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Fatality During Excavator Bucket Wear Plate Removal – Technical Learnings

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By

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Fatality During Excavator Bucket Wear Plate Removal – Technical Learnings

Incident Summary

In August 2017 a fatal incident occurred at Goonyella Riverside mine during maintenance works on the underside of an excavator bucket. A worker was progressively removing large wear plates (1600mm x 2500mm) by arc air gouging them into small pieces. During gouging a large portion of the wear plate suddenly sprang away from the bucket (see Figure 1), striking and killing the worker.

The wear plate had accumulated and stored elastic energy during service. This energy is normally released incrementally as the plate and welds are progressively detached. However, extensive cracking in the welds allowed the release of a large portion of the plate in a single event.

The quantity of stored elastic energy present and the amount of effective restraint vary with use and are not easily identifiable from visual inspection alone. This article discusses the mechanism by which stored elastic energy can be generated and strategies for identifying stored energy and reducing the risk of a similar incident.

Figure 1 – Overview of plate after incident

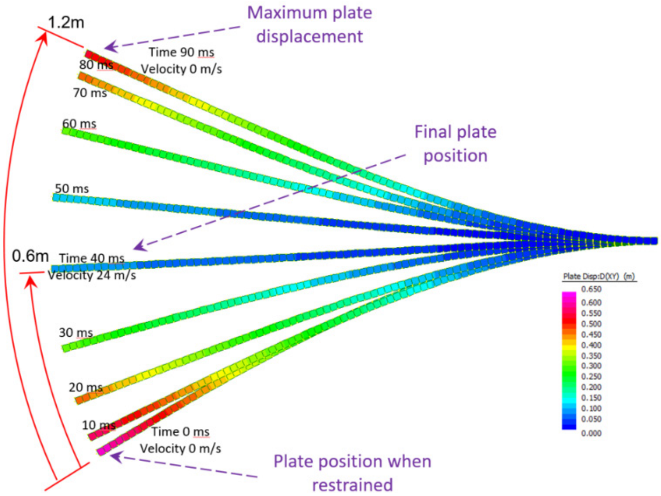

Figure 2 - Transient dynamic analysis of plate after sudden release of restraint

Severity of Hazard

The maximum spring back displacement was determined to be approximately 1.2m, before coming to rest at 0.6m from the bucket (see Figure 2). Modelling estimated that the impact experienced by the worker was approximately 4 times greater than the nominal survivable head injury criterion (HIC) of 1000. This demonstrates the severity of the hazard. Calculations predicted that the worker's head experienced an acceleration of 185 g for a duration of 10 ms, with the plate moving at 20 m/s. This equates to a HIC of 4,650, which is 2.6 times greater than the maximum survivable HIC threshold of 1800 [1, 2].

Sources of Stored Elastic Energy

Removal of material from a cold-formed plate was considered as a possible cause for accumulation of residual stress. The stress analysis indicates that this mechanism creates an imbalance in residual stresses which may contribute to spring-back in some circumstances. Modelling and analysis showed a maximum potential spring-back displacement of 240mm before coming to rest at 120mm from the bucket, which is insufficient in magnitude to explain the incident.

Dogging or forcing of a flat plate to the curve of the bucket during installation, was also considered as a possible cause. This was judged unlikely as it does not explain the transverse curvature observed. Also, the observed indentations quickly override any residual stress present prior to the indentation events.

In this incident, residual stress and spring-back potential accumulated as a result of repeated indentation from forcible contact with hard objects Figure 3. Calculations and finite element modelling showed that this phenomenon is able to explain the full spring-back displacement observed in the incident (Figure 2). It also explains the final position and shape of the incident wear plate, including the observed transverse curvature seen in Figure 1. The many dents observed on the plate are evidence that high contact load events had been experienced, each of which were sufficient to cause plastic deformation (Figure 3).

The residual stresses from indentation, combined with cyclic digging loads, were also a key factor in fatigue cracking of the welds.

Permanent Deformation During Service - Plate Indentation

Introduction

Residual stress builds up in wear plates when large forces or impacts sufficient to plastically deform the plate are applied, permanently changing the shape of the plate. This manifests as observable indentations, for example see Figure 3. It is important to note that residual stresses (i.e. stored elastic energy) only increases in-service due to permanent plastic deformation, not from elastic deformation.

Figure 3 – Dent located at the top of the incident plate (100mm radius of curvature)

Spring-Back Caused by Indentation

By permanently indenting the plate the material is stretched beyond yield. By a combination of compression and bending, the indentation permanently increases the length of the plates' inside surface.

Since the inside surface is expanded, the plate wants to curve to its new dished shape. Figure 4 shows a diagram describing how lengthening the inside surface of a plate forces the plate to form a dished shape, which pushes the edges away from the substrate.

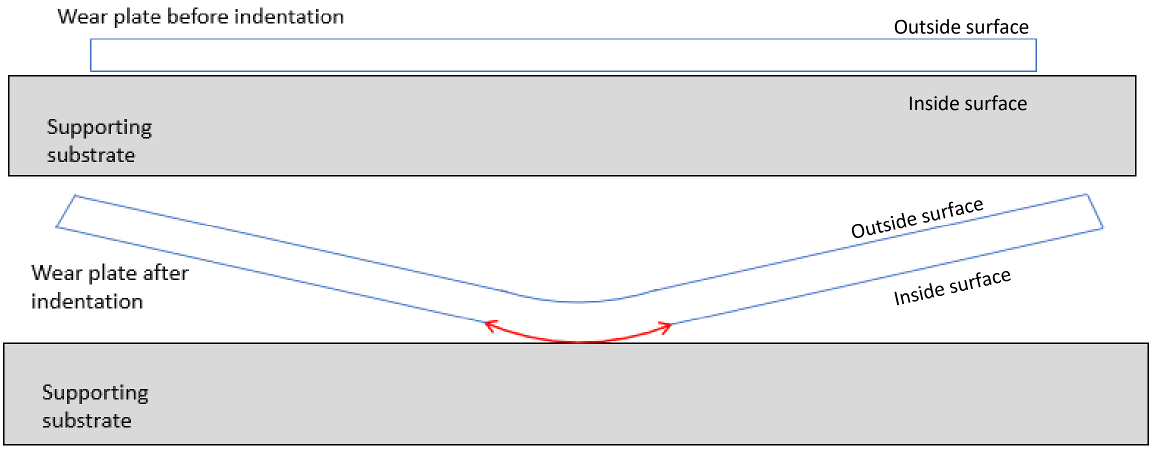

Figure 4 – Diagram of a flat plate before (top) and after indentation (bottom), describing how the inside surface of the indentation expands, forcing the plate into a dished shape.

During service, the welds constrain the plate to the shape of the bucket structure, as shown in Figure 5 top. When a weld is released (either via cracking or cutting), the plate springs into its desired shape until residual stress is once again balanced within the plate section. When only one side is released, the displacement of the released side may be up to twice the displacement of the plate when pivoted about the indentation. This displacement difference can be seen by comparing Figure 4 bottom with Figure 5 bottom.

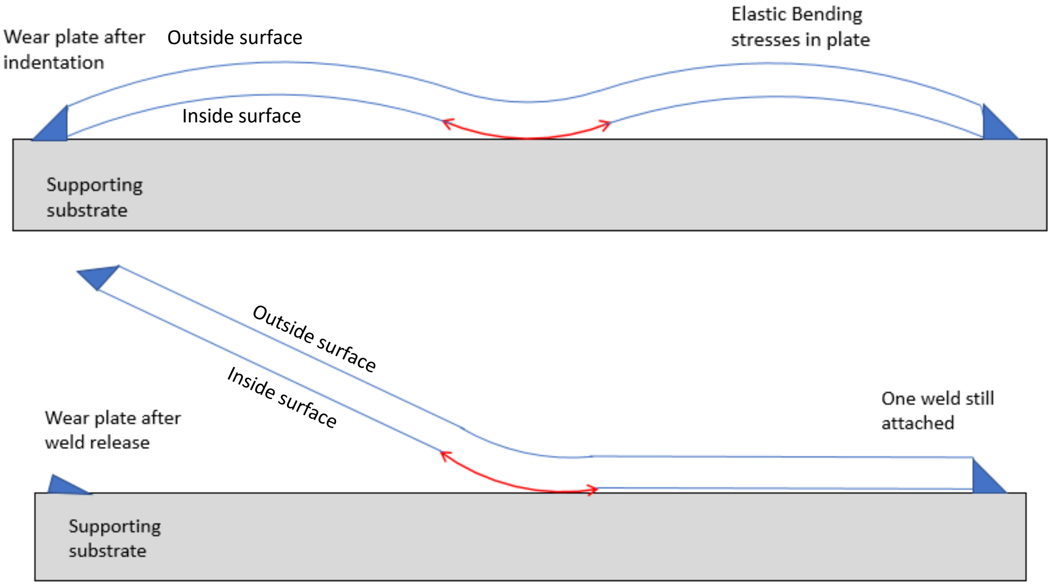

Figure 5 – Diagram of a flat plate indented while welded to a stiff supporting substrate; showing the plate while still welded to the substrate (top) and after release of a weld (bottom). See also Figure 13.

Expansion of Wear Plate due to Indentation

This section attempts to describe how the inside surface of the plate expands due to indentation. Consider a section through the wear plate and bucket structure as shown in Figure 7. When a hard object applies a large force to a small area of the plate surface, a small volume of the wear plate becomes compressed (or crushed) between the indenter and the supporting plate ("compressed volume" in Figure 7).

When this material is compressed in the vertical direction, to conserve volume the material tends to flow in the horizontal directions (left-right and in-out of the page in Figure 7) — a phenomenon called “Poisson Expansion”. As depicted in Figure 7, the Poisson expansion results in a force attempting to expand the plate throughout the full cross-section.

Due to the stiffness and thickness of the wear plate, the contact area between it and the supporting plate can be significantly larger than the indenter contact area, as depicted in Figure 7. Since some of the reaction force applied by the support plate is applied at a horizontal distance from the directly indented zone, it tends to bend the plate. The bending strain elongates the inside surface but tends to contract the outside surface where the indenter contacts. It is this bending that forms the typical dent shape seen in Figure 3. Figure 6 shows a finite element model of the plastic extension at the wear plate inside surface

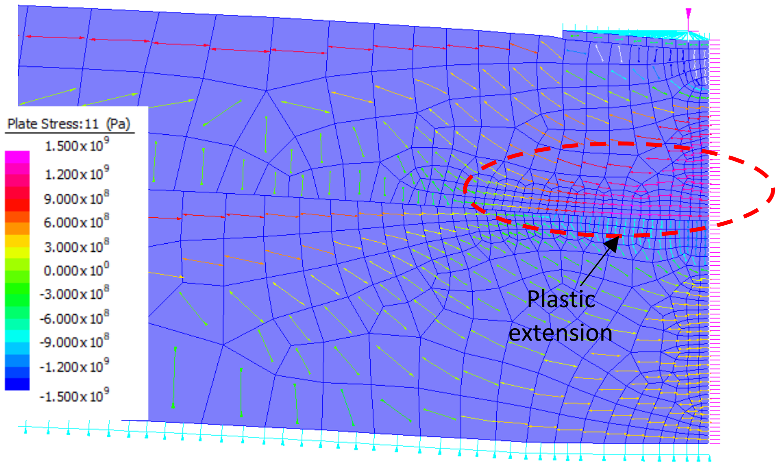

Figure 6 - Vector plot of maximum principal stress at 7 mm imposed indenter displacement showing the inside surface of the wear plate lengthening.

On the inside surface, Poisson expansion and the bending strain are additive, but on the outside surface they are opposed. Therefore, the inside surface will expand, while the outside surface is unlikely to either contract or expand plastically, unless there is a large bias in the relative proportions of Poisson elongation and bending strain (combined strain shown at the right-hand side of Figure 7).

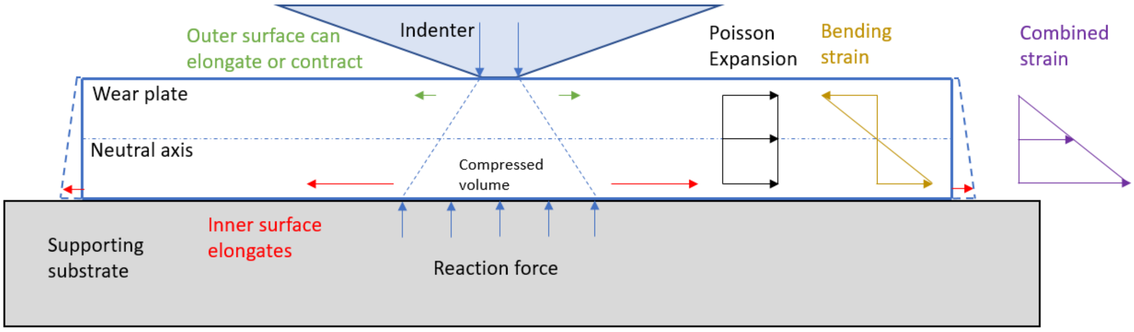

Figure 7 – Diagram showing concept of indentation on the wear plate due to contact with hard objects. The depicted stress combination only exists within the compressed volume (hard substrate shown).

Influence of Substrate

In these indentation events, the forces which change the shape of the wear plate also deform the substrate. The stiffness of the substrate affects the relative portion of bending strain vs Poisson expansion. Hard substrates such as the bucket structure favour Poisson expansion, as the harder substrate does not deform and spread the load, instead localises the load, maximising compressive stresses through the plate thickness as described in Figure 7. By localising the load on the substrate, the distance between opposing forces is reduced, reducing the moment that tends to bend the plate. If Poisson expansion is strongly dominant, the in plane dimensions of the plate can be increased, applying shear stresses to the welds which attempt to restrain the plate. Such shear stresses add to the combined static / cyclic fatigue stress cycle that has caused the welds to crack.

Softer substrates favour bending strain, as depicted in Figure 8, since a softer substrate deforms at the indenter location and spreads the load over a larger substrate area. Bending increases since substrate reaction forces can be further from the indenter location.

Bending strain from indentation adds a larger contribution to plate spring-back potential than Poisson expansion. Therefore dirt ingress should be avoided and is an identifier for potential spring-back.

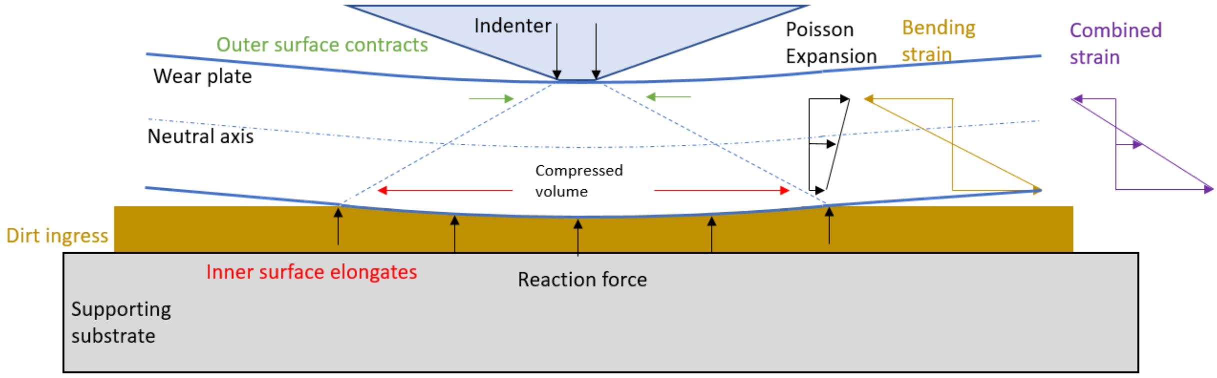

Figure 8 – Diagram showing the difference in stress state when a softer substrate is present, such as a dirt layer, biasing bending strain.

The incident plate contained up to 30mm thick layer of dirt trapped between the wear plate and bucket structure (Figure 9). Dirt ingress occurred due to locations of the wear plate that had perforated from excessive wear (Figure 1 top left).

Figure 9 - Dirt seen beneath the incident plate

The incident spring-back event has evidently occurred as a result of the combined contributions of several large discrete indentations and many smaller indentations, all of which add to the resulting stored elastic energy restrained by the remaining welds.

Effect of Thickness

Material thinning also reduces the bending stiffness of the plate. This factor has the effect of decreasing the spring-back force, but increasing the maximum spring-back deflection. Additional deflection increases the size of the danger zone and hence increases the probability of striking an operator.

In the case that the spring-back force is reduced to half or even 1/5th of the predicted force that would be applied by spring-back of a 20 mm thick plate, the spring-back potential is still capable of causing a fatal head injury.

Weld Cracking

Layout

The bucket's external protection consisted of five pieces of steel wear plate. These comprised four large steel plates oriented vertically (20 mm thick middle plates and 25 mm thick edge plates), and one narrow strip of 25 mm thick steel across the top as shown in Figure 10. The four vertical fingers followed the contour of the bucket in the vertical direction as shown in Figure 10.

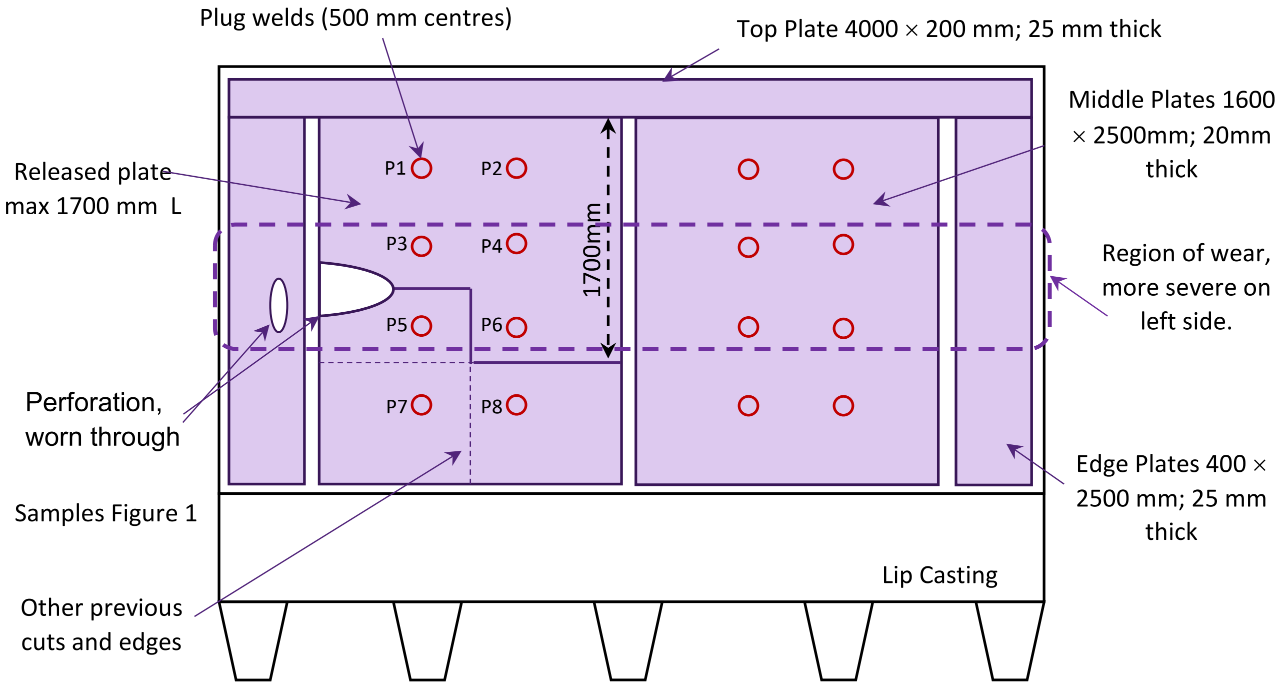

Figure 10 – Diagram of bucket showing basket external wear package, flattened for convenience.

All plate perimeters were welded to the basket structure. The two middle plates also contained an array of plug welds with a centre spacing of 500 mm and approximately 550 mm to each edge. Two perforations were visible on the left side (Figure 10) — one through the edge plate and one through the middle plate.

Attachment and Support

All vertical perimeter welds were cracked and completely detached, whereas all horizontal welds were not cracked or showed only minor cracking. Plug welds P1 – P6 on the incident plate were cracked and completely detached. It was the complete detachment of vertical welds and plug welds that allowed release of the plate, as soon as a horizontal cut was completed (as depicted in Figure 5 bottom).

One critical issue for identification of spring back potential is the visibility of existing welds that remain attached at the time of removal. Attachment of perimeter welds were visibly identifiable. Plug welds however, were only identifiable by either the presence of a surface breaking crack or remaining weld bead (Figure 11). They were unidentifiable when weld beads had worn level with the plate surface. Cracking occurred in one of two possible crack planes, parallel to the plate (crack identifiable) and perpendicular to the plate (unidentifiable), as depicted in Figure 11.

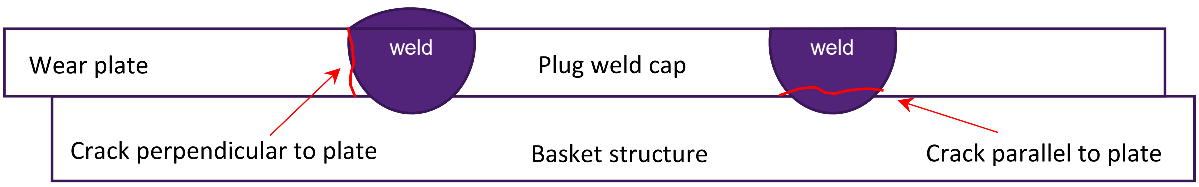

Figure 11 – Depiction of plug weld crack plane and visibility. The perpendicular cracking and unworn welds are visible (left weld), whereas the parallel cracking and worn welds are invisible (right weld).

To illustrate the ability of welds and small amounts of steel to restrain the elastic spring back forces, Figure 12 displays the final ligament of material to fail (approximately 3mm x100mm in size).

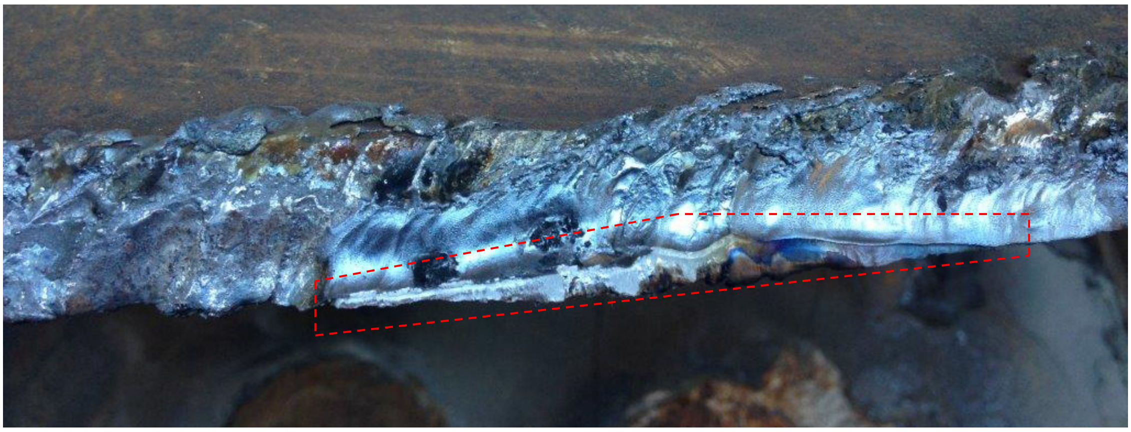

Figure 12 – Bottom edge of the incident plate showing the final ligament of the plate to release. Ligament is approximately 3mm x 100mm long.

Weld design

On the incident plate, the length of weld per square metre of attached wear plate was calculated as being 2.7 m/m^2 with maximum unattached distance between welds of 600 mm. For comparison, the wear package on a bucket armoured with many small plates of 1 m long × 0.2 m wide has 12 m/m^2 and 200mm maximum unattached distance. Thus the small plate example has 4.4 times more weld attachment and 1/3rd of the unattached length than the incident plate.

Stress Applied to Welds

Stress analysis was performed to understand why the welds cracked. Several factors contributed to high cyclic stress in the welds. Since the wear plate spanned up to 600mm between welds, bending of wear plate and bucket structure from point contact, creates high shear stresses in the welds. Elongation and bending of the plate due to indentation (as described in Figure 4 to Figure 8) applies shear and tensile stresses to the welds, which contribute to weld cracking.

Modelling of a single 50t indentation on the wear plate created stresses in the welds above their yield strength. Due to the material flow and redistribution of stresses from yielding, after the load was released the welds carried a high residual tensile stress on the surface of up to 550 MPa (Figure 13 top). The combination of shear stress, applied tension and residual tension from indentations creates a severe stress state in the welds, both static and cyclic, which motivates fatigue.

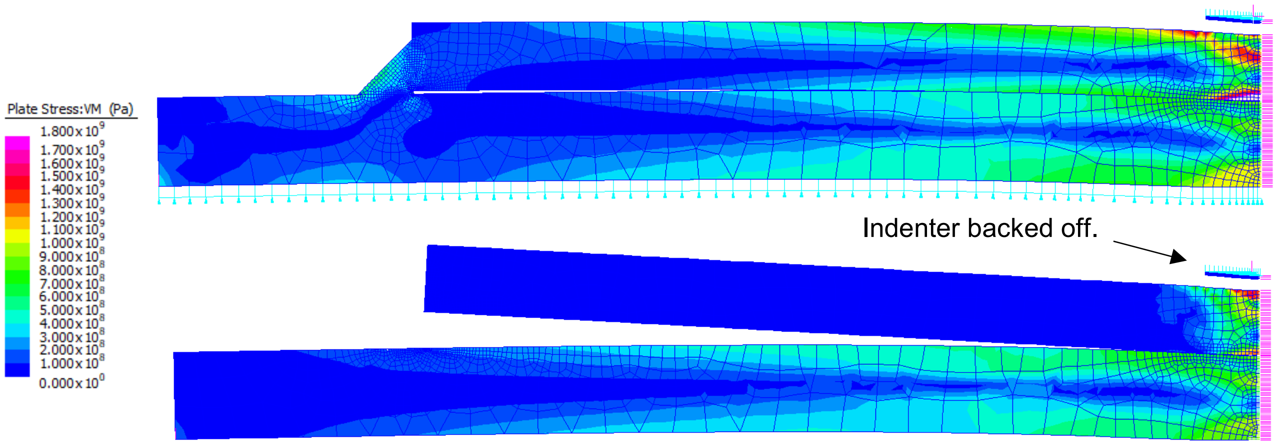

Figure 13 – von Mises stress plot after backing off the indenter with the weld (top) and without the weld (bottom) to simulate the spring back event or weld cracking. The weld shows 550 MPa residual stress. Note the reduction of stress and spring back when the weld is removed (bottom).

Therefore, while the welds were of adequate quality, inadequate weld material was present in the weld design, to carry the stresses of bucket to ground interactions, without cracking during operation.

Recognition and Reduction of Risk

The potential for spring-back of a plate can be identified by examining wear plates prior to removal. Observable features such as indentations, cracked welds, and/or dirt between the plates, are clear signs of a potential for spring-back. Large plates should be treated with particular care, since the potential spring-back amplitude is magnified by the length of the wear plate.

Spring-back occurs faster than any human can react, therefore “getting out of the way” is not possible. To remain safe while removing large wear plates, the residual stress must be released in a controlled manner. Understanding the remaining attachment is critical to designing a safe removal strategy. Ultrasonic testing (UT) could be performed on plug welds to identify the presence or absence of remaining connection. Adding temporary restraint (such as chains or temporary welding) is another important item that must be considered in any planned removal of large wear plates.

However, a superior preventative measure is to design wear packages with many small discrete plates (~0.6m), such that the quantity of angular spring back experienced by a spring back event is not translated to large spring back displacement. This has the side benefit of increasing the amount of weld per unit area and reducing the propensity for weld cracking to occur.

References

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