APPLICATION NOTE

Bend failure mechanism of high-strength steel

Efficient and effective root cause analysis using the Axia ChemiSEM

Introduction

Steel is frequently employed in applications where it needs to be shaped and curved; hence, a certain degree of ductility is required to enable the bending without allowing cracks. For these type of applications, a specific type of alloy steel is used: high-strength, low-alloy (HSLA) steel. HSLA steels are characterized by lower content of carbon, chromium, nickel and molybdenum than other alloy steels like AISI 4140, where the decrease in carbon enables higher formability and weldability. For this reason, prior to being manufactured in its final shape, HSLA steel is evaluated with a bending test. The main reason is to ensure that no cracks or fractures will occur during or after the bending.

Figure 1. Bend test (top) and tested piece (bottom).

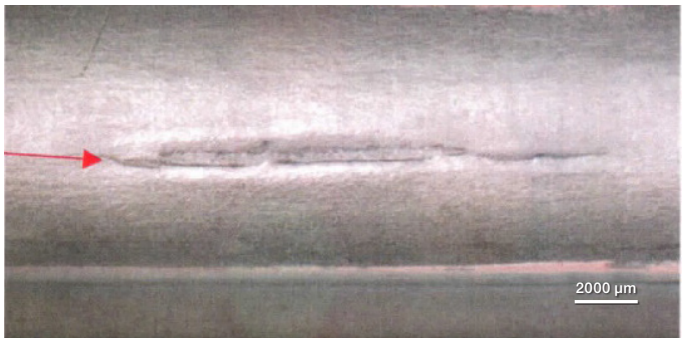

Figure 2. Image of a failed bend test.

However, in the case of any failure, it is crucial to understand the root cause. Common types of cracking include hydrogen cracks (often in weld heat affected zones), hot tears (contamination by copper or tin during solidification), and subsurface non-metallic inclusions. The latter may originate from native or endogenous steel-making inclusions or from foreign or exogenous inclusions, such as slag or refractory.

Steel production requires deoxidation to decrease the dissolved oxygen content to a very low level. Commonly, aluminum is used for this process, where the resultant oxides are micron-sized, high melting-point aluminum oxide particles.

During refining and casting, the pure aluminum oxide inclusions may become contaminated with magnesia, calcia, or slag droplets. Figure 3 shows the Ca-Al-Mg ternary diagram of oxide inclusions analyzed in the steel near the bend test defect, which has been run by a Thermo Scientific™ Phenom™ ParticleX Steel Desktop SEM thresholding the features greater than 1 µm.

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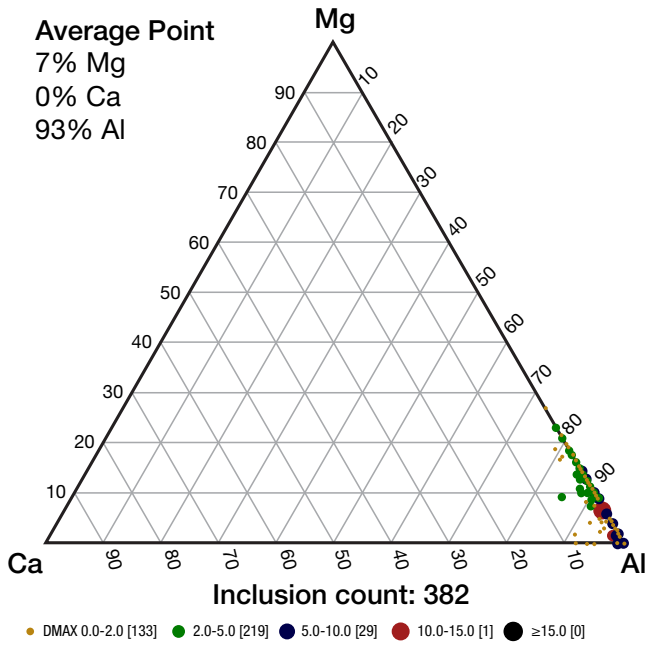

Figure 3. Base inclusion analysis was collected on this sample by the Phenom ParticleX Steel Desktop SEM.

Molten metal transfer from ladle to tundish, or from tundish to mold, often allows reoxidation to occur, where slag, refractory, or air contribute oxygen to the steel just before it is solidified in the mold. This kind of reoxidation allows more inclusions to agglomerate and become trapped in the cast product. Finally, hot rolling can cause the breakage of these large agglomerated inclusions, which are then deformed into stringers or slivers, causing the broken pieces of inclusion to spread out along the rolling direction.

Materials and methods

In this application note, a bend test failure is characterized by using a Thermo Scientific™ Axia™ ChemiSEM. In a short time to result, and with a complete set of information, the Axia ChemiSEM efficiently exposed the root cause of the failure.

The sample of interest is HSLA hot-rolled steel that failed during a bend test. Different cross sections of the fractured sample (Figure 4) were observed using an Axia ChemiSEM.

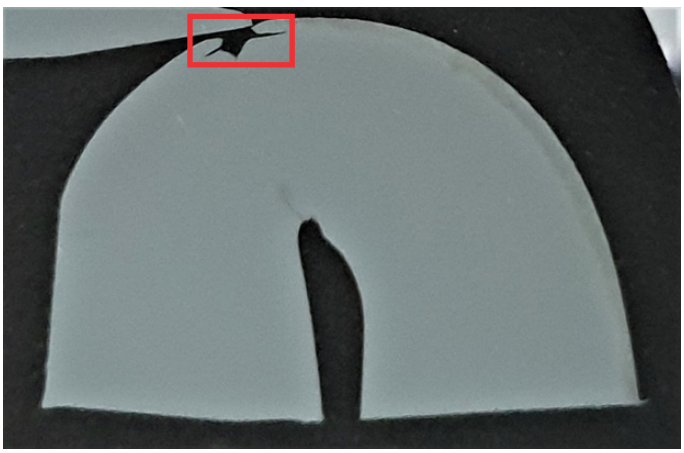

Figure 4. Cross section of a bend tested steel. The crack, propagated on the outer radius, is highlighted in red.

Results and discussion

The imaging of the area of interest and the quantitative elemental information of the investigated features were acquired at 15 kV. A moderately low beam current (0.22 nA) was used in order to reduce the beam spreading and maximize the spatial resolution. Figure 5 shows a lower magnification overview of the crack, which is also visible in the optical image in Figure 4.

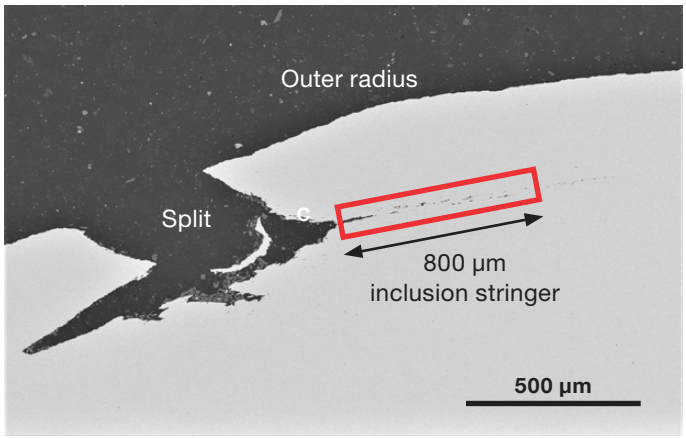

Figure 5. Backscattered electron image of the split. Highlighted area is the inclusion stringer that started at the base of the split (Acc voltage 15 keV, beam current 0.22 nA).

The split on the outer radius opens to a depth of approximately 400 microns. At the base of the split, an inclusion stringer can be observed (Figure 5, in red) extending into the metal at the same depth. To understand the nature of the inclusions within the stringer, further higher magnification images and ChemiSEM maps were acquired.

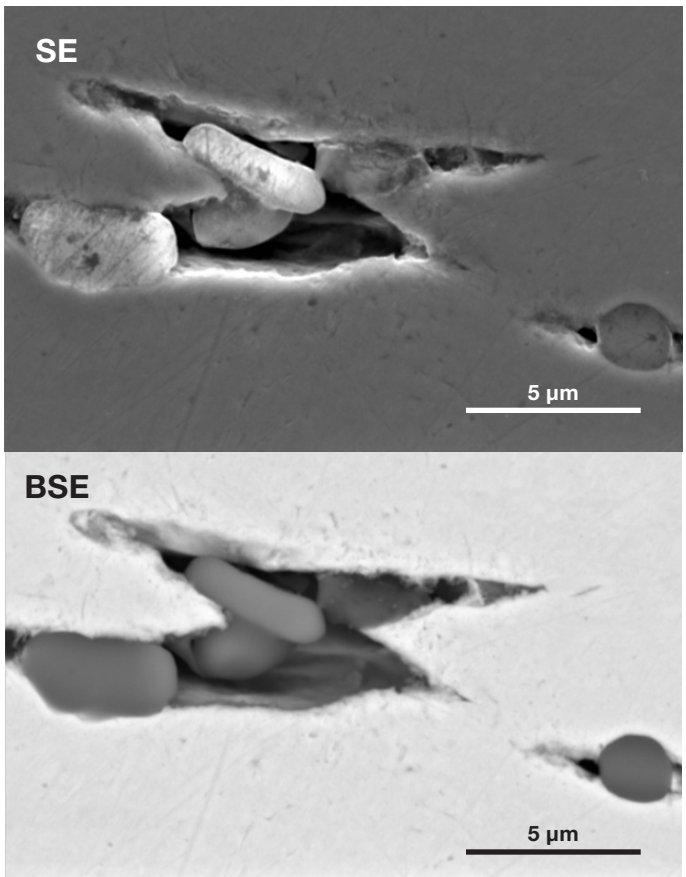

Figure 6. Higher magnification view of the inclusions in the stringer (Acc voltage 15 keV, beam current 0.22 nA, acquisition time 60 s).

Figure 6 highlights some of the inclusions present in the stringer. The top image shows the secondary electron signal, which gives topographical information and shows the presence of voids. Due to the presence of inclusions, voids are often formed during the hot rolling process as the deformed steel surrounding the foreign particles undergoes high tensile stress along the rolling direction.

The bottom image provides the backscattered electron signal, which gives compositional information based on the atomic number of the imaged material. The information gained from this image is not enough to clarify the nature of the inclusions, and the conventional approach would require the operator to switch to a different software, run traditional EDS mapping, and then spend more time post-processing the acquired EDS raw data to access to the quantitative information. However, the Axia ChemiSEM provides instant access to the quantitative elemental information, as the EDS signal collection happens during acquisition of the SEM images previously presented in Figure 6.

The compositional information is just one click away. After the acquisition of the backscattered electron image, the operator is required to turn on only the visualization of the previously acquired elemental information.

The elements have been selectively activated in order to see their distribution within the inclusions, with no overlap in the coloring. Figure 7 immediately shows non-metallic inclusions, with the left group showing a majority of aluminum and the right inclusion showing magnesium as well. 30-second area analyses on the different types of inclusions have been performed on the areas highlighted in Figure 7. The quantifications obtained from the two areas are reported in Table 1.

Element	AREA 1 Atomic %	AREA 2 Atomic %
O	61.3	59.4
Mg	—	8.4
Al	38.7	32.2

Table 1. Quantifications obtained from the areas 1 and 2 presented in **Figure 7** (Analyses condition: acc voltage 15 keV, beam current 0.22 nA, acquisition time 30 s).

The quantification and the ratio between elements suggest the inclusions in the left part of Figure 7, including area 1, are alumina, while the right inclusion is a Mg-Al oxide.

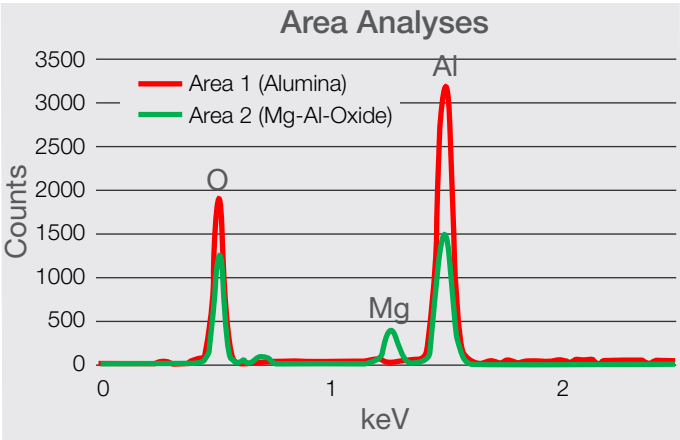

Figure 8. Spectra comparison between the two types of inclusion, showing a clear presence of magnesium (Kα at 1.253 keV).

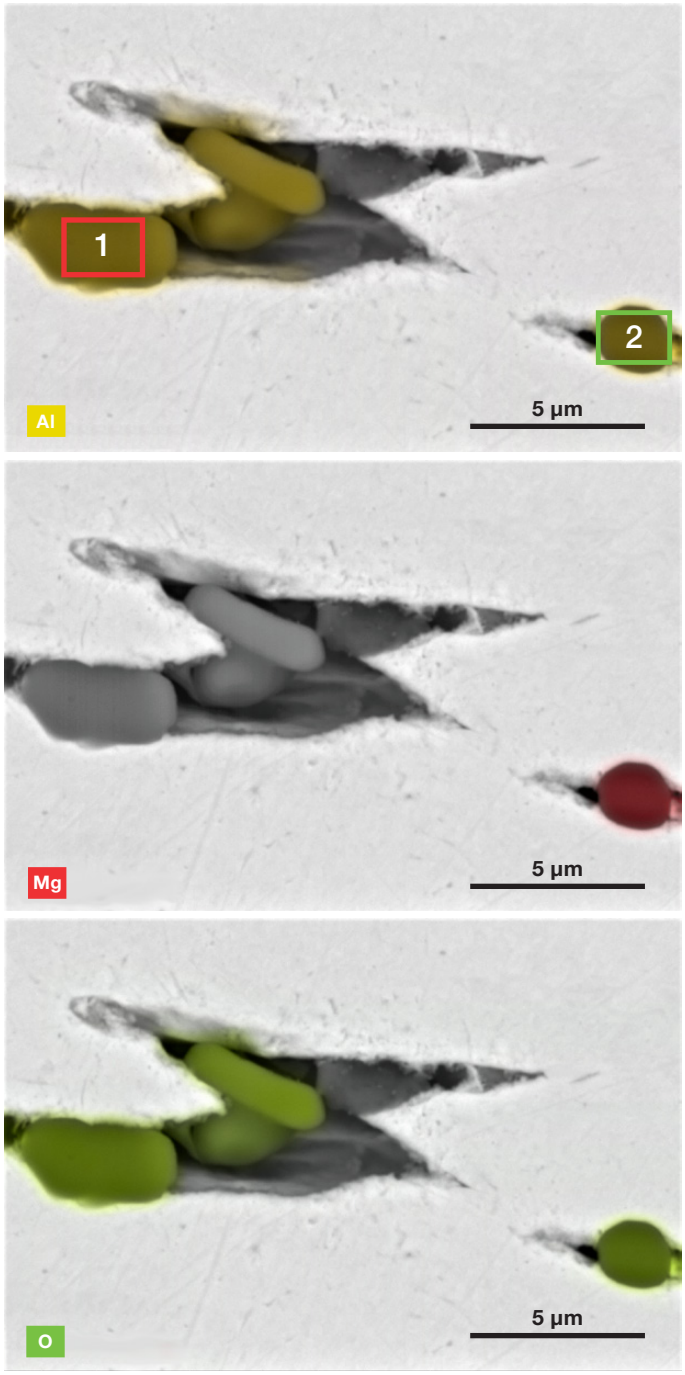

Figure 7. ChemiSEM images (showing Al, Mg, and O distribution, respectively) of the ROI in Figure 6 (Acc voltage 15 keV, beam current 0.22 nA, acquisition time 60 s).

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Conclusions

Bend testing is conducted on steel and other materials to determine ductility and resistance to fracture. When the material of interest is subjected to fractures or cracks, we can surmise that it will fail if employed in similar applications. For this reason, understanding the cause of failure is key to prevention.

In this application note, we have presented a fast and efficient method to achieve the root cause of a failed bend test on a high-strength steel.

With the new ChemiSEM Technology approach, the morphological characterization of the area of interest is no longer separated from the compositional information. The imaging session provides—at the same time—the SEM images and the quantitative elemental data that are acquired in the background during the grayscale image acquisition and then displayed for a better understanding of the elemental distribution. Native steelmaking inclusions were found as a stringer beneath the surface of the steel. The hot rolling process spread out a cluster of non-metallic inclusions into a linear defect, which caused the bend test to fail.

Steel refining is performed in a ladle where deoxidation, desulfurization and inclusion flotation may occur.

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