ние влияния смещения объясняется тем, что при смещении изделия по оси *OY* сигнал возникает в одной паре измерительных обмоток, а при смещении по оси *OX* – в другой, причем в обоих случаях в противофазе. После суммирования продетектированных напряжений, сигналы от смещения в разных каналах взаимно компенсируются.

Предлагаемый метод дефектоскопии на основе использования магнитного поля с разночастотными пространственными компонентами был реализован в дефектоскопах прутков и труб ВДП-401, ЭД-207, ВДП-403. Ниже приводятся технические характеристики дефектоскопа ВДП-403, испытания которого проводились в объединении РОЛТОМ (г. Томск):

- диаметр контролируемых труб и прутков от 12 до 55 мм;
- минимальные обнаруживаемые дефекты в виде продольной прорези длиной 40 мм, шириной 0,1 мм и глубиной 2,5 % от внешнего диаметра;
- максимальное поперечное смещение контролируемого изделия – 2 мм;
- максимальная неравномерность чувствительности к дефектам – 60 %;
- длина неконтролируемых концов изделия от 40 до 60 мм;
- скорость контроля до 3 м /сек.

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NDT AIDED PRODUCTION[1]

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Motivated by the growing cost-push and parallel at the same time increasing quality requirements a steady need to progressive non-destructive testing (ndt) is observed in combination with production automation from industry. Integrated process and condition monitoring by ndt is an accepted procedure to early diagnosis of irregular process conditions followed by feed back control and optimization. It was forecast in different studies of the market, that this process integrated ndt will record two-digit rates of increase within the next years. The paper basically describes the requirements of industry and reports to the progress of ndt in this field of application. The emphasis is mainly in discussing case studies from metal manufacturing and machinery building, i.e. automotive and supplying industries.

1. Introduction

Mankind started to develop automation in order to avoid hazardous or unpleasant manual operations and to increase productivity. Wherever possible, humans have invented devices and technologies for replacing manual labour by utilizing animals and natural energies. Weave looms exist since the Neolithic, and windmills have been known by the Sumerian (3500 bC). The dream,

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[1] This is an improved version of a paper, which was already presented at »ICAMT 2008 for Young Engineers«, Feb, 6-8, 2008, Chennai, India

that «every instrument could accomplish its own work» and «chief workmen would not want servants, nor masters slaves» was already dreamed by Aristotle, 2400 years ago [1].

On the other side, automation always served for cost saving. Manual labour is replaced with less-expensive machines. Therefore automation has to be reflected as a social issue since the early days of industrialization. Today automation of the workforce is quite advanced and is encroaching on ever more skilled jobs. Not outsourcing in emerging market countries but automation must be blamed for the decline in manufacturing employment in Western countries in the recent years.

If the old focus on using automation was simply to increase productivity and reduce costs, currently the purpose of automation has shifted to broader issues. Automation is now often applied primarily to increase quality in the manufacturing process. For example, by replacing the manually mounting of automobile pistons with an automated process, the error rate could be reduced from 1 % to 0.00001 %. Even if automation is viewed as a way to minimize human error in a system, increasing the degree and levels of automation also increases the consequences of error. With increasing levels of automation the consequences of an error rapidly approach the catastrophic. For that reason, a high degree of process automation requires a high degree of (automated) monitoring and control of process and product quality.

Currently, the manufacturing industry is facing significant new challenges. Due to globalization, competition is intensifying. Development times for new products have been drastically reduced. For example, the lead time for vehicle development has gone from something like five to seven years in the past, to 18 to 36 months. Simultaneously, the diversity of products is continuously increasing. In steel industry over fifty percent of current product range has evolved just over the past ten years. The ability to offer a broad range of products with specific, custom-tailored technological properties requires an increasing number of production processes of high complexity (e. g. high-strength steel production, friction-stir and ultrasonic welding, adhesive bonding, etc.). Nevertheless manufacturers are getting less vertically integrated and increasingly rely on external suppliers even in case of highly sophisticated parts and components.

Competition is forcing manufacturers to contain costs and to improve quality. Reduced development time and increased diversity of products and processes also means that there is less time to ensure that the manufacturing processes is capable to produce appropriate product quality, before high-volume production starts. Global out-sourcing requires, that suppliers provide confidence in their product quality by performing the necessary measurements and inspections on their own authority. Therefore, the new challenges of automated manufacturing correspond with new opportunities for ndt aided production.

2. Benefits from ndt-aided production

Besides final inspection of products, ndt can be used during manufacturing in terms of monitoring and even control of process quality, as described in fig. 1. Quality control with ndt combines the advantages of both classical methods of process control, which are statistical process control (SPC) on the one hand and monitoring of process variables on the other hand.

The intent of SPC is to monitor product quality and maintain processes to fixed targets. It aims to get and keep processes under control. But – due to its probabilistic nature – SPC can keep a process under control only to the extent that it can indicate when a process has probably gone out of control. Therefore process readjustments or repairs are always delayed. In principle, a continuous preservation of process quality is not possible with SPC. Another approach is the real-time model-based quality control by monitoring of process measurables (force, pressure, temperature, etc.). A process disturbance can be identified and based on a known control model the process can be readjusted or adapted immediately. But the real-time quality feedback to this disturbance is lacking. An additional quality model is necessary, in order to determine to what extend quality is affected.

Automated ndt is capable of performing all SPC functions in real-time or at least several times faster than standard SPC. As a monitoring tool, it allows to mark and discard all nonconforming parts. Only good material goes «out the back door». Consequently, the process limits can be exhausted, allowing to increase productivity. On the other side, process disturbances affecting the product quality can be detected and located directly. The process can be controlled using its quality characteristics as control variables directly (see fig. 2).

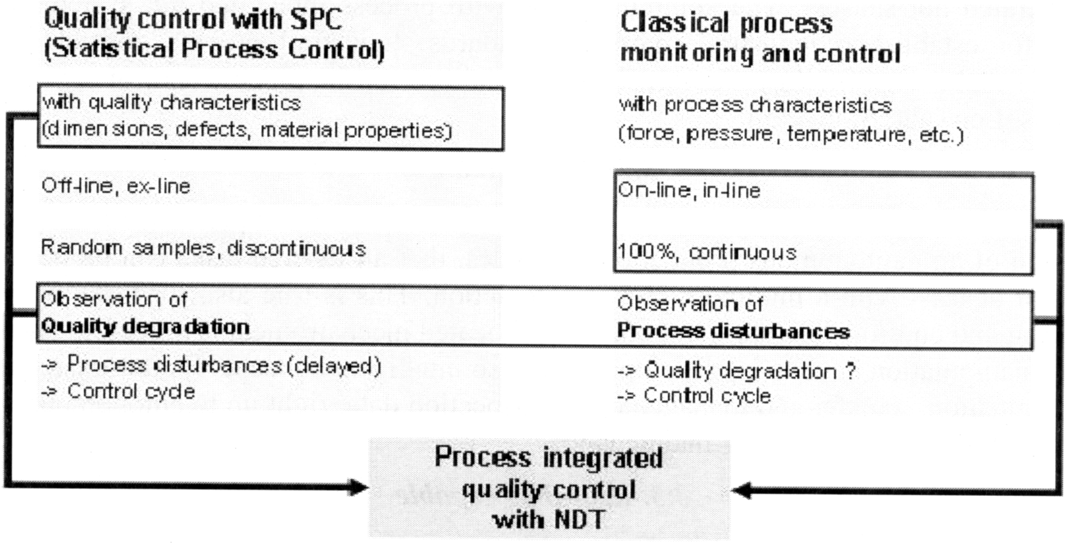

Fig. 1. Quality control with ndt

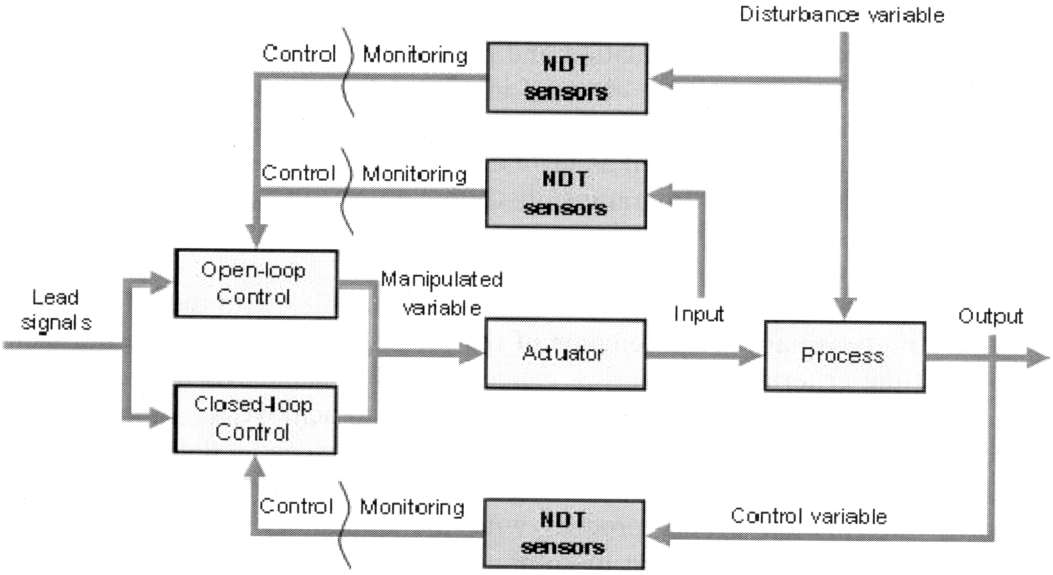

Fig. 2. Process monitoring, open and closed loop control with ndt

3. Requirements for process integrated ndt

Process-integrated ndt has to meet a variety of requirements. Costumers ask for ndt systems, which are integrable, automatable, real-time capable, reliable, profitable and flexible.

3.1. Integrable, mountable

Miniaturized, rugged, low-maintenance ndt sensors at moderate costs are required. An example is described in section 4.2 [2]. As a further example, GMR (giant magnetoresistance) gradiometers allow to design very compact stray flux sensors with integrated premagnetization device [3]. The general trend, that process sensors evolve from simple analogous measuring recorders to so-called «smart sensors» or «intelligent sensors» with integrated signal processing or even with integrated actuator will be transferred to ndt sensors too [4]. Today thin-film technology can be used to integrate temperature or force sensors as a «sensitive skin» on the surface of a machine or a tool [5]. It is expected, that the combination of thin-film technology with other physical measurement effects permits the development of new tool-integrated ndt sensors. The communication with process integrated ndt systems has to account for established industrial interface standards. Industrial process control systems commonly make use of field-buses which are specialized for the process control environment (Profi-bus, LonTalk, SDS, etc.).

3.2. Automatable

For most manufacturing processes the degree of automation is permanently increasing. The vision of an «autonomous production» includes, that all desired tasks can be performed without or at least with a minimum human interaction. This is true also for tasks of quality monitoring and control. Therefore not only sophisticated mechatronical layouts for sensor and / or part manipulation have to be developed, but also intelligent concepts for automated acquisition, evaluation, transfer and management of inspection data, right up to autonomous procedures for self-calibration and self-maintenance.

3.3. Real-time capable

For a variety of ndt techniques (e. g. micro-magnetic methods, nuclear magnetic resonance – NMR) the inspection speed is limited by physical constraints. With these methods, only relatively slow processes can be monitored in real-time. Often not only a slow data acquisition rate but also the subsequent data processing is limiting the testing rate. Especially in case of fast image reconstruction, evaluation and presentation, fast transfer and computation of the raw measuring data is required. «Multi-Link G-bit Ethernet», «Routed Fiber-channel Link», or «Multi-channel LVDS» are non-standard solutions for fast data transfer. Sophisticated data processing algorithms as well as fast devices for parallel computing, like Graphics Processing Units (GPU) and Field Programmable Gate Arrays (FPGA) [6].

3.4. Reliable and comprehensive

The integrated ndt technique has to provide its measurables with the reliability, which is predetermined by the quality requirements of the process. That means, the ndt technique itself has to meet the criteria of measuring gauge capability standards in order to monitor and control the quality capability of the process. In order to achieve a required process capability index cp, the ndt measurement uncertainty must not exceed a defined percentage of the process tolerance range. In some cases a single ndt method is not sufficient to acquire all relevant quality information of the process with the obligatory measuring uncertainty. Therefore, the trend can be recognized to combine several ndt methods with partly divers and partly redundant information.

3.5. Profitable and flexible

Nondestructive testing systems are not mass-produced products. The small number of marketable systems and the specifics of individual test requirements lead to high engineering expenditures at low sales volumes. Especially process integrated ndt systems often are «unique items», leading to high costs for purchase and maintenance. But these costs are faced by a variety of savings, which are overlooked often. These include not only the saved nonconformity costs (costs due to further processing, eliminating the nonconforming material, callback, product liability, etc.) but also the saved costs for manual tests (destructive and nondestructive) and the possibility to increase productivity and yield.

On the other side, ways have to be found to reduce the engineering expenditures for highly sophisticated ndt systems. Flexible, cost-effective solutions for ndt hardware and software could be developed based on modular structured platforms, which support the further development of a preferably large field of individual ndt techniques [7].

4. Case studies

4.1. Quality control in flat steel production and processing

The mechanical-technological properties characterize the fitness for use of a material under various conditions. Besides thickness, width, surface finish and flatness, these properties are of central importance to the quality of hot and cold rolled steel products. These material properties are adjusted during several production steps. Therefore there is the need to monitor and control these quality parameters continuously. State of the art to determine yield and tensile strength is the selection of standardized specimens at the end of the process and destructive testing according to the definition in the inspection laboratory using standard tensile testing machines. Hardness measurements are performed by using standardized indentation techniques according to Brinell or Vickers. This destructive testing is obviously not the adequate solution for online monitoring and control. The traditionally process orientated steel industry has a strong interest to replace these time-consuming and expensive destructive tests by more appropriate methods.

Micro-magnetic testing, i. e. nd material characterization with electromagnetic methods is generally suited for this purpose. In a ferromagnetic steel mechanical and magnetic properties of are influenced by the same microstructural parameters (lattice defects). Therefore on can observe correlations between both, which can be used to predict values of mechanical properties from measured values of magnetic properties [8]. A technically mature application of micro-magnetic ndt is the in-line monitoring of mechanical parameters in strip steel during production [9, 10, 11].

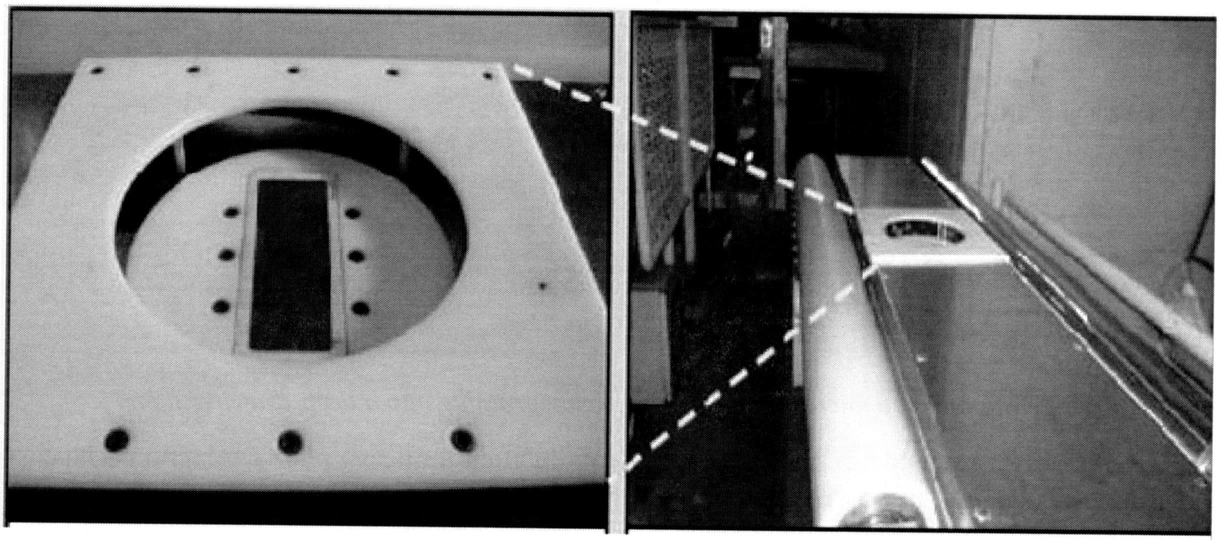

Fig. 3. Sensor holder and table carrier of the micro-magnetic in-line sheet inspection system

Based on a micro-magnetic sensor, a online test system was constructed, which allows continuous contact-less determination of tensile strength (Rm) and yield point (Rp0.2), but also other mechanical-technological characteristics in the running strip (up to 300 m/min).

Another possibility is to attach the micro-magnetic sensor to a robotic arm, as it is shown in fig. 4. This allows the maximum possible flexibility concerning the sensor application to the strip surface.

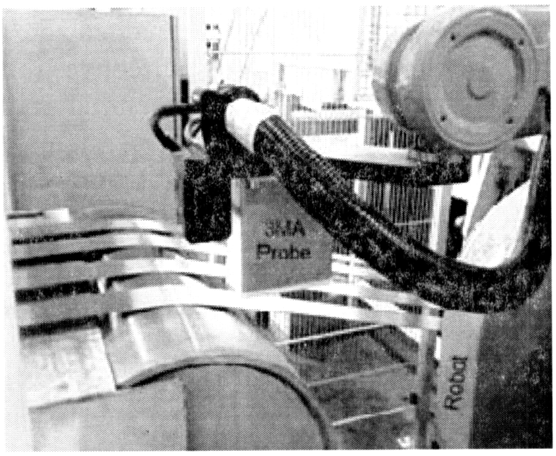

Fig. 4. Sensor attached to a robotic arm for gradual inspection of several parallel running strips

Micro-magnetic testing can be used not only for monitoring and control during steel sheet production also during sheet processing, i.e. deep-drawing. A miniaturized sensor was developed (see fig. 5), which can be integrated into the stamp of a deep-drawing machine. With this tool the material behaviour during the deep-drawing process can be observed. It allows the modification of mechanical properties as well as the arising stresses and strains in the material to be monitored during the process. Based on this method the manipulated variables of the process (stamp force, path, etc.) can be optimized for different conditions (sheet thickness, steel grade, etc.) and furthermore, it allows to prevent process malfunctions (rip-off, spring-back of the sheet) by a feed-back control based on the detected strain hardening in the material.

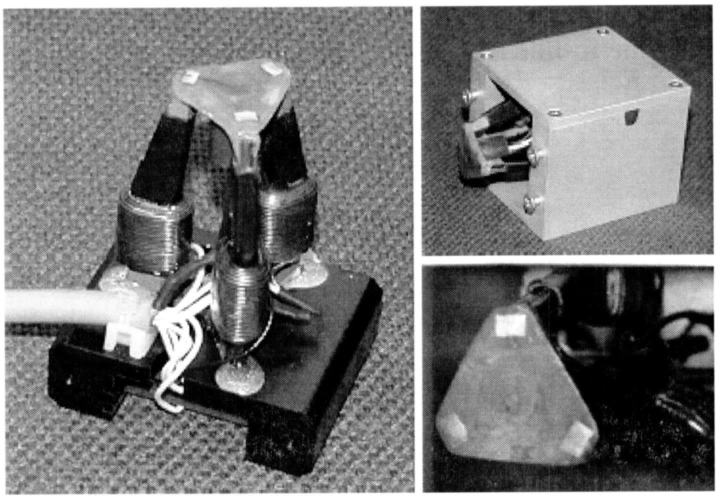

Fig. 5. Miniaturized micro-magnetic sensor, integratable into a deep-drawing stamp

Mechanical-technological properties are also important for heavy plate production. The customer asks for geometrical and mechanical properties, which are uniform across product length and width, especially for high-value grades. For a plate of several meters length the boarders are usually subjected to other cooling conditions than the rest. Indeed, especially the plate ends are known to cool faster, generating an undesired increase in Rm and Rp0.2. State-of-the-art is to determine this so-called «cold ends» based on empirical values and cut them off. The destructive testing of the cold ends follows this cutting. Therefore the cutting itself is not a controlled process and if to much or to less material was cut-off will be visible only with hindsight. This lack of knowledge results in enormous costs due to reworking, pseudo-scrap and delayed shipment release. The European steel producers put their annual costs at 11 million Euros.

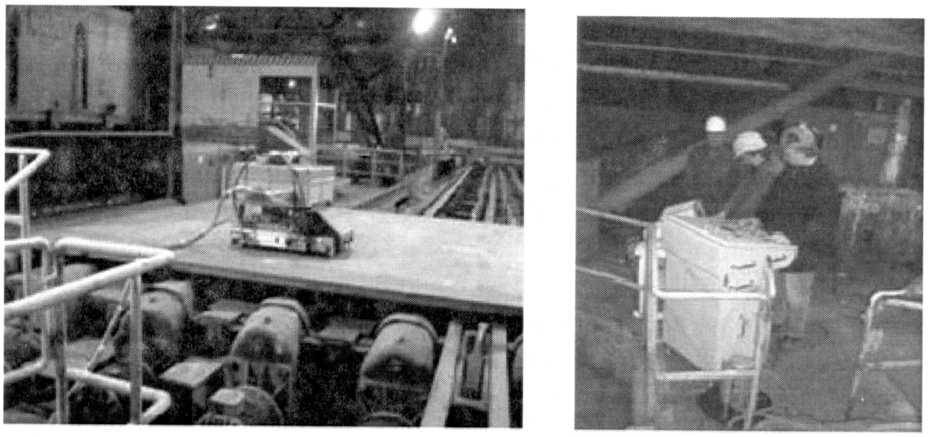

Fig. 6. Inspection trolley (left picture) and remote control desk (right picture)

For that reason a ndt solution to locate the cold ends of the plate was developed. Knowing exactly the contour of the zone with unacceptable material allows an open loop control for the cutting process. It showed up, that for determination of mechanical properties in highly texturized materials, it is beneficial to combine micro-magnetic methods with ultrasonic time-of-flight measurements in order to get more accurate and reproducible results. The ndt equipment was integrated into a remote controlled trolley, allowing the sensor to be half-automatically moved along the surface of the plate. The left picture in fig. 6 shows the trolley in operation on a heavy plate on the roller conveyor and the right picture shows the control desk for remote control.

4.2. Microwave monitoring of gas assisted injection moulding

The plastics industry has an increasing need for online monitoring of injection moulding processes. Gas-assisted processes (gas injection technique GIT) are applied to save plastics material and to assure the constancy of shape of the produced part. The aim of the process monitoring and surveillance is to assure the proper sequence of process steps and the correct position of the gas bubble inside the cavity. Existing monitoring methods like measurement of temperature or pressure inside the cavity provide only indirect information or are often not quick and specific enough with regard to gas-assisted processes.

Fraunhofer IZFP and ICT have built up a miniaturized GIT monitoring system based on the 94 GHz radar sensor (see fig. 7). In contrast to conventional microwave sensors, this module is capable to measure not only amplitude but phase and frequency, too. The entire size of this module is small enough to be mounted into thr gas-assisted injection moulder.

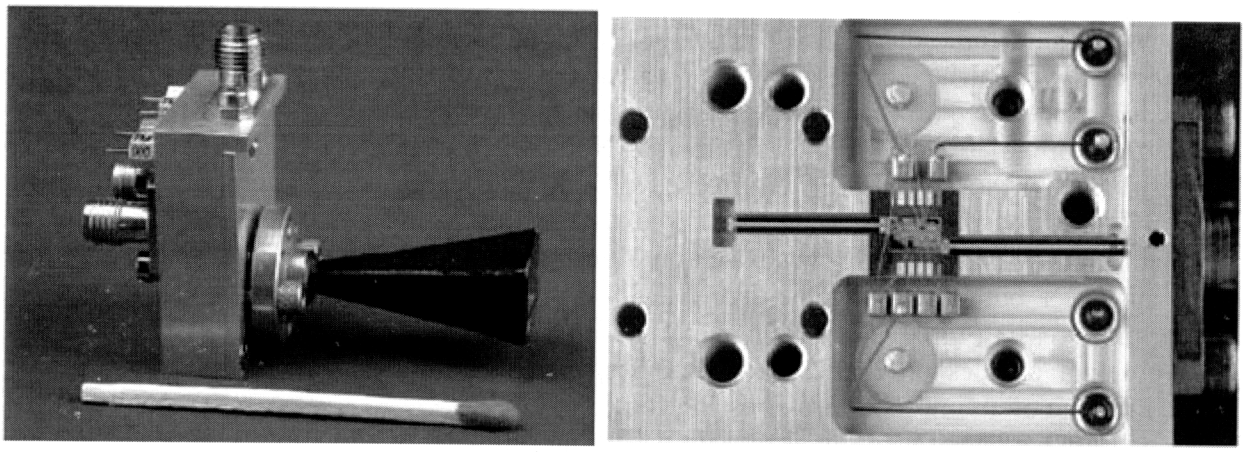

Fig. 7. Radar module with flanged horn antenna (left); Inside view of the module (right)

A high temperature resistant plastics window transparent to microwaves is used as an dielectric antenna and separates the cavity from the waveguide. The left picture in fig. 8 gives the scheme of the measurement arrangement. When the cavity is filled with liquid plastics and when a gas bubble passes over the position of the window the wave propagation inside the cavity is modified resulting in a measurable change of the reflection and scattering behaviour inside the cavity.

The right picture in fig. 8 presents a result gained during an injection moulding test with gas assistance. The important process steps like the passage of the plastics melt and of the gas bubble over the position of the millimetre wave window could be found by abrupt changes of the measuring quantities amplitude, phase and frequency of the IF-signal. They could be identified unequivocally by comparison with a video movie taken during the test through an optical window.

The three measuring quantities can be combined to improve the validity of the method. Theoretical calculations using ANSYS FE code confirmed the findings and can be used in future to optimize the measuring parameters like frequency or type of the millimetre wave window. Thus, the process sequence can be controlled in a quick and direct way.

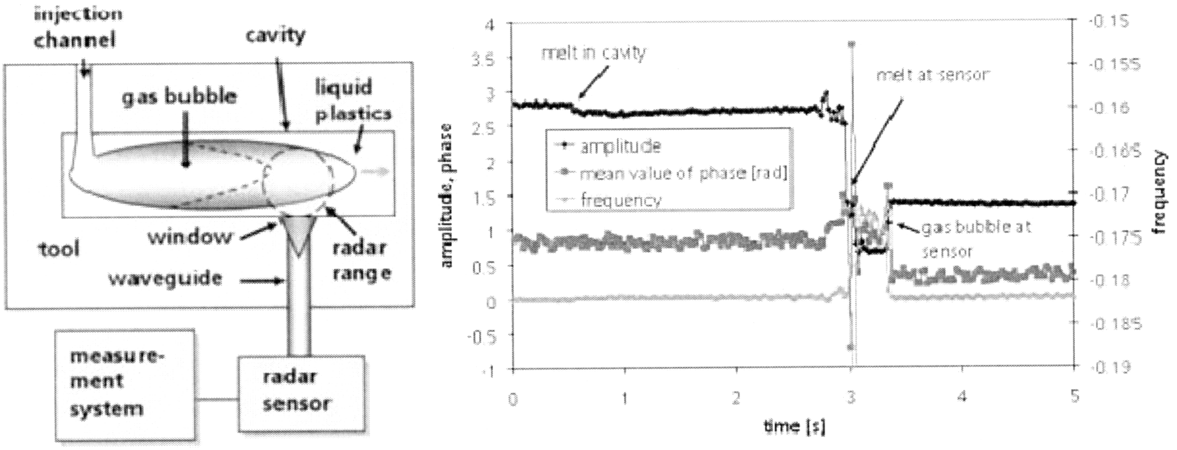

Fig. 8. Schema of GIT monitoring with radar sensor (left);
Measuring quantities vs. time for a typical GIT process (right)

4.3. Tool-integrated ultrasonic systems for control of cold joining processes

In case of screw joints the pre-stressing force is significant for the joint strength and therefore this force can be used in order to control the screwing process. Screw break or joint release after applied load are extreme consequences of an improper adjusted pre-stressing force. In order to control the screwing process, usually the torque moment or the angle of rotation are measured during the process. Both control variables could be incorrect in predicting the pre-stressing force due to the a priori unknown influence of friction loss between screw head and support surface or between screw thread and mating thread.

It is well known, that the screw elongation caused by pre-stressing can be determined by ultrasonic time-of-flight (tof) measurements. Not only the increase of macroscopic screw length but also the decrease of ultrasonic velocity due to the acoustic-elastic effect result in a rising tof, when pre-stressing force is extended (see fig. 9, left picture). Commercially available screwing control devices based on ultrasound measure the tof in the screw only before and after but not during the screw drilling process. Afterwards the screw elongation or the pre-stressing force is determined by means of stored calibration tables. Therefore these conventional devices only allow the final inspection of the screw joint and if necessary the correcting of an improper pre-stressing force.

Otherwise, measuring the ultrasonic tof during screwing would allow a closed loop control of the process. For this purpose the ultrasonic sensor and part of the electronics have to be integrated within the power screwdriver (see fig. 9, right picture). Furthermore the screw itself has to be applied with a ultrasonic coupling / reflection coating on its head / shank. This results in increased piece costs for the screws, impairing the market acceptance of the method. To overcome this drawback, the screwdriver can be equipped with a special coupling sheet in order to avoid a special pre-treatment of the screws.

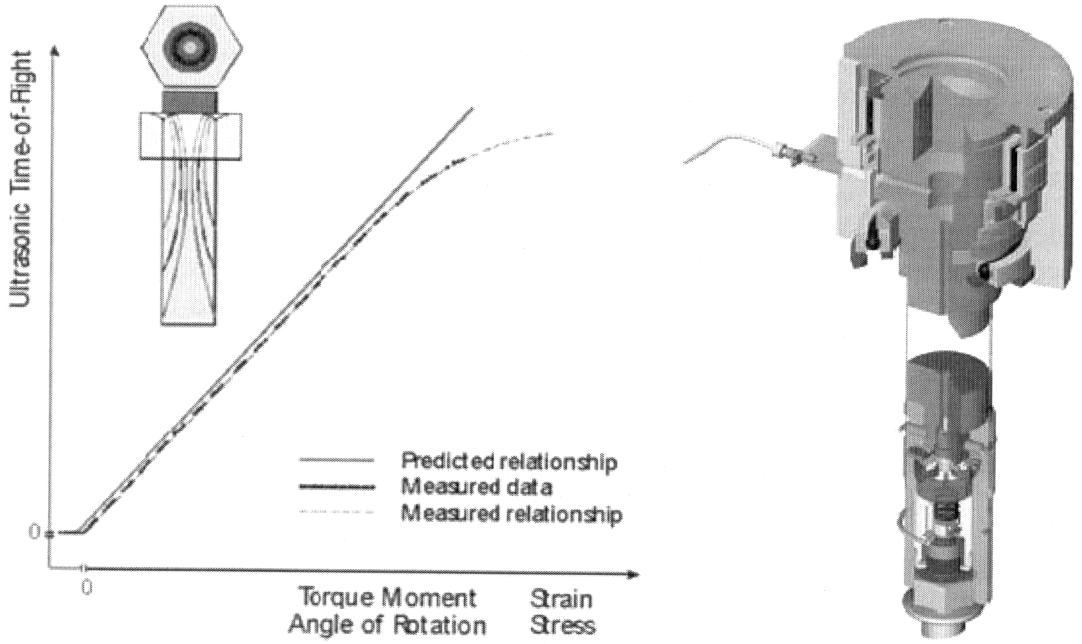

Fig. 9. Ultrasonic time-of-flight through the screw length as a function of elongation (*left*); *Ultrasonic sensor integrated into the screwnut* (*right*)

Clinching, or press joining, is a high-speed mechanical fastening technique for point joining of sheet metal. It is a fast and simple single-step technique requiring no consumables or pre-drilled holes. Clinching can be used on coated and painted materials, and is suitable for joining dissimilar materials. During clinching, the sheets are squeezed between a punch and a die. Due to the high local pressure, the material start to yield, whereby material is expelled sideways forming an interlocking button (see fig. 10, left picture). It is this interlocking button that holds the sheets together.

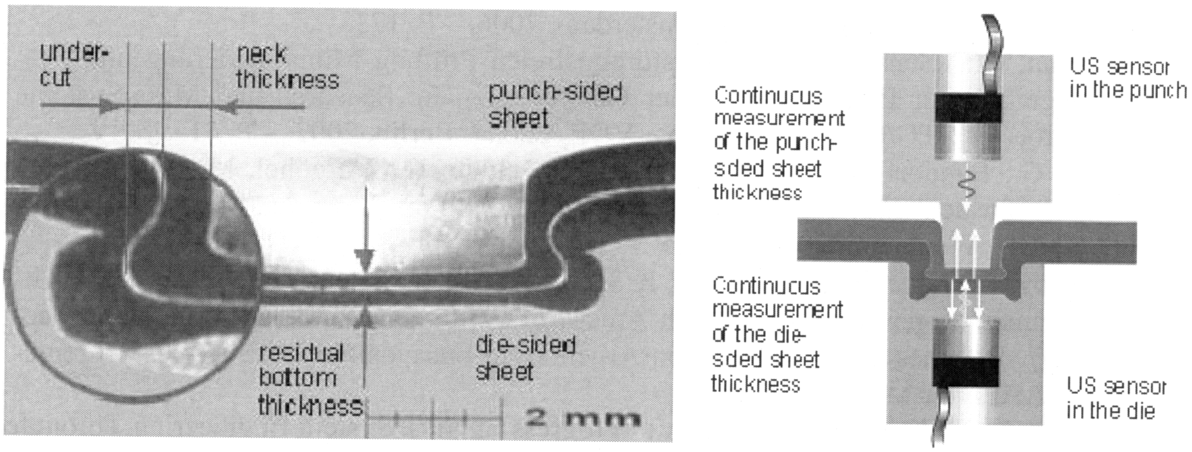

Fig. 10. Interlocking button of a clinch point (*left*); *Ultrasonic sensors integrated into punch and die* (*right*)

Currently, the clinching process is usually controlled by force-travel monitoring. The force-travel curve is controlled in order to follow a predefined target curve. But this method is generally insensitive, because local variations in undercut, neck or residual bottom thickness, which can considerably affect the joint strength are hardly detectable in the force-travel curve.

A new approach is to continuously measure the residual thickness of the punch-sided and the die-sided sheet with tool-integrated ultrasonic sensors (see fig. 10, right picture). Based on these measuring data the residual bottom thickness and with it, the thickness of the undercut can be determined during the process. Determining these quality characteristics in-situ allows a reliable control of the clinching process.

5. Conclusions

The case studies have shown, that ndt aided production provides a significant contribution in order to improve product quality, reduce scatter in properties, minimise scrap and improve process economy. Therefore it is not amazing, that the traditional tasks of ndt – preventive maintenance and off-line quality control – are more and more extended towards process integrated monitoring of quality characteristics and open / closed loop process control. Modern ndt techniques used in manufacturing industry have to follow the still strengthening trend to ever higher degrees of automation. In future ndt will be an essential component of a more or less autonomously running production, assuring product and process quality with a minimum of man-machine interaction. As consequence ndt techniques have to evolve from simple measuring machines to intelligent control systems. Today, the technologies to enhance the automation dregree and the «intelligence» of ndt techniques are available. Advanced miniaturized sensors with integrated signal evaluation techniques, fast electronics and algorithms for real-time data processing along with comprehensive information on the processing conditions and the properties and characteristics of the materials being processed will provide new opportunities for efficient ndt-based real-time process monitoring and control in near future.

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РЕГИСТРАТОР ЭЛЕКТРОМАГНИТНЫХ И АКУСТИЧЕСКИХ СИГНАЛОВ ДЛЯ КОНТРОЛЯ ПРОЧНОСТИ И РАЗРУШЕНИЯ МАТЕРИАЛОВ И МАССИВОВ ГОРНЫХ ПОРОД

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Эффект механоэлектрических преобразований в диэлектрических материалах известен достаточно давно, некоторые из аспектов его объяснения и использования обсуждаются, например, в [1–4]. При механоэлектрических преобразованиях появление электромагнитного отклика из твердотельных диэлектрических сред, в том числе и горных пород, обусловлено в большой степени наличием в них двойных электрических слоев и воздействием на эти слои акустических сигналов. Образование двойных электрических слоев происходит по разным механизмам на границах контактирующих различных материалов, минеральных зерен, включений, прожилков, минерализованных жидкостей и ионизованных газов, на берегах микротрещин и пустот, а также на границах других макро и микро неоднородностей. Воздействующие на эти слои акустические импульсы могут возникать при нагружении материалов и горных пород с усилием, превышающим предел их прочности, прорастанием трещин, при котором часть энергии высвобождается в виде акустических колебаний. Детерминированное акустическое возбуждение при контроле прочности и подготовке разрушения твердых тел может быть создано искусственно, например, с помощью пьезоакустических излучателей или ударом шарика. Акустические колебания приводят в действие механизм, при котором происходят изменения дипольного момента двойных электрических слоев и, как следствие, эмиссия электромагнитных сигналов. Таким образом, параметры электромагнитного отклика или характеристики электромагнитной эмиссии (ЭМЭ) твердотельной среды увязываются с характером ее деформирования, приводящего к движению зарядов двойного электрического слоя. Использование такой связи позволяет контролировать прочность и этапы подготовки стадий разрушения твердотельных материалов и массивов горных пород. Для автономной регистрации электромагнитной и акустической эмиссий (АЭ) в условиях шахт и повышенных электромагнитных помех необходима специальная аппаратура.

В Проблемной научно-исследовательской лаборатории электроники, диэлектриков и полупроводников Томского политехнического университета для этих целей разработан, изготовлен и испытан в лабораторных и шахтных условиях регистратор ЭМЭ и АЭ. Блок-схема регистратора приведена на рис. 1.