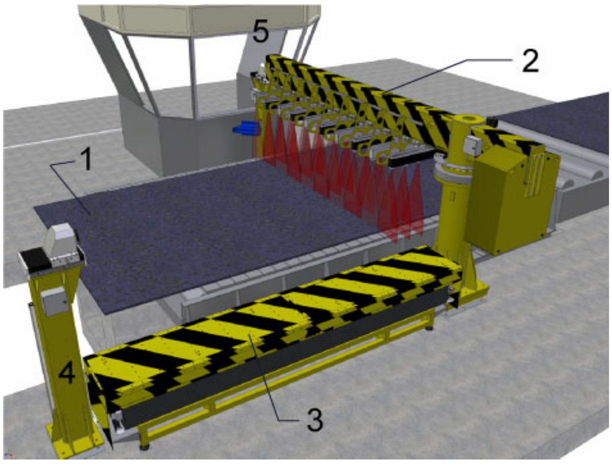


1 View of flatness measuring system with laser sensors (1: heavy plate; 2: rotatable measuring bridge; 3: adjustment station; 4: fixing column; 5: control stand)

2 Flatness measurement with lasers downstream of leveller in heavy plate rolling mill, measuring field with three laser lines (source: ThyssenKrupp Steel)

reduced by a factor of four and higher, compared to white light projectors. This is a critical precondition for the detailed measurement of moving sheet metal and the 'freezing' of the movement of the sheet metal.

Owing to the large scale illumination for white light fringe projection, the distortions of the projected fringe patterns must be corrected for computationally; further, large reference sheet metals are required for an on site calibration. These steps are not necessary for laser based measurements as the laser sensors are calibrated when they leave the factory. Several laser light section sensors of the flatness measurement machine are automatically adjusted on site by a flatness standard which is integrated into the machine. In this way, the traceability and measuring tool capability of the laser based flatness measurement machine is assured and tested regularly.

Figure 1 shows the concept of a laser based flatness measurement facility for a heavy plate rolling mill. The rolled sheets enter the measurement facility from the left side. Ten laser light section sensors are mounted next to one another on a girder, projecting three laser lines on the surface of the object to be measured. These lines run across the sheet metal, are oriented in parallel to one another and are offset in the direction of sheet metal motion. All sensors measure synchronously, so that the current transitory motion of the sheet metal is 'frozen'. By simultaneously measuring the sheet metal surface at the three laser lines, it is possible to discriminate between the sheet metal's own motion and flatness deviations. The topography of the sheet metal is determined from a large number of individual measurements of the traversing sheet metal. For a typical roller table speed the spatial resolution across the conveyor direction is smaller than 1 mm and is about 5 mm in longitudinal direction. Owing to the high spatial resolution perpendicular to the sheet propagation direction, the measurement system is capable to measure the width of the sheet metal (format) at the same time.

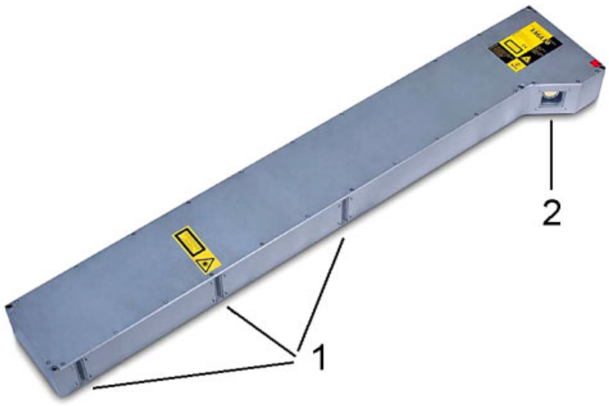
For alignment and monitoring, the measurement bridge located above the roller table is rotated by 90° out of the roller table and brought to a lateral base position. In this position, a long time stable flatness measurement standard is located underneath the measuring bridge inside a protective casing. The top side of the protective casing is opened automatically for the alignment and the laser beams are directed onto the measurement standard. The alignment and monitoring procedure takes only a few minutes. The results are recorded by the systems's computer, so that a complete documentation of the measuring tool capability is possible. Owing to the rotatability of the measuring bridge, the accessibility of the roller table for maintenance purposes and for crane operations is not restricted.

Figure 2 shows a photography of the facility at a heavy plate rolling mill. The sensors are easily accessible and can be replaced quickly during a service call. A replacement of the sensors (inclusive of facility alignment) requires less than 15 min. To a wide extent, the facility is designed to be maintenance free. For a three shift working environment, typical window cleaning intervals are four weeks.

Figure 3 presents a view of one of the laser light section sensors which are installed in the flatness measurement system. Three exit windows for the laser

Table 1 Comparison of properties of flatness measurement systems based on white light fringe projection and laser light section

Parameters	White light fringe projection	Laser light section
Power of light source, W	Up to 5000	<1
Spectral radiance, W cm^{-2} nm^{-1} sr^{-1}	$<10^{-1}$	$>10^4$
Lifetime of light source, h	2500	>50 000
Traceability of measuring tool	Not possible	Every laser light section sensor is calibrated with documented traceability
Measuring tool capability according to MSA 2·0 (Ref. 3)	Not satisfied	Satisfied
Exposure time, ms	> 20	<5
Repeatability for a ruler with a length of 1 m, μm	100 (stationary sheet metal)	<30 (moving sheet metal)



3 Laser light section sensor with three measuring planes (1: laser exit windows; 2: observation window)

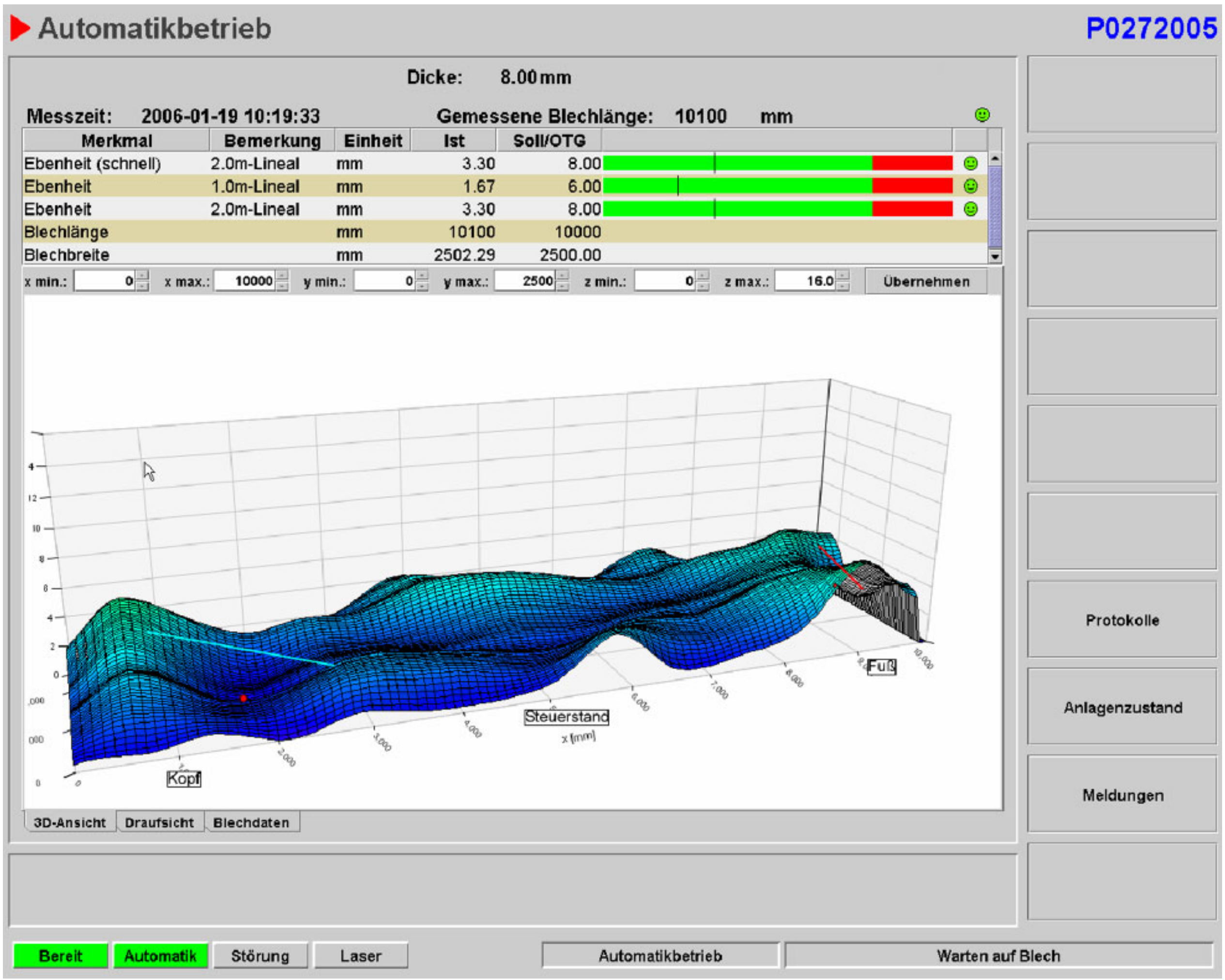
light sections and an observation window for the receiving optics can be identified on the front side.

Figure 4 gives a three-dimensional view of the topography of a measured heavy plate as it is displayed at the control stand. The graphic display is constructed already as the sheet metal is passing through the laser light sections. The flatness is determined according to the ruler method. In the given example, a one metre long ruler and a two metre long ruler are drawn in those locations where the largest flatness deviations have occurred (these locations are marked as red points). The numerical flatness value for both rulers is shown on the display immediately following the passing of the sheet metal. In addition, the length and width of the sheet metal are determined.

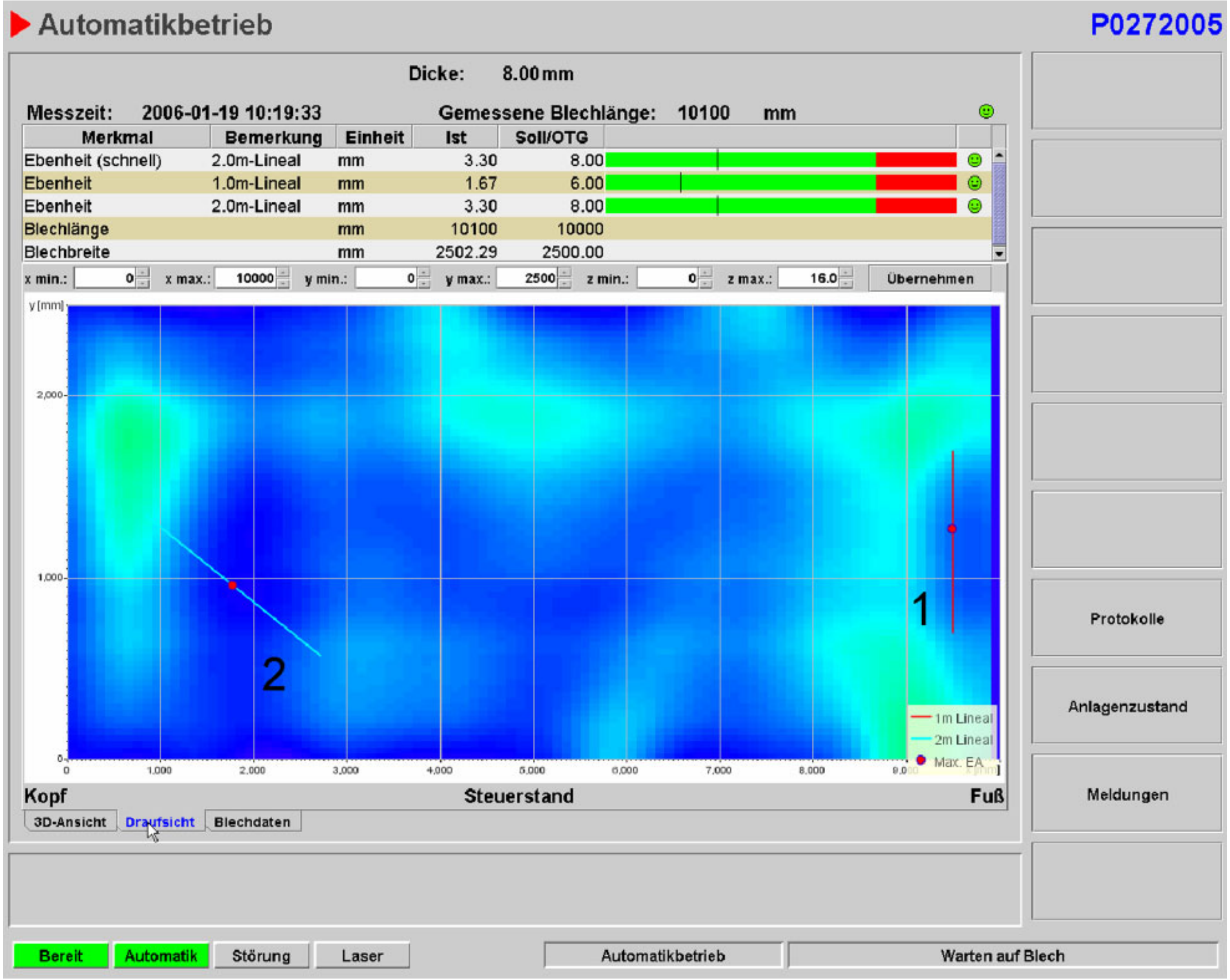
Figure 5 shows a top view of the sheet metal topography of the very same data set. The operator can choose between these two display modes. The position of the flatness defects as a result of the ruler measurement carried out conforming to standards is displayed (*see* markings in Fig. 5).

In order to determine the repeatability, a produced sheet metal having a width of 2100 mm was measured ten consecutive times when passing the laser light sections in one direction at a speed of 1 m s^{-1}. The measurement system determined the flatness deviations for the 1 and 2 m ruler and the width of the sheet. The achieved repeatability for the flatness deviation amounts to 0·03 and 0·07 mm for the two rulers and 0·13 mm for the width.

The laser measurement complied with the requirements of the measuring tool capability according to procedure 1 (repeatability and correct measurement of a component of a known traceable topography) and procedure 3 (measurement system related scattering of actual work pieces in a production environment) of MSA.[3] For $c_g=0{\cdot}2T/(4s)$, where T is the production tolerance and s is the empirical standard deviation, yields $c_g>1{\cdot}33$. Twenty five sheet metals of various



4 Three-dimensional view of topography of measured heavy plate as displayed at control stand



5 Top view of same data as Fig. 4, colour coded presentation of topography of plate (results of assessment of flatness defect conforming to standards using rulers are shown; 1: ruler length 1 m; 2: ruler length 2 m)

thicknesses and dimensions were each measured twice for procedure 3. The measurement system related scattering was 0·2 mm for the 2 m ruler and 0·1 mm for the 1 m ruler.

The laser based flatness measurement facility runs a three shift operation. It provides data for the control of upstream levelling processes and assures that the quality demands according to DIN EN 10029 are observed. The manual inspection is no longer necessary.

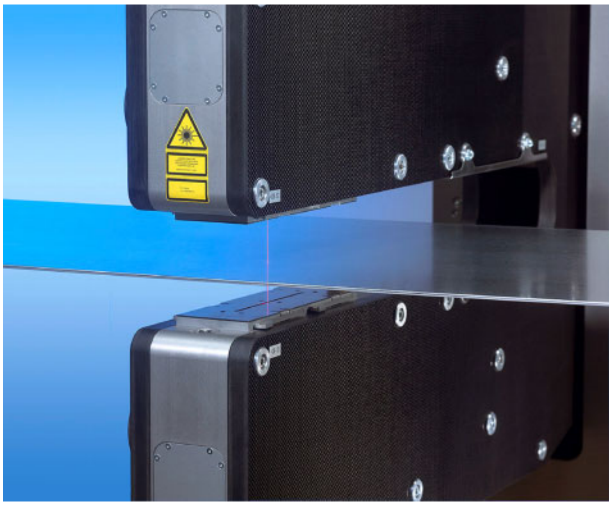
Thickness measurements

Laser based thickness measurement devices permit non-contact and highly accurate thickness measurements during the rolling and downstream production processes. This allows to record and process online control and quality data without adverse influence on the production process.

Laser triangulation sensors are used for laser thickness measurement devices. These sensors generate a measurement spot on the surface of the inspected object and they detect the laser light scattered by the sheet metal surface, in order to determine the distance between sensor and sheet metal. Depending on the measurement distance and the measurement range, measurement accuracies of better than 0·02% of the measurement range can be reached. The laser diodes installed in the laser sensors can achieve lifetimes of up to 100 000 operating hours.

The thickness measurement of rolled sheet metals and strips can take place during the rolling process as well as when the metal is sectioned later. The measurement results provide valuable feedback for the control of the rolling process and they enable a quality assurance of the generated product at the same time.

The measured values for the acquisition of thickness are recorded synchronously on the top and bottom side of the sheet metal, as shown in Fig. 6. The exact distance of the top and bottom sensors with respect to one another is determined before the measurement by an exact calibration of the measurement device on an integrated adjustment station. The sensors are mounted in a temperature stable C-frame. For measurements, this C-frame is automatically moved into the transport range of the objects to be measured. During the feeding and discharge of coils the C-frame moves into a protective enclosure where it is protected from damages (*see* Fig. 7). Table 2 shows typical parameters of a laser based thickness measurement system which were determined during a measurement tool capability inspection using moving gauge blocks. The accuracy of this measuring tool is about 1 μm for a thickness measurement range of 10 mm. The laser based thickness measurement system achieves precisions in the order of 200 to 300 nm.



6 Thickness measurement with laser radiation at cold rolled sheet, thickness measuring range 20 mm, depth of C-frame 530 mm, size of C-frame 100 mm

The non-contact measurement tool assures that there will be no damages such as scratches even for sensitive surfaces. An additional advantage compared to the contact measurement is that even strong variations in material thickness can be processed and inspected without problems. Contrary to radiometric procedures, the thickness measurement with a laser is independent of the alloy composition of the material under inspection.

Advantages of a strip thickness measurement with lasers include the fast response times, the independence from ambient lighting conditions and the quick adaptation to different surface qualities of the objects to be measured. An exact allocation of the measurement results to the measuring position on the sheet metal or strip is possible because of the option of triggering the individual measurements synchronously to the covered distance.

Using measurement frequencies of up to 30 kHz, strips at speeds of up to 2000 m min^{-1} can be measured. Under actual production conditions in a cold rolling mill, a measurement accuracy of less than 2 μm can be achieved with a laser based thickness measurement device. The measurement accuracy of the measuring devices is documented by a proof of measurement tool capability according to established standards.[3]

The laser based thickness measurement device has a Profibus interface, enabling a simple integration into an existing plant control of the roll stand or the sectioning facility. Control of the measuring device is possible via Profibus as well as via graphical user interface. The current strip thickness is displayed on the graphical user interface continuously. The recorded thickness measurements can further be made available to the control system of the rolling mill via analogue output. The thickness measurement devices are characterised by low maintenance efforts. Table 3 shows a comparison of the properties of a laser based thickness measurement with the conventional methods: tactile probe, radiological and ultrasound measurement.

Table 2 Results of 50 repetitive measurements at gauges under production conditions with laser thickness measuring system having measuring range of 10 mm (*s*: empirical standard deviation)

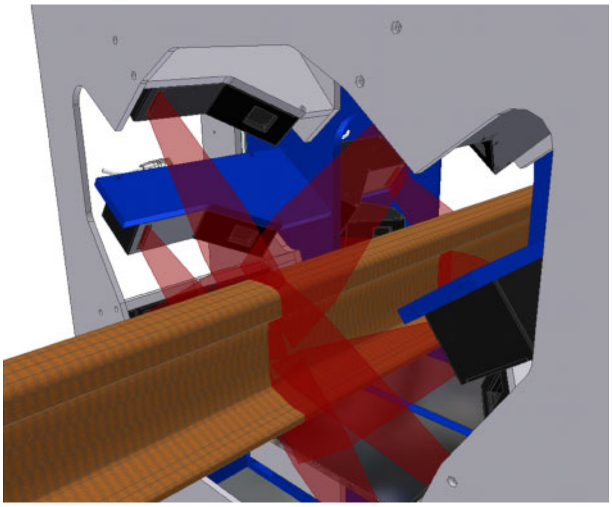
Parameter	Thickness		
Nominal dimensions, mm	2	4	8
Certified actual dimensions, mm	2·0001	4·0000	8·0000
Mean value, mm	2·0011	3·9997	8·0012
s, μm	0·2	0·3	0·3
Accuracy of the mean, μm	1·0	0·3	1·2

7 Laser thickness measurement system with thickness measurement range of 130 mm, depth of C-frame 1000 mm, size of C-frame 400 mm

Radiological methods for the measurement of the thickness of moving striplike materials, such as sheet metals, are based on the measurement of X-ray or gamma radiation transmission. These methods however require the knowledge of the absorption coefficient, which depends on the chemical composition of the test sample and on the specific material density. The advantages of a laser based thickness measurement are: high measurement frequency, high precision, no knowledge of material composition required, minimum maintenance efforts and straightforward safety measures (no radioactive material and no high voltage required). Laser based thickness measurement will replace established technologies such as radiological methods in certain domains in the future. The available thickness measurement ranges extend from 10 mm up to 300 mm.

Profile measurement

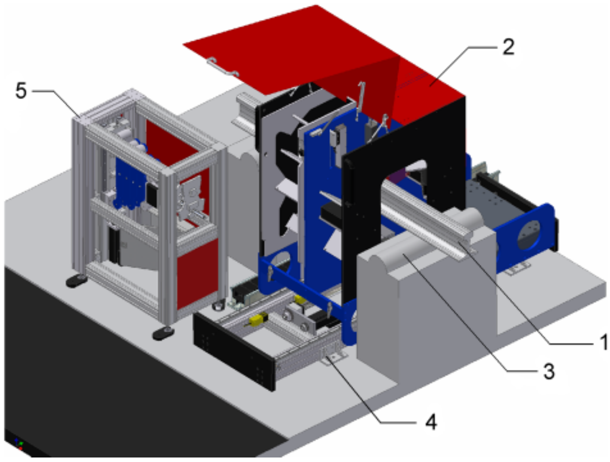
Rail sections are typically measured with templates to find out if they satisfy the customer's demands. A number of characteristic and quality relevant properties must be recorded, such as rail height, rail foot, rail web, rail head, rail shoulder etc. The geometrical testing parameters are fixed in German, European and international standards.[4–7] The permissible profile deviations are in the range of 0·1 mm. Using conventional mechanical templates, which are carried out as reference templates and ±templates, only selected segments of the rail can be inspected by hand. Proceeding in this way, it is not possible to collect information concerning the dimensional compliance along the entire length of the rail. The results are not sufficiently reliable, due to the randomness during the selection of the segment to be inspected, as well as due to inaccuracies during the actual template test. In addition, template inspections are cost intensive processes because of the efforts for the maintenance of all necessary templates for many different rail profiles and their regular certification.



8 Three-dimensional CAD model of measuring unit to measure cross-sectional profile of rails (measuring object shown here is high speed rail UIC 60)

Therefore, it is the goal to automatically record the profile date for the final inspection over the entire length of the rails, and to do so while the rail is passing on the roller table. These measured data can be used for the improvement of the production process as well as for documentation purposes. The otherwise necessary additional time and cost efforts for a separate data recording is eliminated by this approach.

In the following a measuring system for the automatic rail profile measurement with lasers is presented which is in operation at the Rail Inspection Centre at TSTG Schienen Technik GmbH in Duisburg. At the Rail Inspection Centre, the rails are transported on a roller table at a speed of 1·5 m s^{-1}. The available length for access by a profile measurement device alongside the direction of transport amounts to 1 m. A number of rail profiles, e.g. for railroads, tramways or cranes must be inspected. During the automatic inspection, the measurement data must be evaluated in such a way that the measurement procedure of the template inspection is copied, in order to assure the correspondence of the results and their conformity with the standards.



9 General view of 3D CAD model of profile measurement systems (1: rail; 2: measuring unit with laser light section sensors; 3: roller table; 4: translation stage, to move measuring unit out of roller table; 5: calibration station)

The measuring unit of the profile measurement system encompasses 10 laser light section sensors, arranged in a circle around the rail. Figure 8 presents a detailed view of the measuring unit's 3D CAD model. During the actual measurement, the rail moves through this measuring unit. The light section sensors generate a laser line over the entire circumference of the rail profile. The vertical positions of the light section sensors which acquire the rail head can automatically be set for different types of rail profiles.

The temperature of the rail head and the rail flange is measured with two pyrometers as the rail passes through the measuring unit. These data are required as input parameters for the algorithms to determine the various rail profile dimensions. The rail temperature can be between 0 and 80° Celsius. Based on the temperature data, the profile's dimensions are calculated for a reference temperature of 20° Celsius.

Figure 9 shows the overall view of the profile measurement system. The measuring unit can be moved out of the roller table. In the default position on the side

Table 3 Comparison of features of laser thickness measurement with conventional methods*

	Laser measurement	Tactile probe	Radiological measurement	Ultrasound measurement
Process				
Non-contact	+	–	+	o
Fast response to thickness variations	+	–	o	o
Small measurement spot size	+	+	–	–
Low maintenance efforts	+	–	–	o
Rough operating conditions	+	+	+	+
High availability	+	–	+	o
Environment friendly technology	+	+	–	+
Object to be measured				
Contact sensitive surfaces	+	–	+	+
Insensitivity to density variations	+	+	–	–
Insensitivity to changes of material composition	+	+	–	–
Hot surfaces	+	–	+	–
Porous surfaces	+	–	–	–

a b

10 ***a*** **profile measurement at rails running through measuring unit and** ***b*** **view of profile measurement system in rail inspection centre (source: TSTG Schienen Technik)**

of the roller table, offline measurements can be performed on rail segments without blocking the roller table. This position is further used for calibration. For this purpose, a calibration station places different calibration bodies in the measuring unit.

Figure 10 shows photographs of the installed system at the Rail Inspection Centre.

The laser light section sensors measure at a frequency of 200 Hz and they acquire a measurement range of 130 × 105 mm. The average working distance between sensor and measuring object is 272 mm. The laser sensors automatically adapt to the varying scattering properties of the surface of the measuring object. The measurement principle is static triangulation of measurement lines according to DIN 32 877.[2] The temporal repeatability amounts to 65 μm and the spatial repeatability is 130 μm. The sensor signals are transmitted digitally to the control unit of the measurement system.

Specially manufactured rail segments of known dimensions can be inspected in the default position of the profile measurement system. These master parts are used for calibration, to ascertain the measuring uncertainty of the system. The system's alignment takes place automatically. For this purpose, special bodies of known dimensions are moved from the calibration station into the measurement unit.

The profile measurement system introduced here makes a significant contribution to the improvement of the rail production processes because it provides real time data about the rail profile which in turn can be utilised for process control. For most inspection parameters, profile data are available at an accuracy of 50 μm for every rail segment with a length of 10 cm. The measurement system can be easily expanded for the inspection of new rail profiles. The measurement results are visualised on the control stand and the data are automatically exchanged with the operator's quality management system. Over a period of two years, an availability of 99·8% is achieved.

Summary

Over the past years, it was possible to demonstrate successfully that laser based measurement facilities can be used to acquire reliable data about the geometry of rolled products. In comparison to conventional methods, online laser measurement technology can at least be considered as equal, and in some cases it achieves significantly better results.

Laser based measurement systems are easier to integrate into production processes. The low maintenance efforts and the high degree of availability assure an economic utilisation.

The dynamic development of new laser beam sources and electro-optic detectors give rise to the expectation of further improvements of the laser sensor performance characteristics and the next generation of inspection systems based on these sensors in the future.

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