RESEARCH OF ULTRA-HIGH-STRENGTH AND WEAR-RESISTANT STEELS USING ADVANCED TECHNIQUES

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ABSTRACT

The usability of ultra-high-strength and wear-resistant steels has been researched for several years at Lapland University of Applied Sciences. Bendability tests have been carried out by using a commercial press brake and, recently a new "ultimate bending machine" was built up to allow steels with higher strength and thickness to be tested. Research techniques have been developed in cooperation with SSAB and the University of Oulu. The techniques, as well as ultra-high-strength and wear-resistant steels, are reviewed in this paper.

Welding and wearing have also been researched for many years in cooperation with SSAB. The most common welding technique is mechanized MIG/MAG welding in method tests but shielded metal arc welding is also used for repair welding research. The quality and mechanical properties of welds are calculated with destructive testing results.

Wear-resistance tests are specialized field tests conducted under real-life conditions in the Outokumpu Chrome Oy Kemi mine, performed in cooperation with Tapojärvi Oy. The usual test targets of the wear-resistant steels are cutting edges and feed hopper plates. The wear of the wear-resistant plates was measured with the ATOS optical measurement system from GOM GMBH at Lapland University of Applied Sciences.

INTRODUCTION

Lapland University of Applied Sciences has an "Arctic Steel and Mining" (ASM) research team. The main focus of its work has been in the usability of ultra-high-strength and wear-resistant steels, as well as stainless steels. The team has participated together with the University of Oulu, SSAB Europe, and some other organizations in a research cluster which has recently published various papers at conferences and in journals. This paper mainly focuses on reviewing the techniques which have been utilized within these projects, as well as the introduction of ultra-high-strength steels. Detailed results of the projects can be read in the papers listed in the references below.

ULTRA-HIGH-STRENGTH AND WEAR-RESISTANT STEELS

Ultra-high-strength steels (UHSS) are usually considered to be steels with a yield strength of more than 550 N/mm^2 and an ultimate tensile strength of more than 700 N/mm^2. That is at least about 1.5 – 2.5 times higher compared to regular structural steels. Ultra-high-strength steels are suitable for fabrication but their higher strength and lower ductility make their processing more challenging and it becomes essential to follow instructions carefully. The high strength of UHS steels can be utilized in lightweight structures, which influences the costs and increases the lifetime of the devices. They are suitable for applications where, for example, weight is critical. Reducing the weight also reduces the consumption of steel, which also influences the carbon dioxide emissions during the production of the steel. Typical applications of UHS steels are, for example, the booms and frames of cranes, the frames of trucks and their beds, and parts of cages; see Figure 1.

Figure 1. Typical applications of UHS steels

Wear-resistant steels are typically used in applications such as the scoops and lip plates of earth movers, mining machines, the parts of the cement mixer trucks and batching plants that are subject to wear, agricultural and wood-handling machinery, bed structures, feeders and funnels, and the edges of different crushers; see Figure 2.

Figure 2. Typical applications of wear resistant steels

In the example shown below a demonstration is provided by means of a life-cycle approach of how a change from standard steel to UHSS in vehicles reduces carbon dioxide emissions. If, for example, 1.3 million tons of standard steel is replaced with one million tons of UHS steel in the production of cars:

1. when upgrading to a high-strength steel, the application retains its performance even though less steel is used. This results in weight savings for the steel application and means that less steel needs to be produced. Additionally, fewer resources are needed;

2. as much as 90% of the reduced environmental impact can be related to the use phase of lighter vehicles, through reduced fuel consumption;

3. from a life-cycle perspective, this case shows the substantial savings that can be achieved through using high-strength steels.

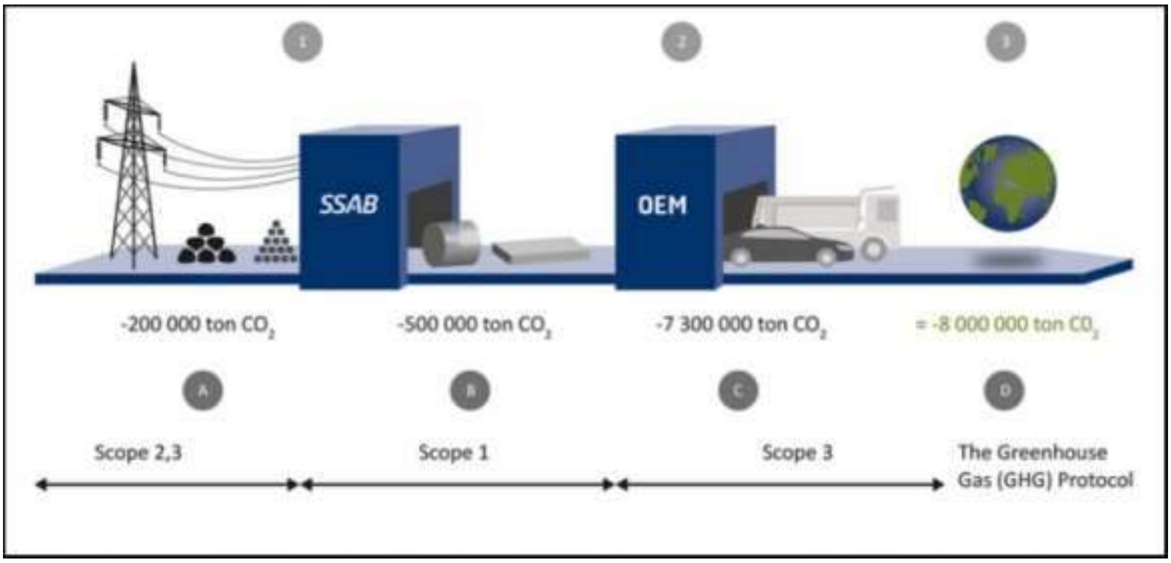

Figure 3. Example of the reduction of the carbon dioxide emissions through the use of UHS steels

A. When 300,000 tonnes less steel needs to be produced, the CO_2 emissions from upstream suppliers will decrease by 200,000 tonnes since less energy and raw material are needed.

B. The reduction in steel produced by 300,000 tonnes results in 500,000 tonnes fewer CO_2 emissions from SSAB's steel production.

C. When the current European vehicle fleet is upgraded, CO_2 emissions will decrease by 7.3m tonnes.

D. The total CO_2 savings arising from this hypothetical case are around 8m tonnes.

BENDABILITY

Manufacturing components for UHS steel applications almost invariably require bending, which is the most used, the best, and in many cases the only choice for forming, especially when the thickness of the sheet is increased. In modern high-strength steel structures (for example new generation boom and bed structures), bending is increasingly used and it often replaces, for example, welding. This leads in many cases to better fatigue durability of the structure at the same time as a reduction of the production costs.

Increasing the strength, however, makes bending more challenging and it becomes very important to obtain information about bendability and the factors which have an influence on the process. While the aim is to have a process that is as efficient and trouble-free as possible, following the instructions must be emphasized. That makes it very important to perform full-scale bendability tests which are carried out with real bending machines and samples large enough to correspond to actual parts. On the basis of the tests, correct instructions can be provided to customers.

In the bending, a steel plate is bent with, for example, a hydraulic press brake using a toolset containing a punch and die. The process, usually considered as three-point bending, is illustrated in Figure 4.

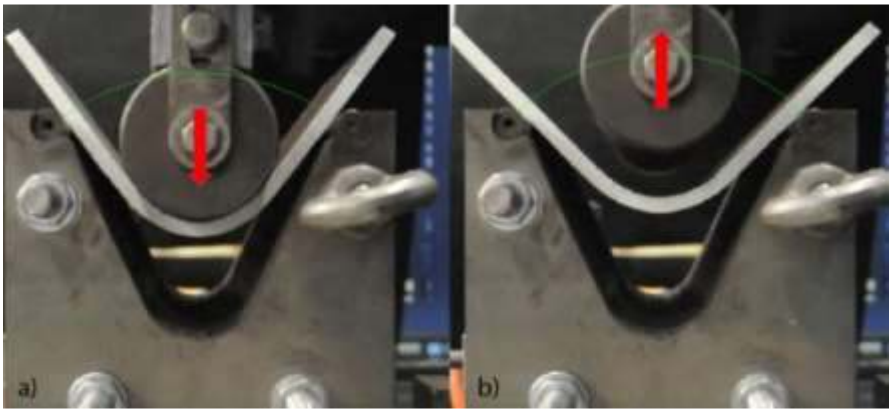

Figure 4. Bending of a steel plate in a V-die: a) punch in lower position; b) punch released

In Figure 4, spring-back may also be noticed. This phenomenon typically takes place in three-point bending. After the punch is released, the angle of the plate is opens as a result of the elastic deformation which is, in addition to plastic deformation, present in the steel. The spring-back may be measured using a video camera. Two images are sampled from the video, one from the lower end of the punch and another after the release of the punch; see Figures 4a and b. The spring-back angle is measured from the difference between the angles detected from the images. In general, greater the strength of the steel, the higher the spring-back, and knowledge of the magnitude of the spring-back is valuable for foundries manufacturing steel products.

When the strength of steel increase, its formability usually decrease. Figure 4 also illustrates the bending radius, which, in practice, corresponds to the radius of the punch. When the bending radius decreases, the strain on the outer surface increases and the probability of failure becomes higher. Therefore, the bending radius has to be large enough to avoid failures. In bendability tests, the minimum bending radius (R_{min}) of the material, i.e. the smallest radius which is able to be used without failures, is usually defined. The result of the test is evaluated by means of visual inspection. Samples which have been bent using various bending radii are shown in Figure 5a-c. As a result, various degrees of failure have been developed on the surface. For the quality of the bend, certain requirements have been laid down and on the basis of these requirements, the result of the test will either be accepted or not.

Figure 5. a) No failures; b) and c) failures appeared in the steel as a result of too small a bending radius

After the minimum bending radius has been reached, a sufficient number of repetitions is carried out using the accepted bending radius. Hence the durability of the material is able to be determined and the steel manufacturer is able to guarantee a minimum bending radius, for example, three times the thickness of the sheet (R_{min}=3xt). The value usually depends on the grade and thickness of the steel and typically varies between 2 and 6 with UHS steels.

In addition to basic bendability testing, detailed investigations of the samples have also been carried out. With the GOM ARGUS 3D forming analysis system, samples have been studied with the aim of getting more detailed information about the metallurgical phenomena involved in bending [Arola et al. 2015, Ruoppa et al. 2014]. In this technique, a grid is marked on the surface of the sample before bending. On the basis of the change in the grid, a computer system calculates the strain distribution on the surface. The system is illustrated in Figure 6a and an example of a strain map is shown in Figure 6b. As a result, information about the processes during failure and the factors affecting them is gained, which helps the steel producer to develop products and customer instructions.

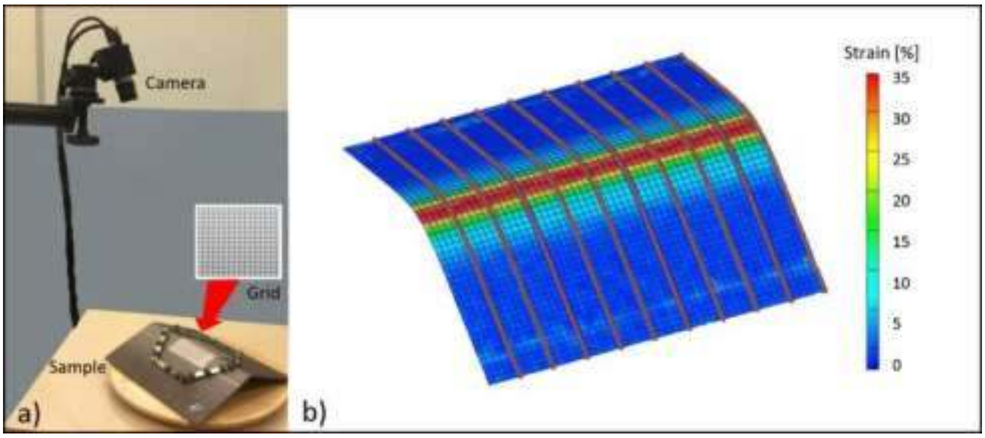

Figure 6. a) Measurement of the strain distribution with the GOM ARGUS 3D forming analysis system; b) example of strain mapping in bent sample

A more detailed study of the samples has also been performed by microscopic examinations. Figure 7 shows a microscopic image of the cross-section of a bend. From the image, scratches beneath the surface, as well as the reduction of the thickness, can be detected. Hardness may also be measured from the cross-section and by means of minimum hardness (red line); the neutral axis has been located in different cases [Kesti et al. 2014 & 2015]. The neutral axis refers to the line which represents zero deformation. By means of the neutral axis the so called k-factor, which is utilized in the design of products which are manufactured by bending, is defined. If the k-factor is known, material loss and the demand for after-treatment are reduced.

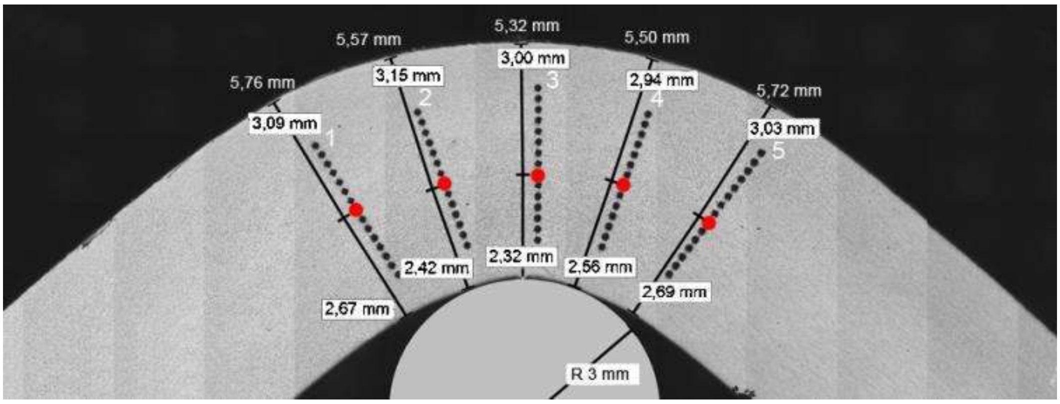

Figure 7. Microscopic image of the cross-section of the bend. The neutral axis is marked by red points based on the hardness measurements

Bending a steel plate by means of a hydraulic press needs a force with a magnitude that depends on the strength and dimensions of the material being bent, as well as the dimensions of the tools being used. When bending tests are carried out, the force is usually measured. On the basis of the measurements, models for the prediction of force have also been developed [Ruoppa et al. 2014] which may be utilized in planning product manufacturing. As the strength and thickness of the steels being tested are increasing all the time, the demand for stronger machines has been rising. Beside the regular 220-ton press brake which has been in use, an idea for a new “ultimate bending machine” was proposed [Toppila et al. 2011] and it was built as well.

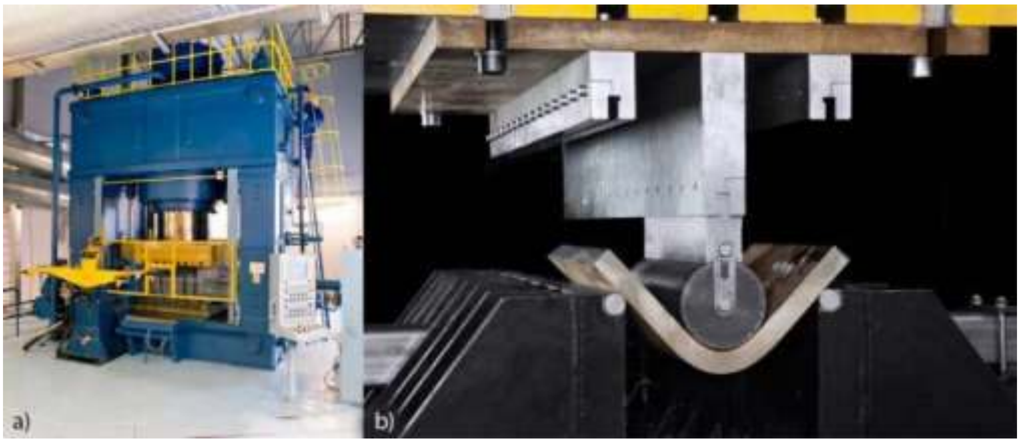

Figure 8. a) Hydroforming machine and b) bending tools built in the machine

Figure 8a shows a hydroforming machine which is located on Tornio campus. The maximum force of the main cylinder is 3000 tons, which is adequate for heavy-duty bending. Using the machine for bending tests was planned in cooperation with SSAB and the special tools shown in Figure 8b were designed and constructed. From now on it will be possible to bend even 60-mm-thick UHS steel plates and the tests have already been started. The results have been encouraging and the research will be continued.

WELDING

The cooperation between Ruukki and Kemi-Tornio University of Applied Science (currently SSAB and Lapland University of Applied Sciences) within welding research has lasted for several years. The first research projects were focused on different cutting methods, welding wires, UHS and welding, and the repair welding of wear-resistant steels. Advanced techniques were used for the investigation of the quality and mechanical properties of the welds.

In the majority of the welding tests, the SFS-EN ISO 15614-1 standard is applied. This standard “Specification and qualification of welding procedures for metallic materials. Welding procedure test. Part 1: Arc and gas welding of steels and arc welding of nickel and nickel alloys” includes all the tests which are necessary for ascertaining the quality and mechanical properties of the welds. The most common investigation cases reported are pWPS (Preliminary Welding Procedure Specification) but in some cases an official qualification to WPS (Welding Procedure Specification) has also been carried out. In order to ensure the reliability of the test results, the ASM (Arctic Steel and Mining) R&D group follows the SFS-EN ISO/IEC 17025 laboratory standard “General requirements for the competence of testing and calibration laboratories”. Some of the investigation techniques being that are used are shown in Figure 9.

Figure 9. Tensile test, impact test, and hardness test

Lapland University of Applied Sciences has also worked in cooperation with the Czech Technical University in Prague. The first research project was focused on the use and evaluation of advanced techniques for the investigation of the behaviour of high-strength steel. The techniques presented included optical strain measurement in tensile tests, a crack propagation study, and the idea of using a hydroforming machine for bending tests. Welded connections of common-grade steels have been investigated and verified for several years; detailed rules for both the welding technology process and structural engineering design are therefore clearly given in design standards and other prescriptions. On the other hand, new or improved steel processing techniques allow structural steel grades with a tensile strength exceeding 1300 MPa to be produced. The main reason why new high-strength steels cannot be used in the engineering praxis is a lack of knowledge about the behaviour of such steels in structures. These characteristics are controlled not only by the mechanical properties of the base material but also with regard to the technological process and its procedures and quantities, such as, for instance, heat input, grade, the diameter and type of welding consumable used, the welding method, number of passes (single or multilayer welds), preheating level, cooling rate, geometry of the weld, and others. [Sefcikova et al. 2015].

The research into Arctic welding has been developed within the TEKES project WELDARC 2015-2017 *(Improvement of productivity and quality of welding on special steels in Arctic conditions).* The aim of this project is to reach a new level of know-how related to Arctic welding and to develop collaboration between steel producers and, downstream enterprises in Lapland as well as research and educational institutes. The eco-efficiency of the welding of ultra-high-strength and wear-resistant steels is developed; the occupational safety of operations is enhanced by developing more precise control for those steels that are susceptible to cold cracking; the monitoring of the conditions of the welding is built up (Figure 10); the enterprise networking and problem-solving capability for the Arctic welding are improved; these are a few examples of the practical applications developed from the project results [Keltamäki 2016].

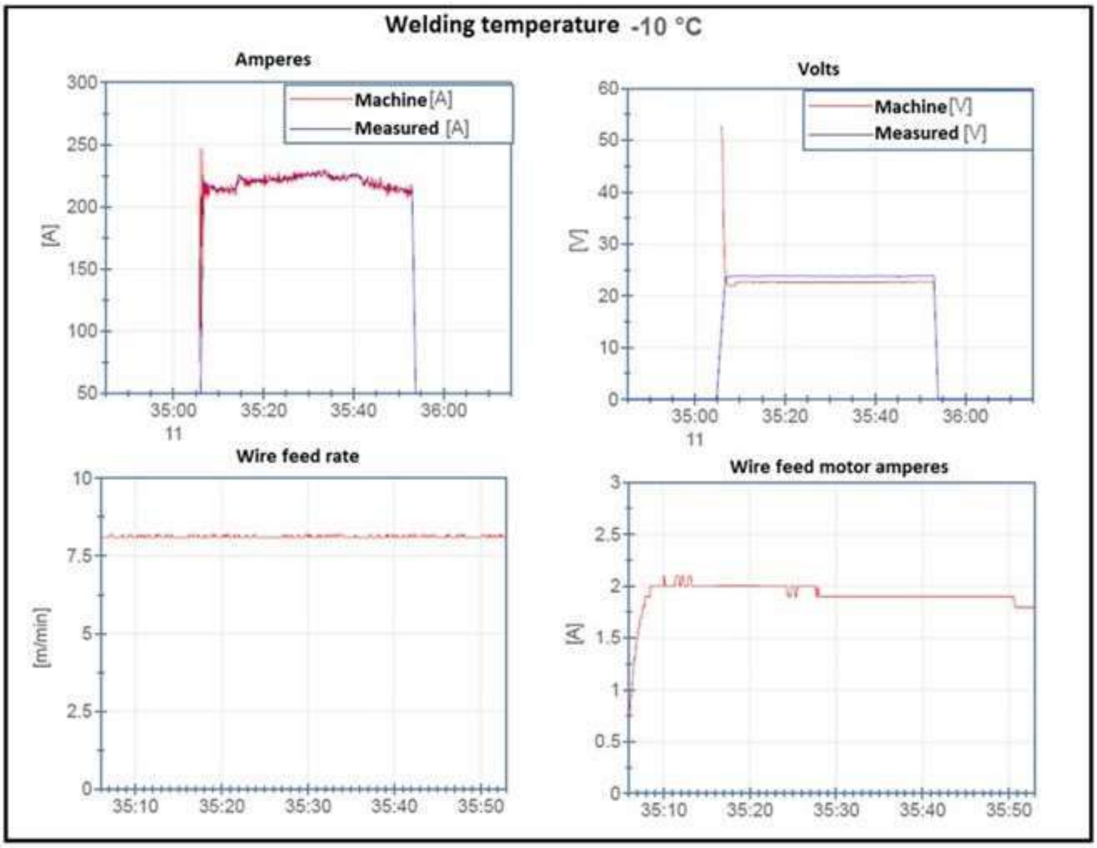

Figure 10. Monitoring of welding conditions (Rovaniemi Arctic Power laboratory)

WEARING

Wearing has also been under research for several years at Lapland University of Applied Sciences. The best places to evaluate wearing conditions are in mines. Finnish mines such as Kittilä, Sodankylä, and Kemi have many targets for wearing research. The Outokumpu Kemi mine, being the nearest one to the ASM R&D group, is the most commonly used one, and conditions in that mine are also the hardest when considering wearing. Therefore it is possible to compare real-life and laboratory tests. Many application-oriented laboratory wear test devices for such purposes have been developed by the Tampere Wear Center located in southern Finland.

Field tests of the cutting edge of a loading machine and the wear plates of a feed hopper were carried out with the aim of evaluating the application-oriented test methods and to get more detailed information for the numerical modelling of the wear. The plates were constructed using the special wear-resistant steels Raex and Hardox. The wearing of the side plates was measured with the ATOS optical measurement system from GOM GMBH at Lapland University of Applied Sciences. The plates were measured by ATOS before assembly and after wearing. Some ATOS measurements are shown in Figures 11 and 12. The weights of the plates were also measured before and after wearing and so it was possible to report the total material loss exactly. Hardness tests and microscopic analysis are also included in the normal procedure.

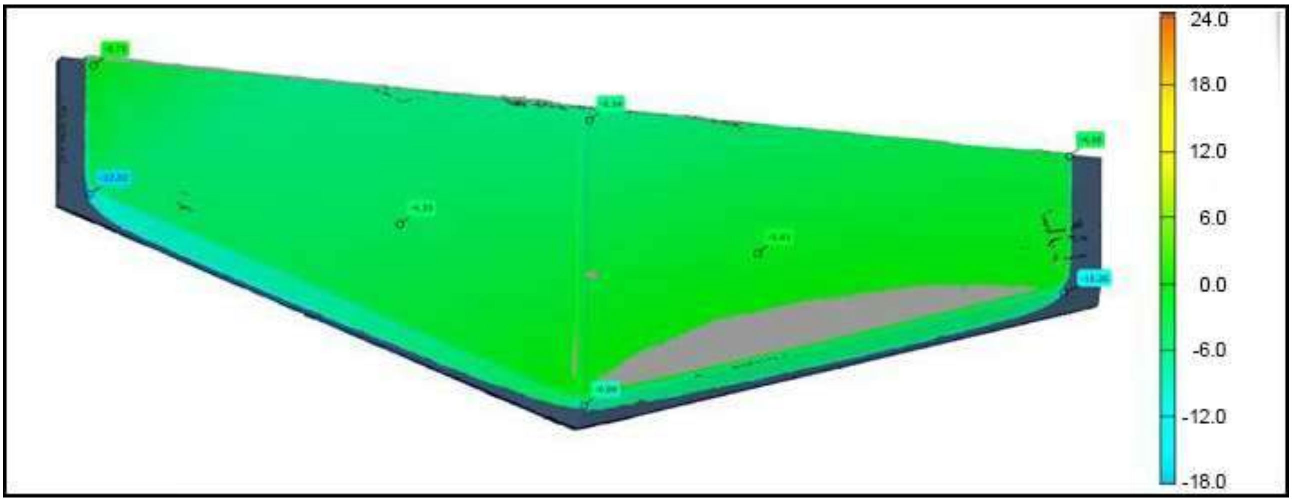

Figure 11. Wearing of cutting edge

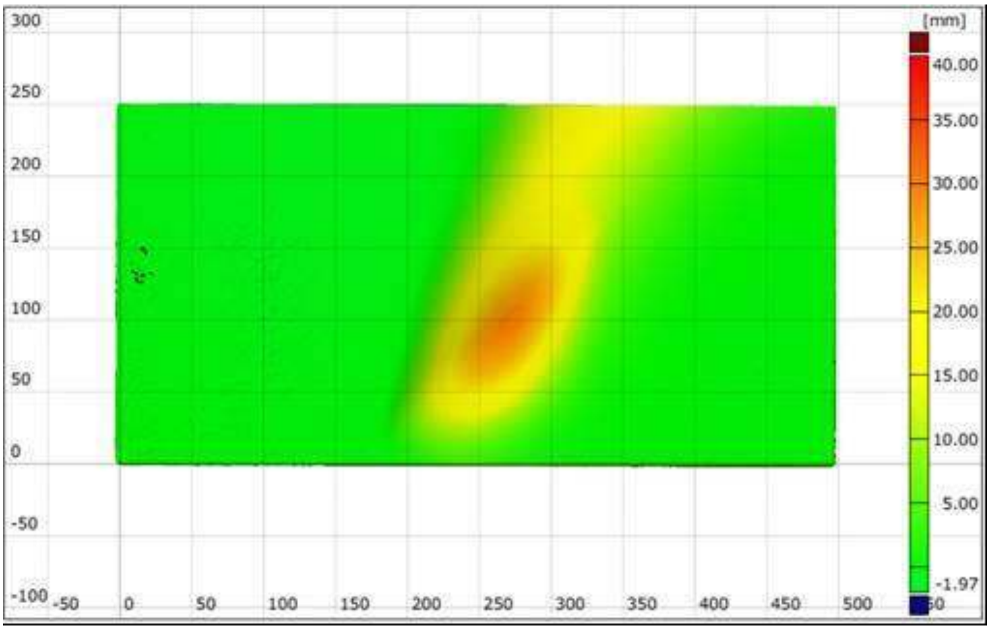

Figure 12. Wearing of side plate

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