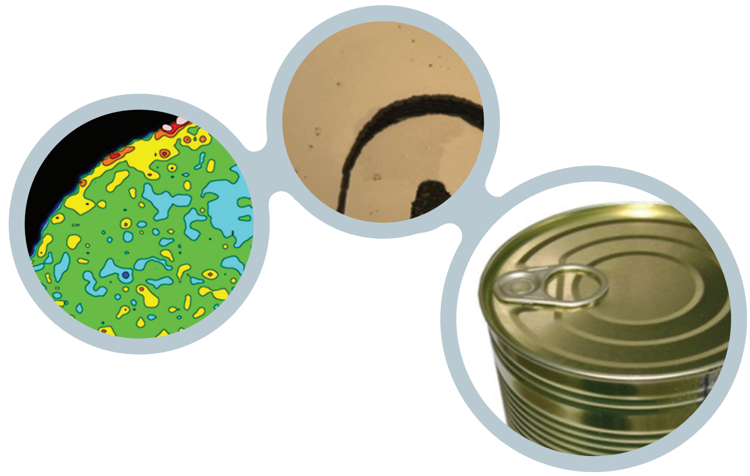

Application Note #1517

# Local Work Hardening of Steel

In metal production, the mechanical properties of wrought material are well controlled during manufacturing but may be altered by subsequent forming into the final product. Welding or joining, as well as deep drawing, causes local changes of materials properties. In the present example, a can has been seamed by folding metal sheets. The local work hardening of the bent metal in the folded areas is of specific interest. Nanoindentation is an ideal method for mapping mechanical property changes and getting work hardening information with micrometer resolution. Moreover, stress-strain behavior can be determined locally using a spherical indenter combined with a CMX load function. These highly localized stress-strain curves can then be compared to bulk tensile testing stress-strain curves.

## Hardness Mapping

The can was mounted and cross-sectioned using conventional metallography techniques. A highly bent location on the sample's cross-section was chosen for nanoindentation testing. In the fold, the inside of the sheet is deformed in compression while the outside of the sheet is deformed in tension—the center of the sheet is neutral. A hardness map was generated from load-controlled indentation tests with a Berkovich indenter to a maximum load of 5 mN, which resulted in penetration depth around 200 nm. The distance between the indents was 6 µm, which was sufficient to prevent the indentation plastic zones from overlapping. The hardness map in Figure 1 shows the hardness is much higher on the inside and outside of the folded sheet in comparison to the center. This corresponds to the expected amount of work hardening induced during the forming process.

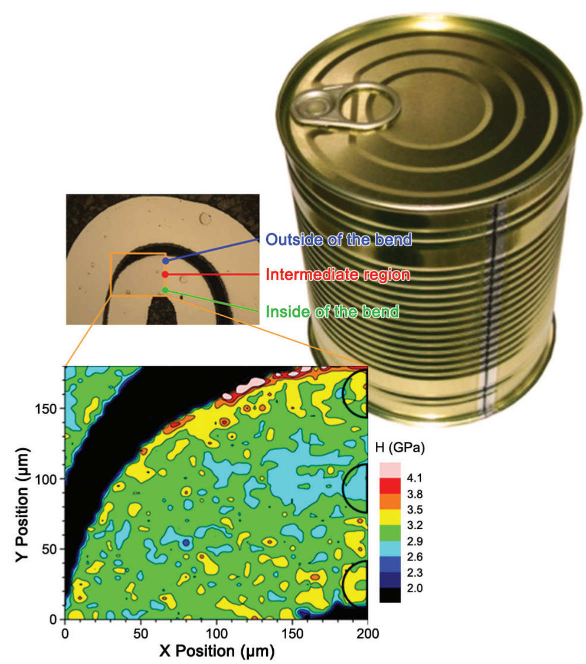


Figure 1. Micrograph of the cross-section of the folded metal in the seamed part of a can. The hardness mapping reveals a low hardness in the intermediate region while the metal sheet is work hardened on the inside and the outside of the fold.

## Stress-Strain Relationship

The stress-strain relationship in materials can be locally investigated using indentation testing. A spherical indenter allows the stressed material to be probed at different strains within a single indentation experiment. By calibrating the indenter area function of the 2 µm radius spherical indenter on fused quartz, the CMX load function can continuously monitor the stiffness, and by extension, the contact area. The representative strain, $\varepsilon$, of a spherical indenter is defined by the angle, ß, between the indenter surface and the sample surface. The stress is given by the hardness measurement that is continuously monitored by CMX starting from a penetration depth of 2 nm. Using the Tabor relationship, $H$[kg/mm$^2$]$\simeq C \cdot \sigma_{\varepsilon}$[MPa], the hardness can be correlated to an equivalent uniaxial stress, σ; $C$=3 [1]. $C$ is the plastic constraint factor that relates the hardness measurement to the tensile stress; the hardness can also be understood as the mean pressure under the indenter.

The resulting stress-strain relationship is shown in Figure 3. The stress-strain curve shows the elastic loading of the surface. A Young´s modulus of 220 GPa was determined from analysis of the slope. A yield stress of 95 MPa was also found for the material, which falls into the range of literature values for mild steel. Comparing the stress-strain plots of two locations, the effect of local work hardening is found to correspond to an increased yield stress. This finding is in good agreement with the hardness map. The hardness experiments are performed with Berkovich indenters at a representative strain of 8%, and show the same trend. There has been experimental evidence that the Tabor method of representing stress and strain during an indentation experiment is suitable for several metallic samples [2,3,4]. The correlation between hardness mapping and stress-strain conversion based upon CMX measurements indicates that these techniques are highly complementary for understanding local work hardening during metal shaping processes.

## Conclusions

Using the Hysitron® nanoDMA® III option with CMX testing, it is possible to monitor the representative stress and strain during an indentation experiment. Small spherical indenters only need a small material volume for testing, which results in a high-spatial resolution and the ability to test very thin films. Bruker´s highly symmetric spherical tips combined with its ultra-sensitive transducer technology allows the experiments to begin in the elastic loading regime, such that the onset of yield can be observed.

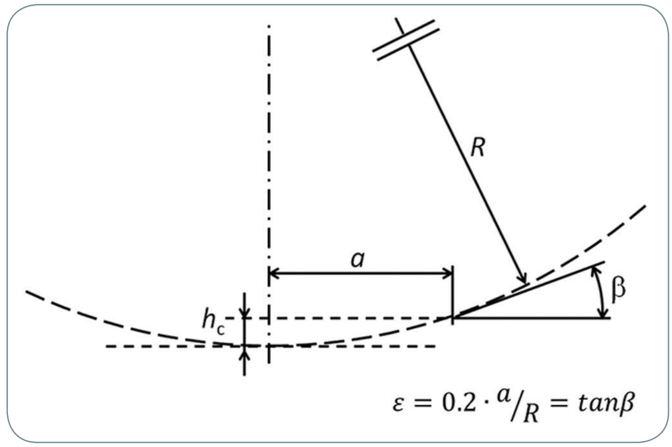


Figure 2. Geometry of the contact between the tip (dotted circle) and sample (horizontal line) showing the contact radius ($a$), tip radius ($R$), and contact depth ($h_c$). The angle (ß), between the sample and the indenter defines the representative strain (ε).

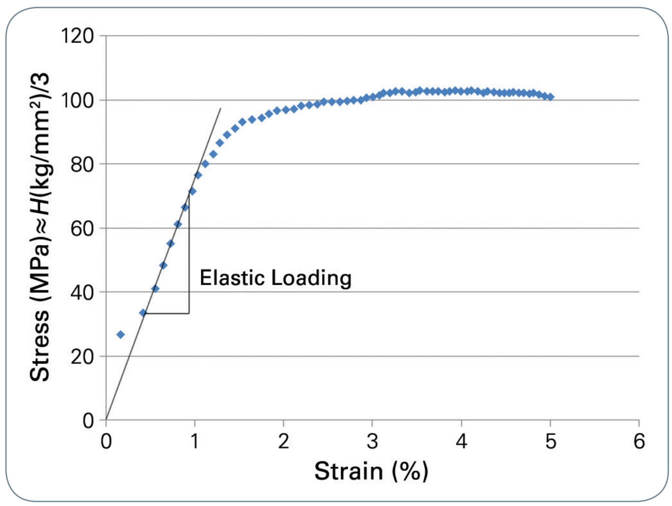


Figure 3. Stress-strain curve derived from a spherical indentation into steel with a CMX load function.

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