Contribution of nanoindentation and tribology to investigation of welds

Relevant for: Indentation testing, Tribology, Metallurgy, Metals, Welding

The quality of welds depends on the materials used and welding parameters. To help optimizing the welding process, it is necessary to perform very local mechanical characterization of the weld. Nanoindentation and tribology are useful tools for analyzing the effects of the welding process on hardness, elastic-plastic properties and wear resistance.

1 Introduction

Welding is an important metallurgical process used to join two or more components together, usually for the creation of more complex structures that cannot be molded directly (tubular frames or structures), for attaching functional parts to a larger component (hinges, etc.) or for surface protection. The most commonly welded materials are metals and thermoplastics [1]. There are many welding processes with the most widely used being arc and gas welding. Other methods such as friction stir welding, electron/laser beam welding or ultrasonic welding exist and are employed in cases of welding special materials or in special environments [2]. During welding, two parts are heated or melted at the joining surfaces and fused together using a filler material. Crucial process parameters for arc welding are arc voltage, passing current, welding speed, weld geometry, shield gas composition, and electrode feed speed. These parameters determine the extent of the thermally affected material around the weld, the so-called “heat affected zone” (HAZ). The HAZ is a part of material close to the weld that has been heated during the welding process below the melting point but high enough to undergo microstructural changes. These changes can lead to changes in mechanical properties such as increased hardness and decreased yield strength. Due to the microstructural changes the HAZ is more prone to cracking and corroding and therefore the HAZ usually acts as the weakest structural point of the component. Therefore, it is crucial to understand and minimize the undesired thermal effects of welding. The typical dimensions of the weld and the HAZ are hundreds of micrometers up to several millimeters. To study the local changes due to the welding process, the methods of instrumented indentation are preferred because they offer suitable spatial resolution. For example, the Anton Paar Micro Combi Tester (MCT^3) or Nano Hardness tester (NHT^3) can measure hardness and elastic modulus or local indentation stress-strain characteristics in different areas of the weld or HAZ. To study the causes of weld cracking, measurements of representative stress-strain curves around the crack tip can be performed. For cases when the weld is in frictional contact with another component or the environment, its tribological and wear properties are also important. The wear and friction properties can easily by measured by a tribometer which measures the coefficient of friction and can be used for wear rate estimation [3].

In this application report we will show several examples of local mechanical characterization of welds and their neighboring areas. We will mention the measurement methods and their benefits for the welding processes.

2 Examples of applications

2.1 Hardness profile across a weld

The first example shows an indentation line profile in the HAZ of an arc welded spheroidal cast iron measured with the Micro Combi Tester (MCT^3). Indentation testing was performed at two positions: on the cross-section of the weld area and on the top surface of the weld. Maximum load 5 N, loading and unloading rate 30 N/min with 1 second pause at the maximum load were used. The line of indentations was done from the unaffected base material through the HAZ to the weld core; the individual indentations were spaced by 0.25 mm. The positioning of the indentations and the corresponding hardness profile along the line of indentations is shown in Figure 1. The results clearly demonstrate the evolution of hardness in the weld proximity. Close to the weld – in the HAZ – the hardness significantly increased before it decreased in the transition zone and stabilized at ~3 GPa in the non-affected base material far from the weld. Similar results were found on the top surface of the weld (increase of hardness in the transition and in the heat affected zone) which confirmed the results obtained on the cross-section.

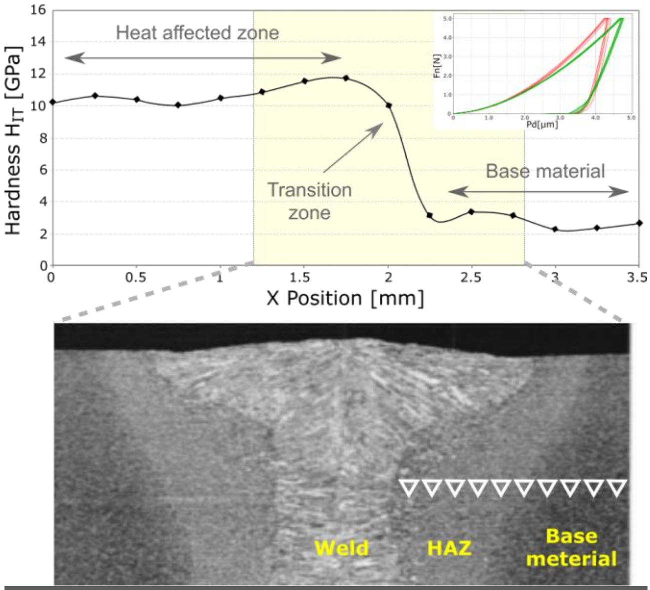

Figure 1 - Cross-section of the heat affected zone and the corresponding hardness profile. Measurements were done with the MCT[3].

This example shows the typical application of how instrumented indentation can contribute to measurement of the influence of welding on the material's properties in the HAZ. Using a hardness line profile allows researchers to estimate the size of the HAZ which can help to optimize the welding parameters.

2.2 Local stress-strain properties by spherical indentation

The recent interest in understanding local elastic-plastic properties led to the development of a new technique using spherical indentation for stress-strain characterization [4]. Indentations using oscillations during loading allow for the determination of representative stress-strain curves of the tested material very locally. Simple stress-strain analysis is implemented in the Anton Paar Indentation software. This method can be applied namely for local characterization of different regions in the weld and in its vicinity. The following sections will show several examples of this method.

2.3 Elastic-plastic behavior near the crack tip in weld

In the first example, nanoindentation was used to obtain the stress-strain properties near to and far from a crack tip in a low alloyed steel weld. The weld fracture is usually triggered by thermal stresses originating from the rapid solidification of the weld during the welding process or by the modification of the microstructure leading to increased hardness and yield strength but decreased resistance to fracture. Since the stress-strain properties have to be determined very locally, nanoindentation is one of the few methods which can provide this information. The goal of the local stress-strain measurement was to help in understanding the causes of weld cracking.

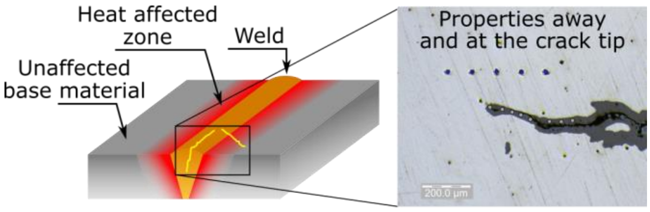

Figure 2 - Indentations near and away from the weld crack tip.

Two samples with weld cracks were measured using the NHT[3] with 20 µm radius spherical indenter, maximum load of 500 mN and a loading rate of 1000 mN/min. To obtain representative stress-strain curves, load oscillations were superimposed on the loading portion of the indentation curve (so-called Sinus during loading method). The amplitude of the oscillations was 50 mN and the frequency 5 Hz.

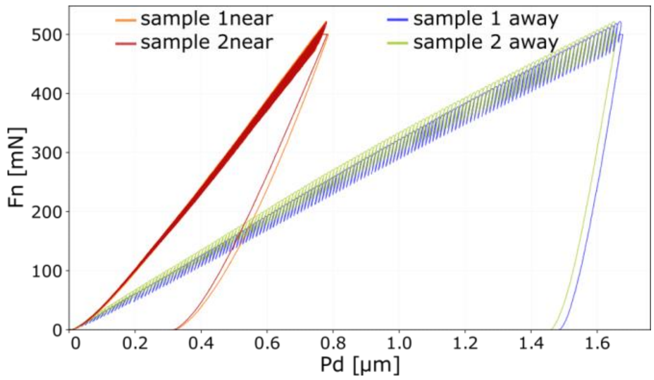

Figure 3 - Sinus during loading indentation force-displacement curves in two areas – near and away from a crack tip.

Figure 3 and Figure 4 show Sinus indentation curves and the representative stress-strain curves obtained from the indentations in both areas. Obviously, the yield strength was much higher in the area near the crack tip than far from the crack tip. Increase of the yield strength is usually associated with a decrease in ductility which can have important consequences on the fracture resistance of the weld. Under externally applied load, the material close to the crack tip – which has increased yield strength – tends to fracture earlier than the base material and therefore acts as a weak point in the whole structure. A fracture in the weld results in failure of the component. The welding parameters should therefore be adapted so that the material near the crack tip has lower yield stress and higher resistance to fracture.

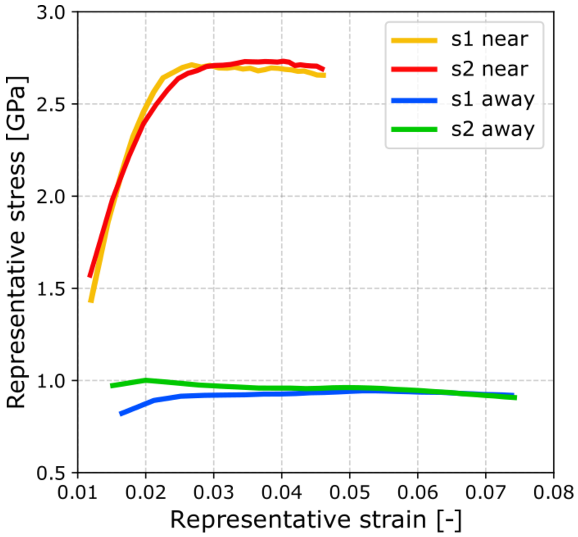

Figure 4 - Representative stress-strain curves obtained from the Sinus during loading indentation measurements near the crack tip and away from the crack tip.

2.4 Stress-strain properties in welded Al alloys

Another typical application of stress-strain analysis by nanoindentation is an investigation of elastic-plastic properties around welds in metals, especially in soft metals such as aluminum alloys. Aluminum alloys are more sensitive to elevated temperatures than steel and as a consequence thermal effects from welding can be more important. In this case study we used spherical nanoindentation with Sinus during loading for local characterization of elastic-plastic properties near the weld of two aluminum alloys. Spherical indentation was used to determine the stress-strain characteristics close to the weld (area A) and about 2 mm away from the weld (area B).

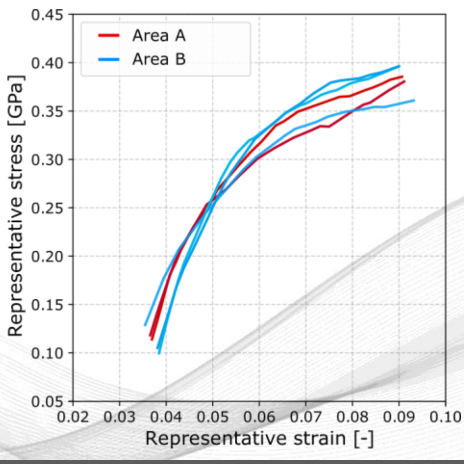

Figure 5 - Comparison of stress-strain behavior in near proximity (A) and 2 mm away from the weld (B).

The measurements were done using the NHT[3] with 20 µm radius spherical indenter, Sinus mode during loading with maximum load 300 mN, loading rate 600 mN/min, and frequency 5 Hz. Figure 5 shows the comparison of the representative stress-strain curves for area A and area B.

Results from both areas show similar elastic-plastic behavior with yield stress ~0.3 GPa. This shows that the influence of heating and cooling during the welding process has negligible effect on the elastic-plastic properties of the materials. However, this is not necessarily true in all cases and the local stress-strain properties in the weld area remain an important information for optimization of the welding parameters.

2.5 Stress-strain in friction stir welded Al-alloys

Friction stir welding (FSW) is often a better choice for welding of aluminum alloys than conventional arc welding which creates large HAZ due to the high thermal conductivity of aluminum. The welding temperature in FSW is well below the meting point and the thermal effects are therefore less pronounced than in arc welding. In this case two aluminum alloys AA6111-T4 (T4) and AA6061-T6 (T6) were welded together and hardness, elastic modulus, and yield stress were studied at a distance of 1.1 mm, 2.2 mm, and 3.3 mm from the weld nugget. The following parameters were used for the indentations: maximum load 300 mN, loading rate 600 mN/min, Sinus amplitude 30 mN and frequency 5 Hz respectively.

Results in Figure 6 show only minor differences in the stress-strain behavior with the increasing distance from the weld nugget. The yield stress was ~0.33 GPa in all three regions (~0.27 GPa in both base materials, not shown in the figure). The hardness of the base material was 0.8 GPa (T4 alloy) and 1.1 GPa (T6 alloy). The hardness in all three regions (1.1 mm, 2.2 mm and 3.3 mm from the weld nugget) was 1.1 GPa which confirms that the elastic-plastic properties near the weld did not change significantly.

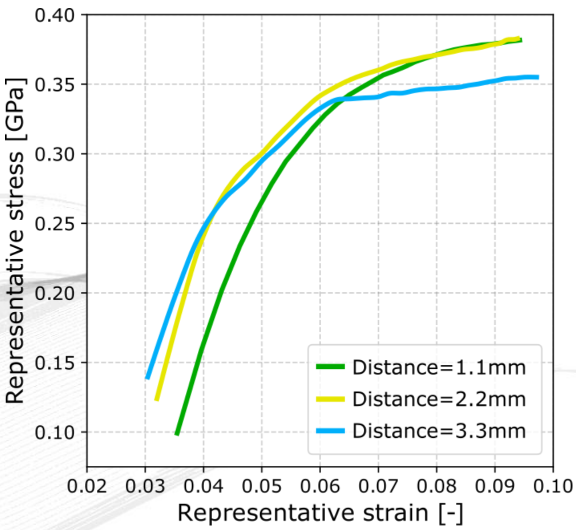

Figure 6 - Representative stress-strain curves at three distances from the weld nugget in two friction stir welded aluminum alloys.

2.6 Tribological properties of hard-facing welds

An interesting application of welding is hard-facing [5]. Hard-facing is a process of welding hard metal on top of a base metal aimed at improving the wear resistance of the base material. It is used for mill hammers, extrusion screws, high-performance bearings, and earth-moving equipment. It can also be used for valve seats and pumps in pressurized water reactors [2]. The wear and tribological properties of such hard-facing welds in frictional contact with other components are crucial for the real applications. The following example shows tribological testing performed on spheroidal cast iron on which a hard-facing layer from cast iron was welded using a plasma transferred arc process.

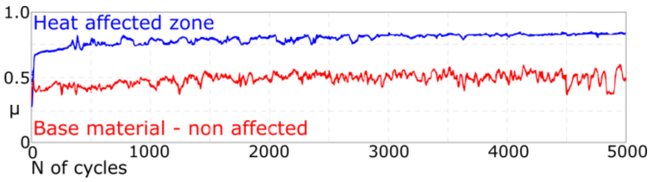

Figure 7 - Friction coefficient against N of cycles for the heat affected zone and the base material.

The thickness of the layer was ~3 mm and due to rapid solidification, the layer had a cementite microstructure with significantly higher hardness than the cast iron. There were two friction tests performed: one on the base material and one in the heat affected zone of the welded material. The tribological test in linear reciprocating mode comprised 5000 cycles with maximum speed 1.6 cm/s at 1 N load. The counterbody was a 6-mm diameter 100Cr6 steel ball.

The friction test results are shown in Figure 7: the heat affected zone (HAZ) of the welded layer exhibited higher coefficient of friction (~0.8) than the base material (~0.5).

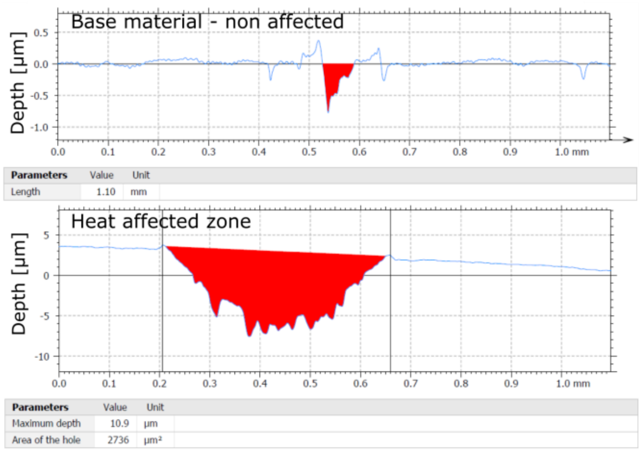

Figure 8 - Wear track profiles on the base material and in the thermally affected zone measured by surface profilometer.

A comparison of typical profiles of the wear track measured by surface profilometer (Figure 8) shows that the heat affected zone has higher wear than the base material. Since both measurements were done with the same parameters, this result shows that the wear resistance of the base material is higher than that of the thermally hardened zone. Comparison of Figure 7 and Figure 8 suggest that the friction coefficient and wear resistance in the thermally hardened zone of the welded layer were negatively influenced by the welding process – despite the increased hardness of the same layer. A solution to this problem could be either changing the welding parameters to increase the wear resistance of the thermally hardened zone or decrease its size to minimize its negative contribution to the wear resistance of the part.

3 Conclusions

This application report shows examples of the use of nanoindentation and tribology for welding applications. It illustrates how the nanoindentation technique can contribute to monitoring of hardness and local elastic-plastic properties in the weld area. These properties are crucial for high quality and structural integrity of weld and welded components. An indentation line profile of hardness across the heat affected zone or welded layer interface provides valuable information about the evolution of elastic modulus, hardness, and indicates the size of the HAZ. Dynamical indentation measurements (indentation with Sinus during loading) with a spherical indenter can help in estimation of local elastic-plastic properties such as yield stress and representative stress-strain curves in different weld areas. Finally, a linear mode tribological test together with surface profilometry were used for evaluation of the friction and wear rate of the base material and the welded layer.

4 References

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