AI-Driven Surface Inspection
Enabling Automated Grinding of Forged Ingots

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Sapotech's Reveal CAST surface inspection system has been successfully implemented in Grinding Machine-3, marking a significant advancement in automated quality control for ingot processing. The collaboration with Daido Steel began in 2019 with a demonstration project using a portable inspection unit, highlighting the high-resolution imaging capability for both forged and ground surfaces. Following this successful demonstration, Sapotech developed a dedicated Surface Inspection System (SIS) designed to detect surface defects across forged and ground ingots.

The Reveal CAST system was commissioned in January 2023, and within a few months, it met all defined performance criteria, providing reliable defect detection and image quality suitable for integration into production processes. This deployment has enabled a more precise understanding of surface characteristics, paving the way for targeted process improvements.

Building on these results, ongoing work focuses on automating the grinding process using insights from Reveal CAST. Integration of automation systems is underway, with rules being established for spot grinding based on detected defects. The goal is to enhance grinding throughput, ensure consistent ingot quality, and reduce manual inspection efforts.

This presentation will outline the development journey of Reveal CAST, from the initial demo to full-scale commissioning, and highlight the system's contribution to process optimization in ingot forging and grinding. Additionally, it will discuss the automation strategy and expected impact on production efficiency and product quality. Sapotech's approach demonstrates how advanced surface inspection, combined with automation, can deliver measurable improvements in metallurgical manufacturing operations.

KEYWORDS: SURFACE INSPECTION – FORGING – GRINDING – ARTIFICIAL INTELLIGENCE – DEFECT DETECTION – AUTOMATION – QUALITY

INTRODUCTION

The production of high-quality forged ingots for demanding applications such as aerospace, power generation, and precision engineering involves a complex sequence of metallurgical operations. Starting from ingot casting, the material undergoes forging to achieve the desired shape and mechanical properties, followed by surface grinding to remove surface defects and prepare the product for further processing or delivery. Each step in this chain imposes strict requirements on surface integrity, and the cumulative effect of surface anomalies, if undetected, can lead to costly rework, material rejection, or, in the worst case, field failures in safety-critical components.

Surface quality control in ingot forging and grinding has traditionally relied on manual visual inspection, a method that is inherently subjective, labor-intensive, and limited in its ability to provide objective, documented, and traceable quality data. Hot and glowing surfaces, heavy scale, variable ambient lighting, and the physical size of the workpieces all challenge human inspectors. The lack of objective, documented inspection data further limits the ability to trace defects back to their process origins or to use quality information systematically for process improvement.

Automated surface inspection systems have been widely deployed in flat and long product manufacturing; continuous casting lines, hot rolling mills, and cold rolling operations, where product geometry and motion are well-defined and repeatable. However, the ingot forging and grinding environment presents a fundamentally different challenge: irregular product geometries and size, intermittent and variable motion, extreme temperature ranges from glowing hot to cold, and the need to inspect both forged and ground surface conditions. Of the two surface conditions, ground surfaces represent the more demanding inspection case: the directional grinding texture and the potential for crack smearing or partial closure during the grinding process make defect detection inherently more challenging than on rough forged surfaces. These combined demands have kept this application segment beyond the reach of established automated inspection solutions. Sapotech's Reveal CAST platform, proven across multiple metallurgical process environments and described in earlier publications [1,2], provided the basis for developing a purpose-built solution for ingot surface inspection.

In 2019, Sapotech Oy, a Finnish technology company specializing in machine vision-based surface inspection for the metals industry, conducted a demonstration project at Daido Steel's Shibukawa Works in Japan. Using a portable Reveal CAST inspection unit, the demonstration evaluated the feasibility of high-resolution laser-illuminated imaging across a representative range of surface conditions and product geometries encountered in the forging and grinding process. The results confirmed that reliable defect visualization was achievable on forged and ground surfaces at both hot and cold temperatures, establishing the technical foundation for a permanent installation.

This paper describes the development journey from that initial demonstration to the commissioning of a dedicated Surface Inspection System (SIS) integrated into Grinding Machine-3 at Daido Steel Shibukawa Works, completed in January 2023. It presents the system design rationale, commissioning results, and the ongoing work to leverage inspection data for automated spot grinding decisions; a step that is expected to deliver measurable improvements in grinding throughput, product consistency, and the reduction of manual inspection effort.

DEMONSTRATION PROJECT

The collaboration between Sapotech and Daido Steel began in January 2019, when a five-day demonstration project was conducted at Daido Steel's Shibukawa Works. The primary objective was to acquire surface images from real production conditions, covering the forged and ground surface types encountered in the process chain, which differ fundamentally in appearance: the rough, scaled texture of a forged surface versus the regular, directional pattern of a ground surface. This data was essential for evaluating illumination strategies and their ability to reveal genuine surface defects on surfaces with very different optical characteristics.

The demonstration was conducted in two separate locations within the plant. The first was a storage and reheating area, where the portable Reveal CAST unit was set up adjacent to a smaller reheating furnace. In this location, ingots were handled by a smaller manipulator operated by a Daido Steel operator, who transported the ingots from the furnace past the imaging unit at as steady a speed as possible. The imaging resolution achieved in this location was 0.3 mm/pixel. The second location was the 7,000-ton open-die forging press, where a large rail-driven manipulator handled the ingots. Here, ingots were first forged and then brought to the Reveal CAST unit for imaging. The ingot subsequently went to grinding and reheating before being returned to the press area for a second imaging pass, making it possible to capture and compare surface images of the same large ingot in both forged and ground condition. The imaging resolution at this location was 0.5 mm/pixel, from a standoff distance of approximately 3.5 meters. Fig. 1 shows the demo setup at the 7,000-ton press.

This two-location approach was particularly valuable because it allowed the demonstration to cover a representative range of ingot sizes and process states encountered in production, from smaller reheated ingots to large forgings, and from freshly forged surfaces to ground ones. It also replicated the actual sequence of operations that the permanent system would need to handle, providing directly applicable data for the subsequent system specification.

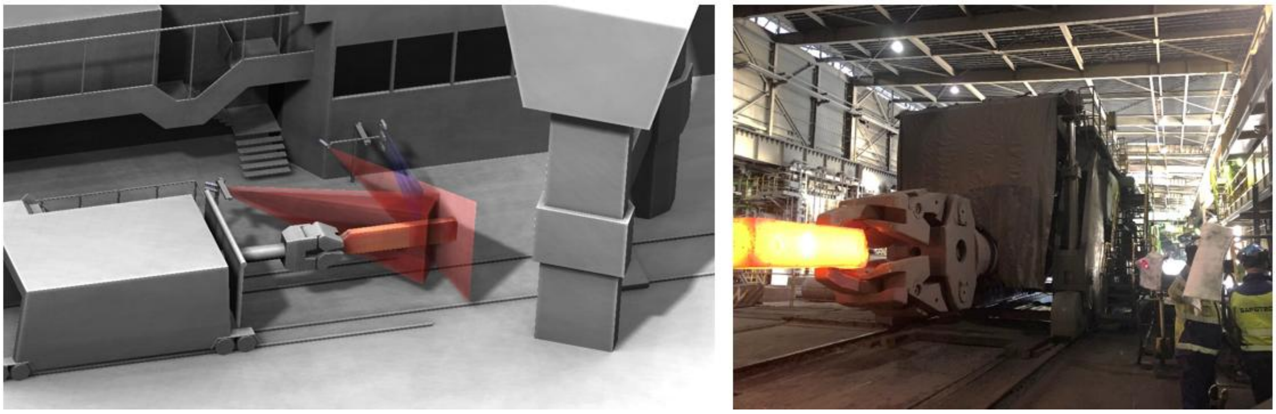

Fig.1 - Demo setup photo in open-die forge

A particularly significant finding emerged from the hot ingot imaging: a direct comparison of images captured with and without laser illumination demonstrated that laser-based illumination is immune to heat-induced optical distortion and interference from ambient and thermal radiation, preserving contrast and enabling defect features to be clearly resolved on glowing hot surfaces. This effect is illustrated in Fig. 2 in which the transversal cracks are visible in the illuminated image, while without the illumination there is no hint of cracks in the corner area.

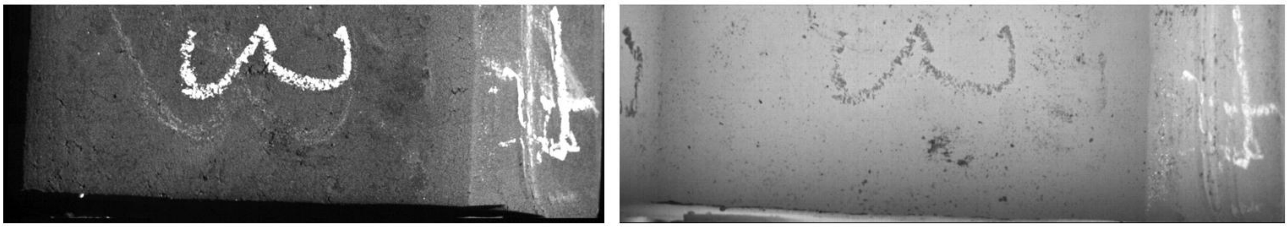

Fig.2 - Hot ingot with/without laser comparison

The test program covered forged and ground surfaces in both cold and hot condition. Direct and indirect illumination configurations were evaluated, with direct illumination proving more effective for the rough, diffusely reflecting forged surfaces and indirect illumination better suited to the more specularly reflective cold ground surfaces. The laser-based imaging approach performed reliably across all tested combinations of surface type and temperature, and surface defects including cracks and longitudinal surface irregularities were readily identifiable in all cases.

The images in Fig. 3 illustrate the surface condition of the same rectangular ingot at two stages of the process. The ingot was first taken from the reheating furnace, forged at the 7,000-ton press, and then imaged with Reveal CAST while the rail-driven manipulator moved it horizontally past the system. The ingot was subsequently taken to grinding, returned to the furnace for reheating, and imaged again with Reveal CAST. The two images therefore show the same ingot, first in its forged condition and then after grinding, providing a direct visual comparison of how the surface appearance changes between the two process steps.

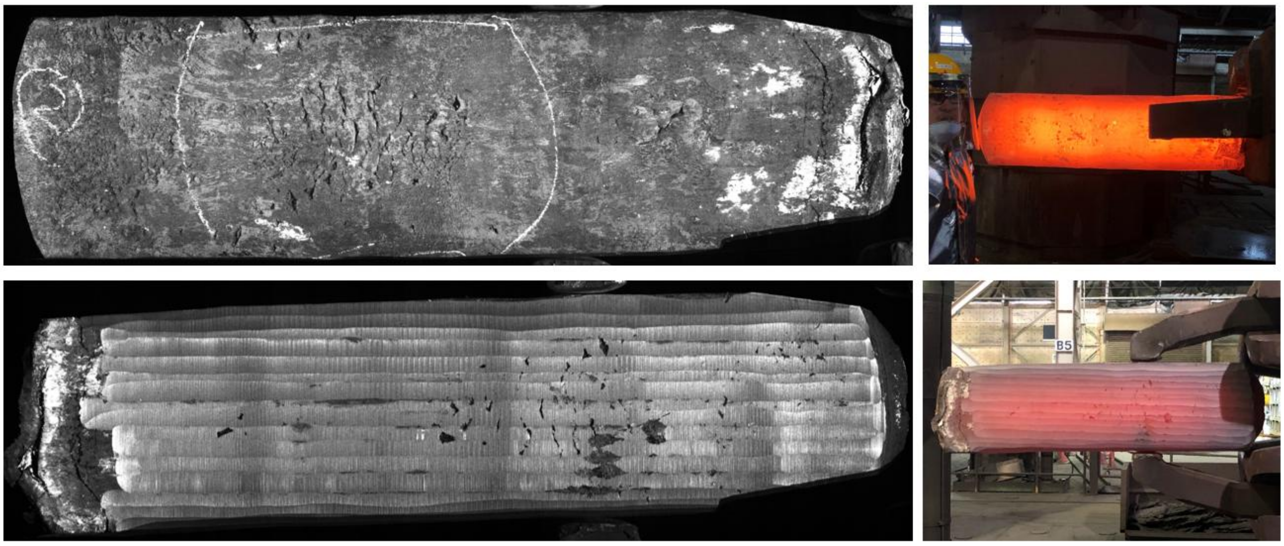

Fig.3 - Forged and ground face of the same object

The demonstration confirmed the viability of the technology and provided sufficient image data to define the specifications for a permanent installation at Grinding Machine-3 at Shibukawa Works.

PERMANENT SYSTEM DESIGN AND COMMISSIONING

Based on the demonstration results, direct longitudinal illumination was selected as the illumination strategy for the permanent installation. While indirect illumination showed slightly better performance on cold ground surfaces during the demonstration, direct illumination was chosen for several reasons. First, the ingots arriving at Grinding Machine-3 are at elevated temperatures, and at high surface temperatures the specular reflectivity characteristic of cold ground steel is likely reduced due to rapid scale formation, making direct illumination equally effective regardless of surface finish. Second, direct illumination is considerably more straightforward to implement reliably in a permanent industrial installation. Third, the grinding pattern at Daido Steel is transversal, meaning that the grinding marks run across the ingot width, and longitudinal illumination is well suited to this configuration as it illuminates along the direction of the defects of primary interest rather than along the grinding texture.

The illumination is applied at a low, grazing angle to the ingot surface, a technique known as dark-field illumination [1]. The crack walls reflect the grazing illumination away from the camera rather than toward it, causing cracks and surface irregularities to appear as dark features against the lighter background of the surrounding surface. This makes dark-field illumination particularly effective for detecting the longitudinal and transverse cracks that are the primary defect types of concern in forged ingots.

One of the most significant engineering challenges in the permanent system design was accommodating the wide variation in ingot thickness encountered in production at Shibukawa Works, ranging from 300 mm to 1,500 mm. The ingots handled at Grinding Machine-3 include square, rectangular, and octagonal cross-sections. Maintaining a consistent standoff distance between the cameras, lasers, and the ingot surface is critical for achieving stable image quality; the motor-driven positioning system achieves this across the full thickness range with no limitations, and detection performance is consistent regardless of ingot size or cross-section shape. The permanent Reveal CAST installation at Grinding Machine-3 is shown in Fig. 4.

Fig.4 - The Permanent Reveal CAST installation

The system was specified to detect surface defects with a minimum width of 1 mm and minimum length of 4 mm, covering the defect classes of primary concern in the forging and grinding process. To achieve the required imaging resolution across the full ingot width, two high-resolution area scan cameras were needed. The ingot surface is illuminated by two high-power lasers, and the cameras are equipped with narrow bandpass filters that allow only the laser wavelength to reach the sensor, effectively suppressing interference from ambient light and thermal radiation emitted by the hot ingot surface. Achieving a sufficiently even illumination pattern across the full field of view is critical, as the individual images captured by both cameras are stitched together both widthwise and lengthwise to produce a single continuous surface image of the entire ingot face. Defect detection is performed by a deep neural network model trained on image data collected from production. The deep learning tools embedded in Reveal CAST, covering defect marking, pixel-level annotation, model training, and production inference, follow the development methodology described in [1]. Detection results are delivered to the operator within 15 seconds of scan completion, enabling timely decisions within the production workflow.

Commissioning of the system took place in January 2023 and proceeded without major setbacks, reflecting the thorough preparation and planning carried out in advance. During commissioning, the imaging sequence was successfully executed across the full range of ingot dimensions, confirming that the positioning system and illumination performed as designed. With imaging and hardware performance validated, the system was ready to enter the next phase: production data collection, model training, and performance validation, which are described in the following section.

INSPECTION RESULTS AND PERFORMANCE

Following successful commissioning, the system entered the data collection phase, during which production ingots were scanned and the resulting images were used to build the training dataset for the defect detection model. Data collection covered some tens of ingot surfaces, and given that individual surfaces can contain hundreds of defect instances, several thousands of defect samples were available for model development. The annotation process was carried out collaboratively between Daido Steel and Sapotech in a two-stage workflow: Daido Steel quality staff marked defect bounding boxes directly in the Reveal CAST user interface, leveraging their process knowledge and familiarity with the defect types relevant to the forging operation, while Sapotech experts performed the detailed pixel-level annotations required for training the deep neural network model [1]. The training dataset was split into 60/20/20 for training, testing, and validation respectively, following established practice for deep learning model development in surface inspection applications [1].

The primary defect classes targeted by the model were longitudinal and transverse cracks, which represent the principal surface defects generated during the open-die forging process, as identified by Daido Steel based on their process knowledge and quality requirements. Model development proceeded through three training and refinement iterations, with each cycle incorporating feedback from production results and additional annotated data. All software updates and model deployments were carried out remotely via VPN access to the application servers at Shibukawa Works, without requiring on-site visits from Sapotech, demonstrating the practicality of the remote service model for international installations.

The target detection rate of 90% for longitudinal and transverse cracks was achieved within 4 to 5 months of commissioning, meeting the defined performance criteria within the planned timeframe. The performance figure was validated by Daido Steel by comparing Reveal CAST detections, made on ground ingot surfaces at temperatures well above 1000°C during production, against manual cold inspection results for the same ingots. The comparison is therefore conservative: manual inspection of a stationary cold ingot is a more favourable condition for human inspectors than hot in-process imaging, making the achieved detection rate all the more significant. The primary application of the system is the inspection of ground surfaces, which present a more demanding detection challenge than forged surfaces due to the directional grinding texture and the potential for crack smearing or partial closure during grinding. This result is consistent with detection performance reported for Reveal CAST in other industrial deployments [3,4], confirming the robustness of the deep learning approach across different product types and process environments. The Reveal CAST user interface with automatically detected cracks on a production ingot surface is shown in Fig. 5. The quality impact of the system is evidenced by production results: following implementation of Reveal CAST, zero surface defect non-conformities were recorded across 61 ingots through to final finishing, providing direct confirmation that the inspection and targeted grinding approach is effective in preventing surface quality escapes.

Fig.5 - Detected defects in Reveal CAST User Interface

The system has since been taken into daily use by the grinding machine operators, and while it introduced some changes to their working routine, the overall inspection process has become more efficient. Operating the system requires additional steps compared to conventional practice, including positioning the system on a correct height based on the ingot thickness and running the grinding machine over the ingot surface to capture the image. However, the inspection itself is now conducted entirely from within the operator pulpit, with the full ingot surface visible on screen and defects clearly marked. Beyond efficiency, there is a meaningful safety benefit: operators no longer need to approach the high-temperature ingot surface during inspection, reducing direct exposure to heat and the associated operational risk. The introduction of Reveal CAST also enabled a fundamental change in the grinding process. Before the system was in use, the standard approach was to perform two full-surface grinding passes on each ingot face, with grinding parameters adjusted manually by the operator based on visual judgement. Manual inspection required the operator to leave the pulpit, walk to the ingot, rotate the worktable to expose the ground face, perform a visual inspection lasting approximately one to one-and-a-half minutes, rotate the ingot back, and return to the pulpit, a sequence taking roughly three-and-a-half to four minutes per face, with outcomes depending on individual operator experience and judgement. With Reveal CAST, the process changed to one full-surface grinding pass followed by one targeted spot grinding pass based on the detected defect locations. Replacing one full-surface grinding pass with precise spot grinding has improved material yield by reducing unnecessary material removal from defect-free surface areas.

GRINDING AUTOMATION

The long-term objective of the Daido Steel deployment is to close the loop between surface inspection and grinding machine operation, eliminating manual defect marking and enabling fully automated spot grinding.

When an operator initiates an inspection cycle on the grinder HMI, the Grinding Machine traverses the ingot while Reveal CAST captures images and runs the AI-based defect detection pipeline in real time. Upon completion of the traverse, Reveal CAST identifies the ingot corners and all defective surface areas, transforms the detected defect coordinates from the image domain into the Grinding Machine coordinate system, and validates the result against the encoder-measured ingot length. If the discrepancy between the image-derived and encoder-measured length exceeds a configured threshold, a fault is raised and the data transfer is aborted, preventing incorrect grinding coordinates from being acted upon.

Once the data is validated, defect area bounding boxes are transferred from Reveal CAST to the Grinding Machine PLC via an industrial communication link. Individual defect detections are clustered into grinding zones before transfer; the minimum grinding area is 300 mm in length and 50 mm in width, reflecting the physical constraints of the grinding process such as wheel size and positioning accuracy. Since Reveal CAST is a 2D imaging system with no depth measurement capability, the automation approach is iterative: the surface is inspected, defective areas are spot ground, and the surface is re-inspected until cracks are no longer detected. The PLC uses the transferred coordinates to execute automatic spot grinding of the affected regions, area by area, without further operator input. After the grinding cycle is complete, the Grinding Machine returns to standby, ready for the next ingot.

At the time of writing, the integration is under active commissioning. The rules governing the clustering and segmentation of defective areas into grinding zones are being established jointly by Sapotech and Daido Steel, based on accumulated inspection data from the Reveal CAST system.

The potential benefits of automating this process are significant. Manual inspection and defect marking are time-consuming steps that introduce variability: operator judgement affects both the extent of grinding applied and the consistency of quality outcomes between shifts. Replacing manual marking with data-driven, coordinate-level instructions from a calibrated AI system removes this variability and ensures that every defect identified by the inspection system receives an appropriate response. Grinding can be targeted precisely to the affected areas, reducing unnecessary material removal on surfaces that do not require it, which in turn extends grinding wheel life and reduces consumable costs. Cycle time savings are expected as well: by eliminating the manual marking step and enabling the Grinding Machine to begin its cycle immediately after the inspection traverse, non-productive time between ingots can be reduced. In the current Daido Steel installation, the Reveal CAST inspection scan accounts for approximately two minutes of a total grinding cycle time of around 12.6 minutes per ingot face, an overhead of approximately 16%, which is well justified by the process improvements it enables. For a high-throughput forging line, these gains deliver measurable improvements in yield and product consistency.

CONCLUSIONS

This paper has described the development journey of the Reveal CAST surface inspection system at Daido Steel Shibukawa Works, from the initial demonstration project in January 2019 to a fully operational production system and ongoing grinding automation work.

The 2019 demonstration confirmed that high-resolution laser-illuminated imaging is applicable to the challenging conditions of an industrial forging and grinding environment, producing clear and informative surface images across forged and ground surfaces in both hot and cold condition. The immunity of laser-based illumination to heat-induced optical distortion was identified as a key enabling factor for reliable inspection of hot forged surfaces.

The permanent Surface Inspection System commissioned at Grinding Machine-3 in January 2023 successfully addressed the specific engineering challenges of the application, including the wide variation in ingot thickness from 300 mm to 1,500 mm across square, rectangular, and octagonal cross-sections, through the development of a motor-driven PLC-controlled positioning system that achieves stable standoff distance across the full size range. The system detects longitudinal and transverse cracks with a minimum size of 1 mm in width and 4 mm in length, and delivers detection results within 15 seconds of scan completion.

The collaborative model development approach, combining Daido Steel’s metallurgical process knowledge with Sapotech’s machine vision and AI expertise, proved effective. The target detection rate of 90% for longitudinal and transverse cracks on ground ingot surfaces at production temperatures above 1000°C was achieved within 4 to 5 months of commissioning through three model training iterations, with all software updates deployed remotely. The result was validated by Daido Steel against manual cold inspection of the same ingots, providing independent confirmation of the system’s performance on the more demanding ground surface case.

The ongoing integration of inspection results into grinding process control represents the next step in the development, with the aim of establishing a fully automated, quality-driven grinding operation that improves throughput, reduces material loss, and minimizes reliance on manual inspection.

The work demonstrates that advanced machine vision and AI-based surface inspection can be successfully deployed in the demanding environment of ingot forging and grinding, delivering measurable quality control benefits and providing the data foundation for process automation. Production results at Daido Steel confirm the practical value of the system: zero surface defect non-conformities were recorded across 61 ingots following implementation, and the shift from two full-surface grinding passes to one full-surface pass combined with targeted spot grinding has improved material yield.

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