THE ROLE OF PROCESS CONTROL AND SENSORING IN CONTINUOUS CASTING ACCORDING TO THE VALCRA RFCS PROJECT

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The constant request of new steel grades with improved properties and higher quality demands on current and future steel production increases the demand for new measurement techniques, enhanced data processing techniques and numerical modelling for industrial plants to optimise thermal process control:

- Steel melt temperature measurements in-line in the mould,
- Enhanced data processing based on Big Data technologies to really exploit various and heterogeneous existing and new data from ladles down to quality supervision in real-time,
- Numerical modelling coupled with real industrial casting data to understand disadvantageous casting conditions and derive countermeasures,
- Continuous observation of the mould powder surface and derivation of its influence on melt temperature as well as lubrication and with it on surface quality,

The analysis of European funded research concerning the occurrence of crack formation in continuous casting in the dissemination project VALCRA proved that measuring techniques and new control system tools play a strategic role: in fact, all the countermeasures that can be identified to optimise the process assume a suitable, reliable and integrated system to acquire useful data and exploit them specifically. The main output is the optimisation of casting conditions, powder consumption and steel quality.

This described topic is related to the evolution of measuring instrumentation and control system tools and how they acted in increasing the performance of the continuous casting process in terms of safety, energy and raw material savings and reduction of defect occurrence on the final product.

KEYWORDS: CONTINUOUS CASTING – MEASURING SYSTEMS – PROCESS CONTROL - ADVANCED SENSORING – ROAD MAP

INTRODUCTION:

Continuous Casting (CC) of steel has been a major development of the steel industry during the last 50 years. CC has increased the competitiveness of the steel industry due to both, the higher productivity ratios of this route, and the lower production costs. As a consequence, the ratio of steel produced by the CC route has continuously increased along this period time. Additionally, another important factor of the CC route is the reduction of the environmental footprint when compared to the ingot casting processes.

On the other hand, the major disadvantage compared to the ingot-casting route is the complex solidification process and the frequent development of cracks inside and on the surface of the CC semis. Due to this problem of the CC route, many European funded projects have been devoted to study the causes of the semis cracking, and to alleviate this problem. It could be thought that after so many years of research, the quality problems could already be solved, however, the updated situation is that although the quality has clearly improved, the situation is still far from being completely solved. There are several reasons for this outcome, among others, the followings are relevant:

1. The complexity of steel grades which are produced by CC is increasing year by year: microalloyed steels grades, partly with high sulphur contents to increase machinability; boron steel grades, high manganese steels.
2. The demands for higher productivity have raised the casting speeds of the CC machines along with associated cracking problems.
3. Many of the defects are linked to in-mould solidification. The studies have shown that a good contact between the solid shell and the copper mould is of a paramount importance in order to avoid defects. To achieve this, parabolic taper moulds have been designed. However, each steel grade and each casting speed would require an optimum taper, which is impossible from an industrial practice.
4. Customer requirements for better surface quality and better internal product quality have increased along years.
5. Improved methods and tools have been developed which detect also small defects in as cast semis and in rolled products.

All the above reasons have increased the interest of the steel producers in crack development during CC processes.

In the project VALCRA all the collected European funded projects were analysed in order to evaluate the influence of the research on the improvement of continuous casting process.

The present document is concentrating on the role of process control and sensoring in the European continuous casting technology panorama.

The process control & sensoring topic is related to the evolution of measuring instrumentation and control system tools and how they acted in increasing the performance of continuous casting processes in terms of safety, energy and raw material savings through reduction of the defect occurrence on the final product.

The analysis of European funded research concerning the occurrence of crack formation in the continuous casting process proved that measuring techniques and the development of control system tools play a strategic role: in fact, all the countermeasures that can be identified to optimise the process assume a suitable and reliable system to acquire useful data. The main output is the optimisation of casting conditions, powder consumption and steel quality.

Measuring systems

The innovative instrumentations that directly measure the casting parameters and other process variables that are related to surface and internal quality of the final product are described in numerous sources. The most studied sensor systems are related to Fibre-Optical-Temperature-Sensors (FOTS). The sensors with this technology found many applications and have frequently been applied during various RFCS projects in various applications. In [EU-7.] (*MASTERBILLET*), two FOT sensor equipments tracked the thermal field at top of the mould and the mould steel level and powder layer thickness. In that project (*MASTERBILLET*) also a system for a mould powder sensor based on resonance of electromagnetic waves in a confined space on the mould (RF sensor) was developed. Successful plant trials highlighted the effects of manual powder feeding and meniscus level oscillation on the mould wall temperature. Continuous online information on gap lubrication and rim formation was achievable for the first time in long product casting. This system was further developed to identify irregular casting conditions with particular reference to mould powder feeding, slag rim formation and irregularities in initial solidification.

In the project *FOMTM* [EU-8.] forty temperature measurement positions were spread onto four faces of each mould. Two moulds were equipped and about 340 heats were measured. No significant indications of wear caused on the harsh environment at the caster could be observed, neither after the revamping procedure. Project aim was the development and operation of a better control of initial solidification at meniscus level to enhance the surface quality of as-cast products. The pilot installation of the novel measuring technique using FOTS has demonstrated that this technology can survive under the harsh environment conditions of a caster. With the chosen layout and corresponding handling, it was possible to withstand the revamping procedure while the FOT Sensor was inserted in the mould. The FOTS-system gives the opportunity of analysing events that happen inside the mould but could not be detected before. A relationship between those events and the surface quality of the products has been observed, which has helped to determine new solutions to improve the process control and the strand quality. Strategies for optimised casting powder addition and corrective actions for assurance of a better quality of as-cast products were derived.

FOT sensors have been successfully used to monitor the mould wall temperature with indications of the current thermal profile, the position of the meniscus level and the influence of electromagnetic fields like stirring systems or brakes [EU-4.] (*INNOSOLID*). This system shows a higher resolution in space and time. Additionally, less space is necessary in comparison to thermocouples. A thick slab mould was equipped with two sensor rows including 10 measuring positions each. In the meniscus area the distances between measuring positions were lowered, so the operator of the casting machine was enabled to monitor the meniscus more precisely based on the temperature results. Optimisation measures were derived by physical and numerical modelling and tested in operational trials. Operators were enabled to react on malfunctions at an early stage also by generated alarm values. The benefits were:

- More detailed measurement of heat dissipation in the meniscus area.
- More sensitivity of early identification of troubles based on strand shell growth.
- Improved monitoring and optimisation of the casting process
- Reusable design with the advantage to be used for several mould plates and to avoid damage during revamping

A FOTS measurement system was also successfully implemented in the narrow face of a slab caster [EU-4.] (*INNOSOLID)*. Modification of the cooling circuit led to the expected change in heat removal but did not affect product quality clearly. The application of grooves to the copper mould walls was found to be a promising approach. The aim of the project was to adjust the heat removal inside the mould.

M-EMS (Mould Electromagnetic Stirring) was taken into account and numerical modelling was performed in the project [EU-14.] . The work of this project aimed at the improvement of surface and sub-surface quality of as-cast billets and improvement of the process route. Main requirements of the casting mould are to produce a solidifying shell that is of adequate and uniform thickness and is free from surface defects, such as corner cracks and longitudinal cracking. For many years numerous casting plants which have the traditional mould thermal monitoring systems have developed algorithms to detect the onset of surface defects, such as longitudinal cracking. These developed systems generally have had only limited success, because of the very localised nature and initial small size (a few millimetres in length) of most surface defects. Even though thermocouples have been installed in mould walls of billet casters to measure and analyse thermal profiles in some studies [EU-1.] (*DIRECT DEFECT TOOLBOX-DDT)*, operational problems have appeared (the signal quality affected by M-EMS, water leakages arisen from huge amount of cables that need to exit from mould cassette, complex manipulation). In addition, thermocouples have to be uninstalled from the mould before revamping it. Thus, it is necessary to install thermocouples again once the mould is revamped. Due to the necessity of using an individual cable for each thermocouple, the amount of measurement points has to be limited because of the lack of space in the mould.

These disadvantages have shown the necessity of developing an innovative technology that avoids those difficulties. However, even though there have been many efforts to develop monitoring systems that could help to identify abnormal situations inside the mould for long product casters, there is still a long way to go in terms of feasibility, reliability and process robustness. The reasons for abnormal situations are numerous and can be put into several categories, namely sticking in the mould, longitudinal corner or off corner cracking, mould hangers/finings and other related mould issues, start of cast, arrested teem failure following a stop period (including a flying tundish change, non-metallic entrapment, mechanical consideration (mould oscillation) and miscellaneous (loss of stopper control, loss of auto-level control). In many instances key process measurements, such as mould temperature measurements and the related thermal contour maps are not available.

The conditions of the continuous casting machine strongly influence the slab quality like surface defects or internal cracking. The segment rolls should be aligned exactly to the desired positions before the beginning of casting. Therefore, a Caster Strand Monitoring System (CSM) was developed by Lee et al. [1]. The CSM is designed to measure the roll gap, roll bending, roll alignment, roll rotation and the strength of the water/mist spray for slab cooling. A mathematical model for the position control and alignment of the continuous casting machine equipment was developed by Sholomitskii et al. [2] based on high-precision geodetic measurements.

Online Control systems

The online control systems are addressed to the improvement of caster and process stability to reduce cracking. It includes control of mould level, process parameter and secondary cooling pattern.

The various control systems adopted in RFCS projects and other scientific literature have been developed to manage one or more specific aspects of the process, according to the influence of the process parameters to the occurrence of crack formation.

In the frame of crack formation, it has been found that the transient conditions are particularly critical in terms of defects formation. Studies have been done in the project [EU-6.] (*TRANSIENT*). The project is aimed at understanding the causes and effects of transient conditions on surface and internal quality. Different measurement systems were developed, e.g. a mould powder coverage monitor. It was found that insufficient mould powder coverage has a tremendous influence on the strand surface quality. Transient conditions included casting speed variations, flow rate changes, ladle changes, flying tundish changes, start and end of casts, and grade changes. Innovative caster monitoring systems and advanced models using CFD, FEM and finite difference methods, as well as artificial neural networks were developed. Plant trials on five industrial casters covering a variety of formats and grades led to the identification of a set of transient phenomena. This has allowed for the development of new operational practices to eliminate or reduce quality problems associated with transient events and of new rules for downgrading as-cast material following transient events.

Breitfeld et al. [EU-5.] (*Advanced methods for an improved mould heat transfer control)* utilised experimental, analytical and numerical tools in order to conduct research on cooling systems in slab casting moulds. Transient thermocouple readings, mould powder properties, phase transformation during solidification, surface quality, friction forces, local and global heat withdrawal from slabs and billets were correlated with process conditions. It was concluded that mould heat flux cannot be applied for process control itself but is an excellent means for off- and online process observation. There are still some parameters that are difficult to assess and control, such as the complete thermal profiles of the four faces of the mould. This information could bring a very important advantage in terms of identifying risky situations as, for example, a non-homogeneous growing of the solid shell. There are some devices and technologies that have been developed to analyse thermal profiles inside the casting mould. A widespread one is the installation of a large amount of thermocouples along the whole mould walls supplying mould thermal monitoring systems, [25]. Presoly et al. [27] assumed a considerable effect of initial solidification on surface quality and casting productivity. Therefore, they installed an online thermal monitoring system. It was found that the quality of the strand surface decreases with increasing temperature fluctuations in the mould.

Secondary cooling control was not covered in deep in European research projects. Popular control models for secondary cooling and their principles and characteristics were reviewed by Dou et al. [29]. Based on this review a new control model was developed combining the advantages of the available models and estimating temperature profile and crater end position. Current problems with secondary cooling control and the related development trends were discussed.

Fluctuations of the position of the metal level in the mould disrupt solidification, entrain slag and lead to many quality problems. The liquid level is usually measured with a commercial system using a suspended eddy-current level sensor or a radiation detector. Optimised sensors for mould powder thickness and mould level are presented in [9], [10], [11]. Another potential method to quantify the metal level during continuous casting is to utilise the temperature measured continuously by thermocouples embedded in the mould copper [23].

The application of a liquid metal model was used to produce a set of novel tools to predict the formation of defects. Microstructural evolution of cracks was observed [EU-1.] (*DIRECT DEFECT TOOLBOX-DDT*). The developed numerical models predicted the microstructural evolution of the shell. Direct defect prediction was possible through numerous plant trials and liquid metal experiments to characterise the heat transfer and dynamic behaviour of the slag-bed and meniscus (particularly, at the meniscus corner where initial solidification occurs). The microstructural evolution including the formation of defects (cracks) was observed through novel in-situ experiments and steel properties were addressed through high-temperature measurements. Numerical models that predict metal-slag-argon flows, heat transfer, mould oscillation, solidification, stress-strain, shell microstructural evolution and the explicit formation of defects were developed in order to provide the steelmakers with a new set of tools to improve the casting practice.

Various control systems have been developed with the aim to improve safety conditions during continuous casting. In [EU-2.] (*DEFFREE*), critical parameters affecting steel quality have been analysed and safety ranges to ensure good quality in continuous casting have been found. Several fundamental and semi-empirical models were developed and used for process simulation in the project. Cracking indices, fluid flow parameters in the mould and segregation severity parameters are examples of critical parameters defined in the project. Safety ranges inside which the critical parameters had to stay during casting were determined for steady-state casting conditions.

Discussion

Cracks and hard spots are common quality problems of the cast products. Hard spots are local areas with increased hardness on the surface of semi-finished or end products in steel manufacturing. As the incident rate of hard spots is extremely low, only a 100% inspection of production can ascertain their detection.

Schneibel et al. [16] presented an eddy current based inspection. Current data and results from in-production inspection show the capabilities of the new technique. An outlook towards a 100% inspection system is given.

In the project *EDDYCAST* [EU-9.] a methodology for crack detection was developed. It was successful in several plants for billets, but for crack detection at continuously cast slabs at Dillinger the proposed and tested method did not work properly since

a) The slab temperature at exit of caster was in a critical range for a good in-line eddy current measurement application (i.e. around Curie temperature). In slab yard at lower slab temperatures the system worked better.

b) The cracks in the investigated area of the slab corners were mainly closed at the slab surface due to rolling forces in the caster (soft reduction and driving rolls). This caused a bridging of steel that enabled "normal" eddy current flow, i.e. the cracks could not be detected.

The project *NDTCASTING* [EU-12.] has shown the performance of the EMAT (Electromagnetic Acoustic Transducer) system on hot surfaces with oscillation marks and scale. The project demonstrated that sensitive flaw detection under these difficult conditions is possible - defects with a length less than 10% of the chosen wavelength (λ = 14.9 mm) can be repeatedly detected.

- EMAT-EMAT – A prototype was developed capable of detecting surface and subsurface defects on-line at high temperatures (below the Curie temperature of steel).
- Laser–EMAT - A prototype Laser-EMAT system has been developed. The system has been proven in the laboratory on cold samples. Hot trials have been of limited success with surface defects just being detected in some samples.
- Conoscopic holography – The existing plant system has been extended for detecting other defects in addition to the current longitudinal crack detection: Defects such as very thin and zigzag cracks can now be reliably detected. Overdetection has been decreased.

In the project *NDTSLAB* [EU-10.] the EMAT system has been demonstrated to be capable of finding defects in as-cast steel slabs that cannot be found visually with grinding or scarfing of the surface. With tuning of the signal to noise ratio in the surface scan image defects as small as 5 mm^2 can be detected. Defects smaller than this are not readily detected by the EMAT system.

Hooli [13] developed a system for the visual inspection of hot slabs during casting (*Reveal CAST*) which is able to define the surface quality of slabs.

Fibre optical temperature sensors (FOTS) have shown their potential during applications in the previous years [5], [19], [18], [20], [21]. FOTS systems are characterised by a very short response time and are not influenced by electromagnetic systems. These advantages provide the potential for application in moulds with EMS. To-day modern temperature measurements with short response times enable the control of EMS systems. Feld-meyer et al. [EU-8.] (*FOMTM)* introduced a FOTS fibre optical measurement system successfully to a billet caster system. This technique is basically able to control the casting process in real-time due to the very quick response time.

The work of Stamp et al. [EU-15.] (*CONSOLCAST*) includes comprehensive monitoring of solidification. Ra-mirez Lopez et al. [EU-16.] (*SUPPORT-CAST*) take into account novel online-monitoring and advanced mod-elling aiming at adjusted process control. Real-time measurement of shell-thickness aims at product improve-ment in the work of Barbero et al. [EU-17.] .

Excessive meniscus steel level fluctuations were suspected to be one of the sources for exogenous non-metallic inclusions as well as possible source of surface defects. Rohac et al. [17] successfully suppressed the influence of stir systems on electromagnetic Mould Level Measurement Systems (MLM System) in two steel-works.

Temperature control plays a major role in the continuous casting process (CC). Especially the avoidance of surface cracking for different steel qualities and different slab sizes needs optimisation of the thermal control. However, the internal thermal and flow state within the mould, in particular in the crucial area of solidification below the meniscus, is extremely complex. Considering the interacting influences of melt temperature and flow, solidification, cooling and mould powder main parts of the internal processes are still not understood despite a large number of research projects covering several decades.

This is still an issue in industrial operation since the melt temperatures fluctuate significantly due to the discontinuous processes in the steel shop. The melt temperatures supplied from ladles and tundish frequently change due to varying melt levels, holding times or ladle changes. The research and development effort in the last decades achieved a large degree of monitoring and control of CC plants, but unfortunately just the conditions in the crucial area around the meniscus cannot be directly measured yet but have to be roughly estimated from single temperature measurements in the mould copper. Furthermore, it is hardly possible for the operational staff to assess even the limited existing data since the results from quality supervision are only provided hours or days later, and in a format (e.g. spatial measurements) which is difficult to combine with other measurements.

As consequence, the relevant thermal conditions in the mould and their influences on surface quality are still highly non-transparent and automatic control of this important part of the process is still clearly limited. While many crucial aspects of the continuous casting process are not yet understood and are non-transparent, the corresponding control actions have to be done manually by experience. Steel industry needs to go towards Industry 4.0. There is urgent pressure to strongly improve the levels of knowledge, digitalisation and control.

In the following some examples are given for the most promising and useful emerging development lines and future trends concerning measurement techniques:

Atzlesberger et al. [14] and Kareem et al. [15] described a system for continuous temperature measurement in the tundish basing on the thermoelectric effect (also called Seebeck effect).

Lamp el al. [1] developed the measurement system DynTemp®. An optical fibre was continuously fed into the melt of an LD converter and yields continuous monitoring of the melt temperature. Kordel et al. [4] applied this approach also successfully to a ladle furnace. The innovative technique has proven to give valuable information on liquid steel temperature evolution. Thus, up to now the DynTemp® based liquid steel temperature measurement was applied to a converter, an EAF and a ladle furnace. In these applications possible slag entrainment caused by the moving fibre does not degrade the melt quality at this early stage. The application of this innovative technology to the mould, where entrainment of liquid mould powder has a huge influence on melt cleanliness, will provide very precise temperature information of the steel melt. But the careful introduction of the fibre into the melt through a refractory tube supported by an inert gas like Argon is a big challenge. This will be done for the first time in the running project RealTimeCastSupport [EU-18.].

Influence of transient effects like a ladle change on thermal evolution can be analysed in detail.

Three different measurement techniques will be applied and utilised in parallel in the running project

- (1) IR-based monitoring at the casting powder surface,
- (2) local temperature measurements in the copper mould plates with thermocouples and with FOTS,
- (3) DynTemp® based liquid steel temperature measurement in the tundish and in the mould.

Additionally, FOTS will be applied to a mould equipped with a multi-mode EMS. Quick response of the FOTS system enables the control of melt temperature and flow indirectly with the multi-mode EMS.

In the running RFCS-project *SHELLTHICK* [EU-17.] a solidification process optimisation tool providing the operators with real-time information on the billet solidification process as cross-section shell thickness is developed. Additionally, the tool provides the operators with real-time information about surface defects (bulging, depressions & rhomboidity) on the billet and (based on the output of the previous tools) would allow the operators and/or managers to define the optimal continuous casting process parameters to improve quality (minimising the generation of surface defects) and productivity.

Weidermann et al. [37] developed a new technology for flow measurement in liquid steel to determine the time-dependent liquid flow through a submerged entry nozzle (SEN). The measurement system reaches a resolution of 0.5 kg/s with a response time of 100 ms for a 2.5 kg/s mass flow jump. The device performance has been evaluated under laboratory conditions. A first operational trial in a steel plant has been done.

Contactless inductive flow tomography (CIFT) was implemented at several physical models of slab casting moulds by Ratajczak et al. [38]. As a conclusion, these innovative measuring techniques should be further developed in the future:

- Continuous temperature measurement in the tundish
- Control of melt flows

- Monitoring of mould powder layer
- Measuring of temperature in mould copper walls
- Monitoring of spray cooling
- Measuring the temperature of the strand surface
- Detection of cracks

Overview of the development (in view of the road map)

The occurrence of surface and internal defects during continuous casting can be induced by several parameters that have to be considered all together, since they are linked. Many efforts have been done in order to better understand the correlations of the defects with process parameters: in that frame the development of reliable models, quality prediction systems and sensoring & monitoring tools play a strategic role.

As general view, the RFCS research led to actual important results, in terms of basic knowledge of physical and chemical phenomena inside the steel, definition of possible countermeasures to reduce the incidence of one or more defects, the development of new powder concept, set-up and application of digital tools to control the process and/or monitor the plant events.

The disposal of reliable methods to collect and process data is fundamental since it allows to have useful data to "feed" every developed model or to predict the behaviour of the process. In this field, the use of Fiber-Optical Sensors (FOTS), and steel melt temperature measurement in the mould represent the most studied technologies, with a TRL 6/7. Online control systems are also strongly studied in EU projects, but they suffer from missing knowledge of the combined influence of all parameters. Furthermore, barriers remain for continuous observation of mould powder surfaces and continuous temperature recording in tundish and mould, due to the limited accessibility conditions. Systems for the detection of cracks are developed with the use of eddy current measurements: An EMAT system has been proven to be able to find defects is as-cast steel slabs. In the future, it is reasonable to improve the system in order to catch defects smaller than 5 mm^2 .

Table1 summarises the main points of discussion.

Tab. 1 Compilation of control and sensoring techniques including TRL level and main barriers

TRL level	Main barriers	Overall comments
Steel melt temperature measurements in-line in the mould: **Thermocouples** **Fibre-Optical-Temperature-Sensors (FOTS)** **TRL 6/7**	Signal quality of thermocouples is affected by M-EMS; water leakages may arise through cables exit; complex manipulation; thermocouples have to be uninstalled from the mould before revamping it. Amount of measurement points limited due to the necessity of using an individual cable for each thermocouple.	The pilot installation of the FOTS technique has demonstrated that this technology can survive under the harsh environment conditions of a caster. FOTS show a higher resolution in space and time, need less space in comparison to thermocouples. Continuous online information on gap lubrication and rim formation was reachable for the first time in long product casting
Continuous observation of the mould powder surface **TRL 6**	Harsh conditions, limited accessibility	It was found that insufficient mould powder coverage has a tremendous influence on the strand surface quality
Online control systems **TRL 6**	Considering the interacting influences of melt temperature and flow, solidification, cooling and mould powder main parts of the internal processes are still not understood.	Even though there have been many efforts to develop monitoring systems that could help to identify abnormal situations inside the mould for long product casters, there is still a long way to go in terms of feasibility, reliability and process robustness
Continuous temperature measurement in the tundish and in the mould **TRL 5**	Limited accessibility. The careful introduction of the fibre into the melt through a refractory tube supported by an inert gas like Argon is a big challenge.	Up to now the DynTemp® based liquid steel temperature measurement was applied to a converter, an EAF and a ladle furnace
Detection of cracks **TRL 5**	Crack detection by eddy current measurement at continuously cast slabs does not work properly if the slab temperature at exit of caster is near the Curie temperature. In slab yard at lower slab temperatures the system works better. The cracks cannot be detected if the slab corners are closed at the slab surface due to rolling forces in the caster. EMAT-EMAT – A prototype was developed capable of detecting surface and subsurface defects on-line at high temperatures (below the Curie temperature) Laser–EMAT - A prototype Laser-EMAT system has been developed and proven in the laboratory on cold samples. Hot trials have been of limited success with surface defects being detected in some samples. Conoscopic holography – The existing plant system has been extended and now reliably detects longitudinal cracks, very thin and zigzag cracks. Overdetection has been decreased.	An eddy current measurement system was successful in several plants for billets. But for 6-strand equipment the system would require capital expenses of over 2 M€, which provides insufficient payback. The EMAT system has been demonstrated to be capable of finding defects in as-cast steel slabs that cannot be found visually with grinding or scarfing of the surface. With tuning of the signal to noise ratio in the surface scan image defects as small as 5 mm^2 can be detected. Defects smaller than this are not readily detected by the EMAT system.

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