Hardness of a carburized surface layer on AISI 316L stainless steel from high-use Spallation Neutron Source target vessels after irradiation

OAK RIDGE National Laboratory | SPALLATION NEUTRON SOURCE

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Introduction

During operation the mercury-facing surfaces of the 316L target vessel at the Spallation Neutron Source (SNS) are damaged by cavitation-induced erosion. To increase the lifetime of targets, a surface hardening treatment called Kolsterising® was implemented to increase the resistance of the target surfaces to cavitation-induced damage.

The treatment increases the carbon content at the surface to ~6 wt%, which gradually decreases to the base metal carbon concentration of ~0.2 wt% C at approximately 50 µm. While the treatment increases the resistance of the surface to erosion, damage to the surface eventually occurs in the form of pits, as shown in Figure 1, followed by steady-state mass loss.

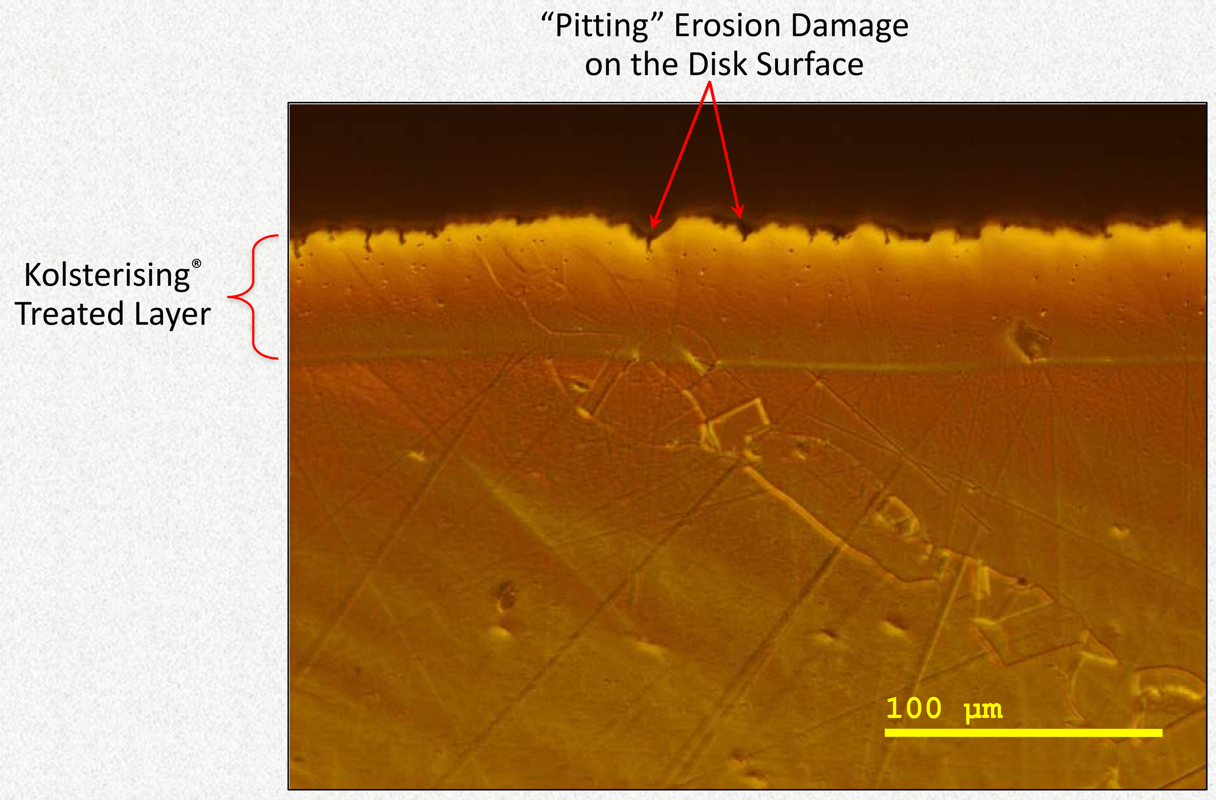

Figure 1. Cross section micrograph of specimen from SNS mercury target vessel containing a Kolsterising treated layer pitted by erosion damage.

Previous research has demonstrated that the Kolsterising® treatment increased the resistance of a 316L surface to cavitation-induced erosion. But, while the treatment improved the resistance to erosion, the stability of the carbon in the heavily saturated Kolsterising® treated layer (K-layer) under particle irradiation was unclear.

For the purpose of the SNS target vessel, stability of the K-layer is defined as maintenance of a hardened surface layer with no large precipitate formation during irradiation that embrittle the layer. This report summarizes microhardness characterization and optical microscopy of the K-layer on specimens from SNS Targets 8 and 9.

Experimental Procedures

Disk-shaped samples, shown in Figure 2, were removed from the beam entrance region of SNS Targets 8 and 9 using annular cutters after removal from service.

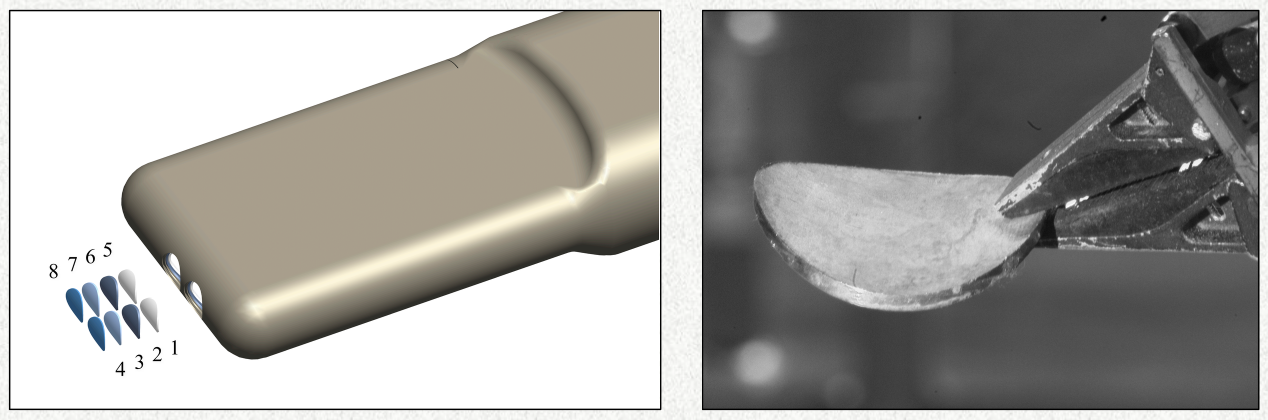

Figure 2. Diagram of specimens removed from beam entrance region of SNS targets and an example of disk-shaped sample from target vessel.

Several different specimen types were machined from the disk-shaped samples by wire electrical discharge machining (EDM), as shown in Figure 3. The specimens from microhardness testing were mounted such that the cross section of the disk is viewed after grinding and polishing.

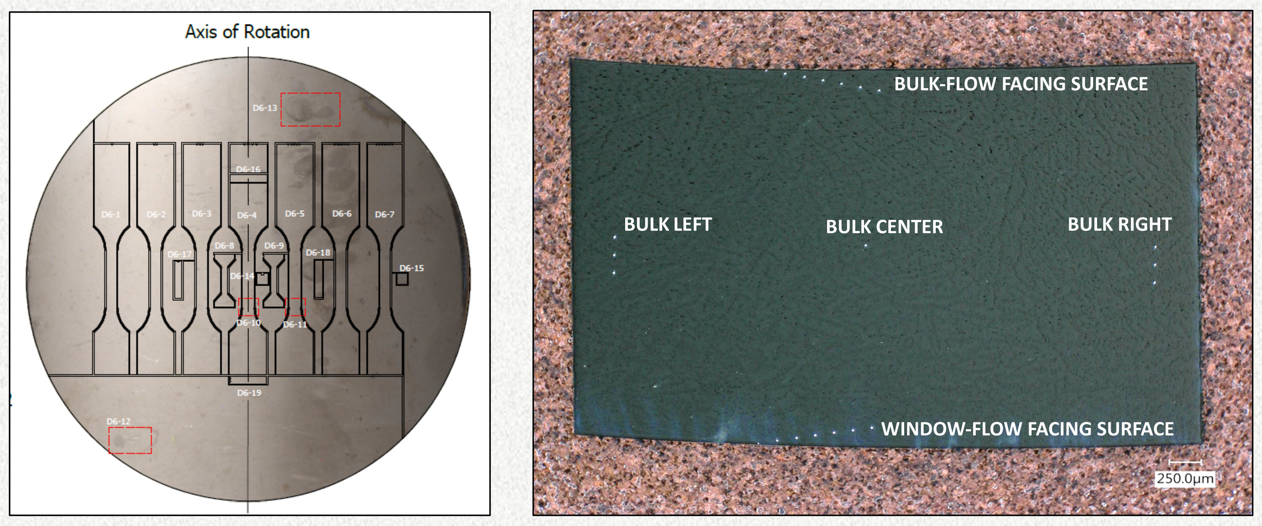

Figure 3. Machining map for SNS target disk-shaped specimen (left) and indentions on hardness specimen D6-19 from Target 9 (right).

The Vickers microhardness of the K-layer and bulk material was measured using a Wilson® Tukon 2500 with a 50 g load. Indentations to characterize the hardness of the K-layer were performed in a closely spaced staggered pattern of seven indentions near the vessel surface, as shown on a specimen in Figure 3. The bulk material hardness was also characterized with a series of indentations. The manufacturer recommended dwell time of 15 s was used for indentations.

Optical microscopy was performed on hardness specimens using differential interference contrast, and optical micrographs were obtained of the K-Layer for most specimens.

Results

Hardness testing was performed on a total of eight specimens removed from Targets 8 and 9; four specimens per target. The K-layer was present on all samples, but several different surface conditions were observed during testing.

A typical hardness profile and micrographs of the microhardness testing indentations for specimen D6-17 (7.25 dpa) from Target 9 are shown in Figure 4. The average base metal hardness was approximately 345 $HV_{0.05}$, and the K-layer was present on both the bulk-mercury facing surface and the surface facing the window flow. The peak hardness values (759 and 852 $HV_{0.05}$) were measured at approximately 10 µm from the vessel surface. The gradual increase in hardness near the surface was an indication that the carbon atmosphere had maintained a hardened surface layer.

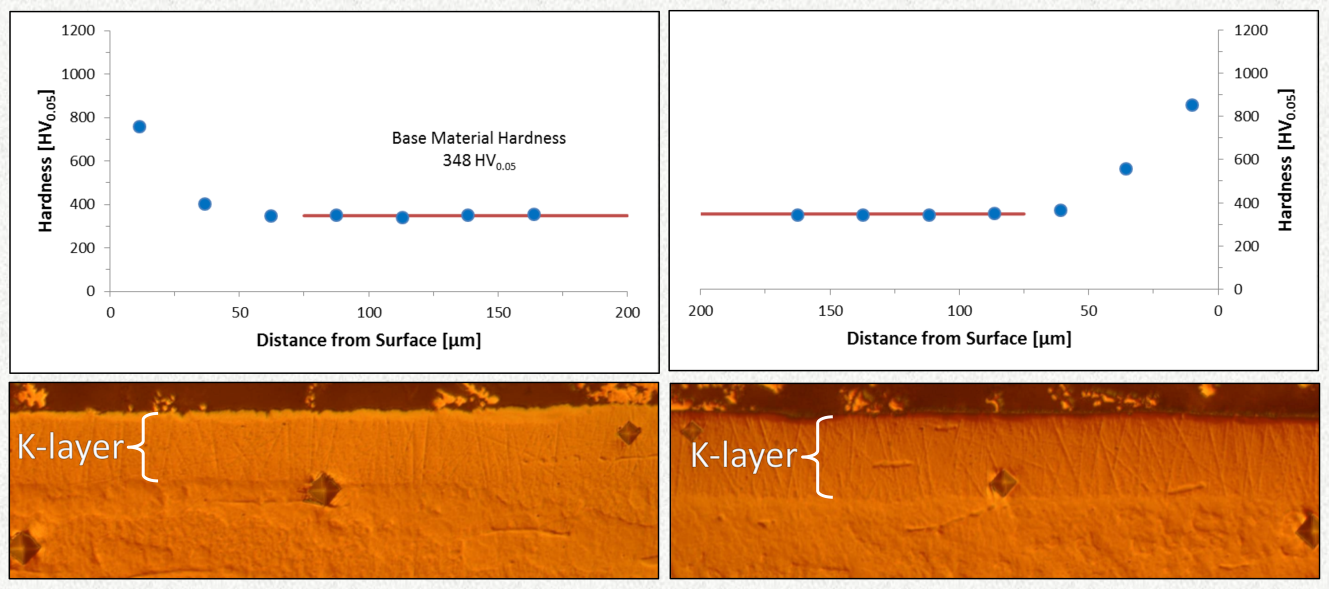

Figure 4. K-layer hardness profiles for Specimen D6-17 from Target 9: bulk mercury facing surface (Left) and window flow facing surface (Right).

On some specimens, there were areas observed where cavitation-induced erosion had penetrated the K-layer and enhanced erosion of the substrate had begun, as shown for specimen D6-18 (7.4 dpa) from Target 9 in Figure 5. No hardened layer was measured in areas where the K-layer was absent or thinned appreciably, an example of pitting damage to D6-15 from Target 8 is shown is Figure 6.

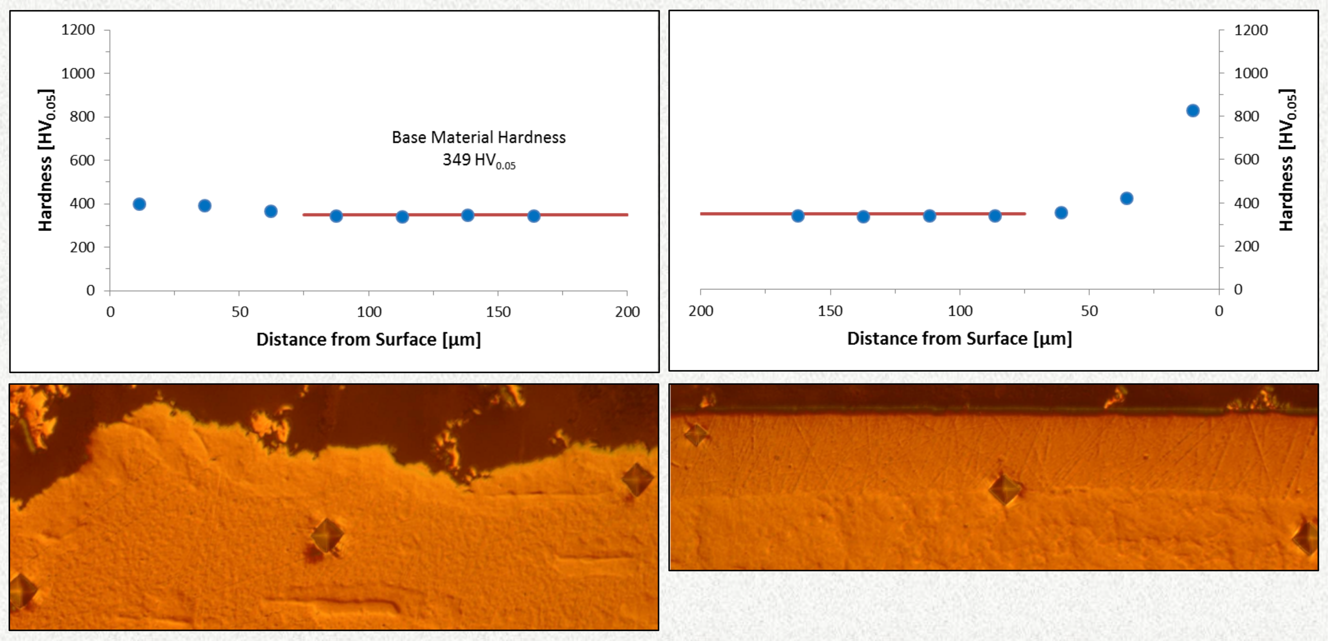

Figure 5. K-layer hardness profiles for Specimen D6-18 from Target 9: bulk mercury facing surface (left) and window flow facing surface (right).

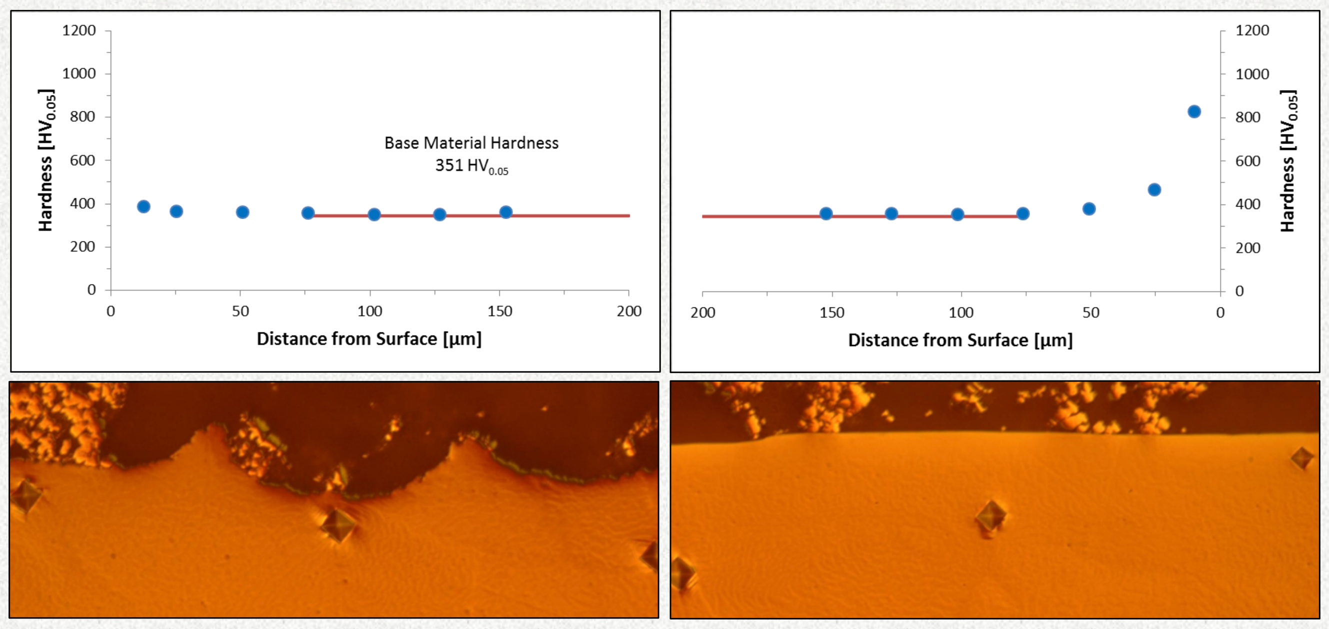

Figure 6. K-layer hardness profiles for Specimen D6-15 from Target 8: eroded surface facing the bulk mercury (left) and window flow facing surface (right).

For most specimens the surface facing the bulk mercury flow appeared to be more eroded compared to the surface facing the window flow, as shown in Figure 7. This observation was also made previously on specimens examined from Targets 1 and 2. These observations show that surface facing the window flow was better protected from cavitation-induced erosion due to the mitigating effects of high velocity flow and narrow channel confinement between the inner and outer windows.

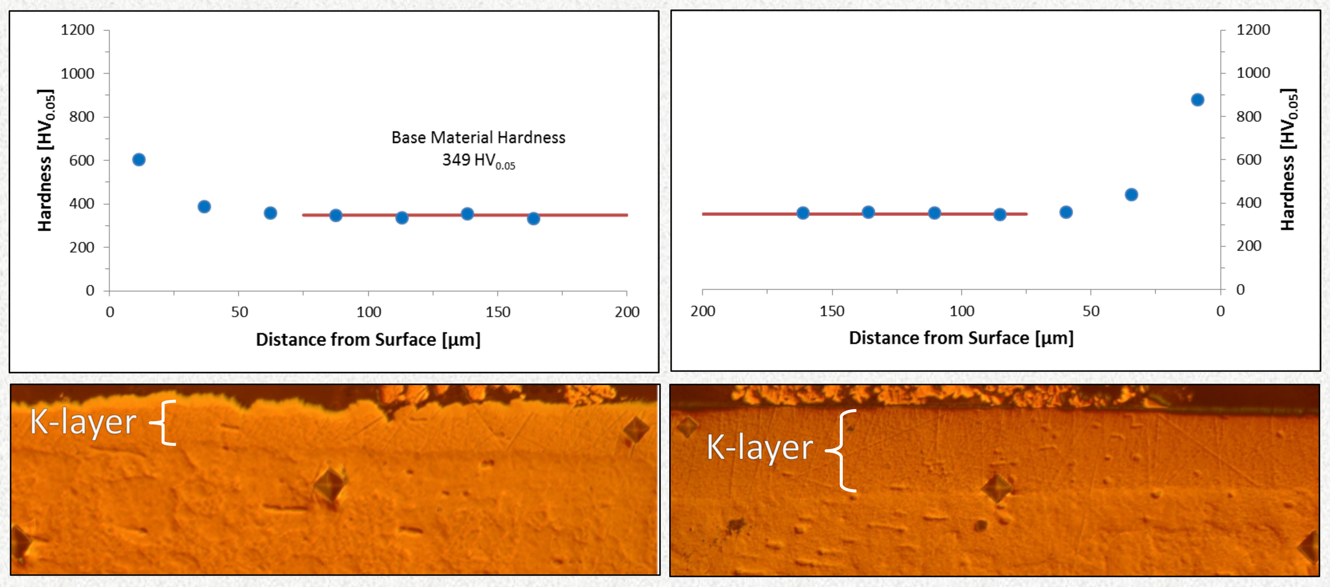

Figure 7. K-layer hardness profiles for Specimen D6-19 from Target 9: bulk mercury facing surface (left) and window flow facing surface (right).

Metallography of the K-layer specimens captured the K-layer in different stages of erosion damage. Three set of images from Target 9 specimens are shown in Figure 8. The region in Figure 8 (a) was a relatively undamaged area on the specimen, whereas the images in Figure 8 (b) was from a region of the specimen where erosion damage to the K-layer had commenced. The K-layer of the specimen in Figure 8 (c) was completely compromised and accelerated erosion of the base metal was underway.

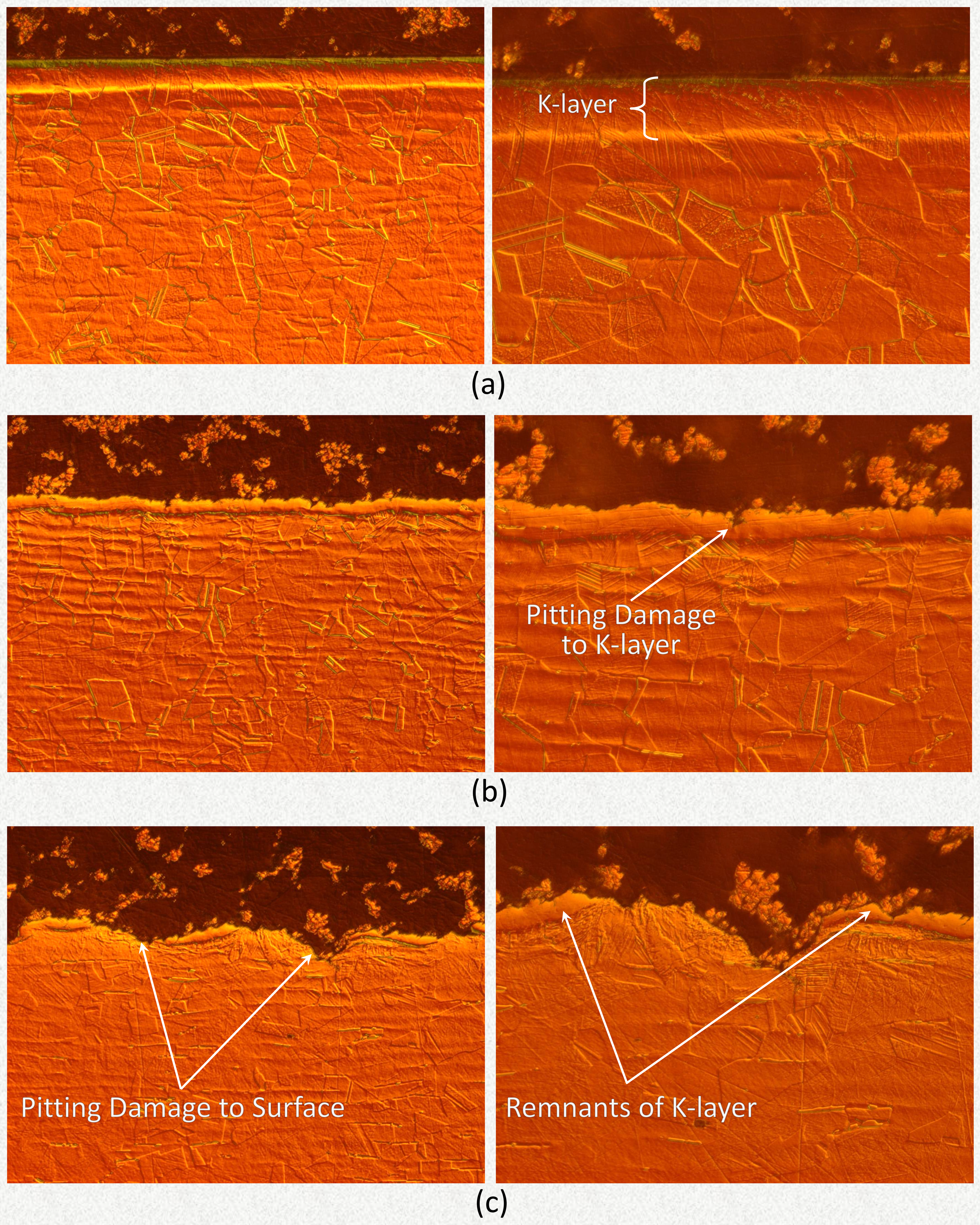

Figure 8. Examples of the various stages of cavitation-induced erosion damage: (a) little or no damage, (b) moderate erosion to K-layer, and (c) heavily damaged K-layer and vessel surface.

Conclusions

- The hardened Kolsterising® treated surface layer was still present in specimens irradiated to ~7.2 dpa
- No appreciably large precipitates were observed in the Kolsterising® treated layer after irradiation
- Several stages of cavitation-induced erosion were observed in the Kolsterising® of several specimens
- The Kolsterising® treated layer appears to be stable after irradiation to ~7.2 dpa and should continue to provide protection for SNS mercury target vessels at higher operating levels

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