Understanding of the microscopic stress states in ultra-high strength steel

Material failure and induced fractures are the limiting factors in the usage of high-performance stainless steels in many commercial and industrial applications. Especially in ultra-high strength steel (UHSS). What causes this failure? Mechanisms such as Hydrogen embrittlement (HE) lead to these material failures in UHSS. One prerequisite for HE is residual stresses. These stresses are often introduced to the UHSS by machining processes, for example cutting. The understanding of the microscopic stress states at cutting edges are extremely important reduce the stresses and to optimize the machining procedures to, at the end, widely use UHSS in industrial applications.

THE CHALLENGE

The investigation and optimization of internal stresses introduced during the cutting process is extremely important to enable the wide usage of UHSS in vast industrial applications. Direct measurements of residual stresses on the microscale, indicating how the cutting processes introduces internal stresses in the material, opens new ways for optimizing materials and cutting processes. Sensitivity towards HE caused by high edge stress may limit the use in this field.

With the realization of high energy X-ray sources, with high penetration power and a small probe beams at modern synchrotron radiation facilities opens the path to analyze the residual stresses at the micrometer scale. In this work, a consortium consisting of the Swedish steel company SSAB Europe AB and Swerim AB conducted high resolution X-ray diffraction measurements (XRD) at the Swedish Materials Science Beamline P21 at PETRA III on the DESY campus in Hamburg, Germany.

METHOD

In this work X-ray diffraction measurements (XRD) were conducted at beamline P21 at PETRA III to map the residual stresses with a resolution in the micrometer scale. This has been done to be able to localize regions of stress concentration that have been introduced via cut operations of the UHSS. As seen in the stress maps shearing will introduce concentrations of tensile stress. Tensile stress gradients mediate hydrogen diffusion leading to an enhanced penetration to critical areas in the material while compressive stresses hinder the hydrogen to diffuse, indicating the importance to in detail map the introduced stress states. Milling of the sheared edges removes the strain and stress patterns seen from the sheared surfaces. At the uppermost surface compressive stress is induced. A laser cut sample, which also has been studied and which has not been processed mechanically, shows a stress profile that instead is induced thermally.

The Material used in this study was a commercial steel of grade with trade name Docol. It was provided by the projects industrial partner SSAB in Borlänge, Sweden. The studied material is used in the automotive industry and is fully martensitic with a minimum tensile strength of 1200 MPa. The material was cut using three different methods; shearing, shearing followed by milling, and by using a CO_2 laser. The material was cut with a power shearing device using recommended cutting parameters. The milling after shearing and laser cutting methods serve as methods to relieve stress in the cut region of the samples. Thin cross sections of the UHSS perpendicular to the cut edges were prepared, and the measurements were made in transmission mode at beamline P21 at PETRA III (see Figure 1). In Figure 2 and Figure 3 the sheared cut edge and the blank and fraction zone of a UHSS sample are shown.

SOLUTION

For mapping of the residual stresses, a 30 µm beam was scanned over the sample and a diffraction pattern was collected every 50 µm. Residual macro stresses (or type I stresses) were evaluated by examining the peak shift at the north and east direction of the detected Debye-Scherrer rings. With that the residual stresses have been studied with impressive resolution. Figure 4 shows the shows the 2-d stress maps for the differently treated samples. The dangerous localized tensile stresses were only found in the sheared samples. These stresses could serve as driving force for crack propagation during HE. Subsequent milling was found to introduce compressive stresses in the immediate surface and therefore reduce the sensitivity for HE.

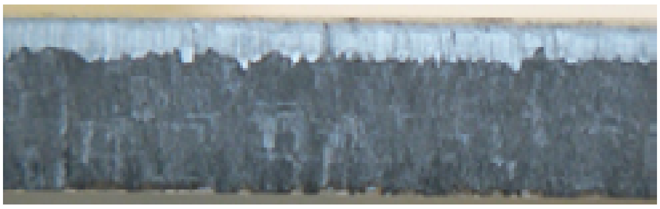

Figure 2 | Light optical microscope image of a sheared cut edge. The bright area is the blank zone. The dark area is the fracture zone

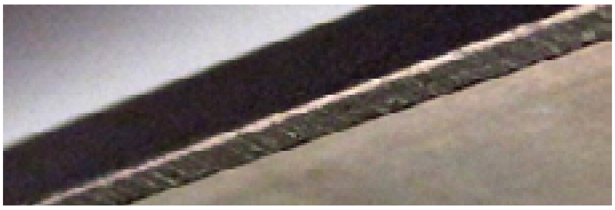

Figure 3 | Photograph of a sheared cut edge of a UHSS sample

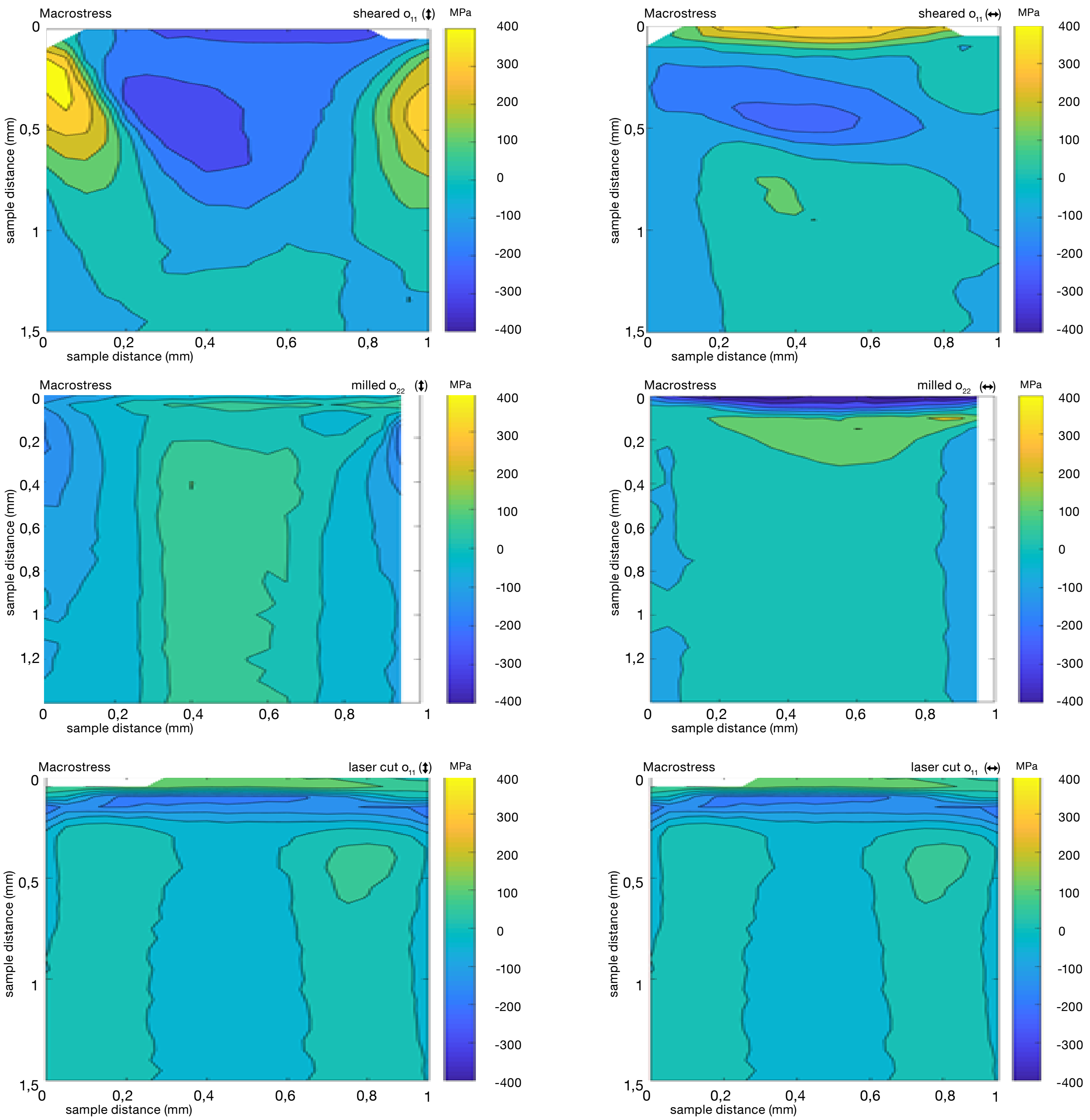

Figure 4 | This figure shows the stress value 2-d maps calculated from the strain values. The Images a and b are from the sheared material, c and d from the sample that were milled after shearing and e and f the laser cut edges. The map color range is shown in MPa.

BENEFITS

Residual stress measurements of cut edges of ultra-high strength steel using synchrotron radiation provides a method to map mechanically and thermally induced stress states at high resolution. This study shows how the methods shearing, milling after shearing and laser cutting introduce stress to the materials. Hence it can be used to refine the cutting processes to avoid high stress locations and gradients that could be detrimental for example in situations where hydrogen embrittlement is a risk. This at the end will help to optimize the machining processes of UHSS and will enhance the usage of UHSS in structural components of automotive applications.

> This unique XRD method can explain why certain cutting methods should be avoided for processing of UHSS in order to reduce high local tensile stresses and improve HE resistance. It will be a valuable tool for modifications of materials and cutting processes.
>
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