## 54.0 LUBRICIOUS PVD COATINGS FOR FORGING DIES

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This project initiated in Spring 2021 and is supported by the Defense Logistics Agency (DLA) through Advanced Technology International (ati.org) and the Forging Defense Manufacturing Consortium (FDMC). The research performed during this project will serve as the basis for a Ph.D. thesis program for Jesus Vazquez.

### 54.1 Project Overview and Industrial Relevance

This project investigates whether surface modifications, including permanent coatings and/or texturing, applied to forging die surfaces can reduce friction during metal forging. In the forging industry, lubricants are sprayed on the die faces to reduce friction between the workpiece and dies, reducing required forces, improving material flow. and minimizing the buildup of forged material onto the die faces. The use of the lubricants also has a few disadvantages, including possible reduced part quality from inhomogeneous or incomplete lubrication, decreased die life caused by thermal fatigue, increased cycle time for the required spraying operation, and the inherent environmental and cleanliness issues.

An alternative to eliminate or at least minimize the use of lubricants in metal forging is to reduce friction between the workpiece and the dies by applying a permanent lubricious coating to the dies and/or texturing the die surface. Ring forging testing has been used for decades to determine the friction factor during forging [54.1-54.3] because it is a simple and repeatable test that does not require knowledge of the workpiece material properties. The values of the friction factor ***m*** for the forging die and workpiece are determined by measuring the changes of the inside diameter (ID) and height of forged ring samples according to the analytically derived curves shown in Figure 54.1.

A reduction of friction during forging will allow industry to use lower loads to form components, reduce production cycle time, improve part quality, increase die lifetime, and the reduce or eliminate lubricants and their environmental consequences, which will lead to cost reductions in the forging industry.

### 54.2 Previous Work – Proof of concept of friction reduction in forging with PVD coatings

A Forging Industry Educational and Research Foundation (FIERF) project [54.4] demonstrated that the use of PVD coatings on forging die surfaces can reduce the friction between the dies and forged workpiece. The project identified and validated the ring forge test, RFT, [54.1] as a viable experiment that provides a quantitative measurement of the friction coefficient between different die coatings using equipment available at Colorado School of Mines. All tests were performed under the FIERF project on Al 6061-T6 samples using a 445 kN (100 kip) hydraulic press at displacement rates of 2 mm/s.

The work included examining different forging temperature from room temperatures up to 200 °C for uncoated and coated dies, and various lubrication conditions. Their results showed that it is possible to reduce the friction coefficient as shown in Figure 54.2 with nanocomposite thin-film PVD coatings available commercially, from a value of ***m***=0.8 on an unlubricated and uncoated die to a value of ***m***=0.35 using a commercial PVD coating when testing at room temperature, see Table 54.1.

Experiments from this initial work on the use of pin-on-disk tribometry measurements showed that they do not correlate directly to the forging as coatings that had low friction factor on the pin-on-disk had higher values of ***m*** in the ring forge tests. They also analyzed the effects that temperature has on the coatings and showed that the coatings that provided the lowest friction factors did suffer performance degradation after higher temperature forging, which needs to be investigated as part of a design of a robust coating for forging.

**54.3 Recent Progress**

A baseline study was performed using the 6:3:2 geometry samples tested at room temperature in the RFT with uncoated and unlubricated dies but varying the surface roughness by using both directional and non-directional grinding and/or polishing. The uncoated dies were ground with different grits from 60 to 1200 SiC grinding papers as well a polished using 1 μm diamond slurry to understand the effects of the surface roughness on the friction factor ***m***. All tests were performed at room temperature with a maximum force of 425 kN an using 6061-T6 aluminum rings that had the forging surfaces lapped and polished to a surface roughness <300 nm. Figure 54.2 shows the results of an average of three tests using directional grinding, D, and ten tests for non-directional grinding, ND. For D, the condition that showed the highest value of ***m*** was the surface finish polished to 1 μm, ***m***=0.72 followed by the 60-grit finish with ***m***=0.64. In the case of ND, the 60-grit surface showed the highest value of ***m***=0.71 followed by the polished to 1 μm surface with ***m***=0.67. The rest of the surface conditions showed similar values of ***m*** between them ranging between 0.55 and 0.62.

Coated dies with commercially available coatings including i-Kote, ZrOC, ZrOC with a $ZrO_2$ top layer, AlCrCN, AlTiN-BN, and CrN-BN were selected due to their lubricious properties as well as they resistance to oxidation at the range of temperatures used on aluminum forging; these coatings were tested using the RFT at room temperature with a maximum force of 425 kN to determine the value of ***m***. Figure 54.3 shows the results for the average value of ***m*** for ten tests using the lapped and polished 6061 aluminum rings. All the tested coatings showed a reduction on the friction factor when compared to the uncoated die baseline, and the i-Kote showed the lowest average value of ***m***=0.32.

Characterization of these coatings before and after forging using SEM/EDS, profilometry, XRD, and optical microscopy is underway to better understand the mechanisms that lead to the reduction of friction during the RFT.

A Keyence 3D optical microscope has been used to assess how much aluminum has adhered to either uncoated or coated dies after RFT, as well as to study the surface morphology of the coatings after forging. Figure 54.4 shows micrographs of the CrN-BN die after 30 room temperature forgings, and image processing has been used to estimate the total area of the die used during forging and the percentage of that area that has aluminum build-up.

A wavelength interference profilometer was used to determine the surface roughness of the dies before and after RFT. Figure 54.5 shows the profilometer results of the ZrOC-$ZrO_2$ coating at the aluminum build-up area after 30 room temperature forgings to 425 kN.

After RFT, i-Kote shows an interesting surface morphology in which concentrical grooves centered at the middle of the forging zone are formed during the RFT. Figure 54.6 shows the profilometry and Figure 54.7 shows an optical micrograph in the middle of the forging zone for the i-Kote coating after 10 room temperature, 425 kN forgings highlighting the concentric grooves. The original surface for i-Kote is shown on Figure 54.8 for comparison.

Suppliers for new coatings have been contacted and we are expected to obtain the following coatings to start testing in the coming months: i-Kote $WS_2$, i-Kote-BN, VCN and two types of DLC.

**54.4 Plans for Next Reporting Period**

- Continue literature review and assemble a thorough review of previous work and coatings or surface topographies that have the potential to result in improved friction performance in forging at temperatures relevant to aluminum and steel forging.
- Initiate microstructure characterization and continue surface characterization of coatings.
- Tests a new series of coatings: i-Kote $WS_2$, i-Kote-BN, VCN and the DLC coatings.
- Start elevated temperature testing using the 445 kN (100-kip) hydraulic press using an external furnace.
- Fabricate heated die holders to perform tests at consistent higher temperatures and utilize an 1800 kN (400-kip) hydraulic press.
- Design a die holder for the 1800 kN (400-kip) hydraulic press to be able to forge at higher deformation temperatures and forces.

**54.5 References**

[54.1] A. Male, M. Cockcroft. A method for the determination of the coefficient of friction of metals under condition of bulk plastic deformation. J. Inst. Metals 1964–1965, 93, 38–46.

[54.2] B. Avitzur Metal forming: processes and analysis. New York: McGraw Hill, 1968.

[54.3] H. Sofuoglu, J. Rasty On the measurement of friction coefficient utilizing the ring compression test. Tribology Intl., 1999, 32, 327-335.

[54.4] T. Kehe, S. Randell, S. Midson, A. Korenyi-Both, K. Clarke. Laboratory Testing to Identify Permanent PVD Coatings to Minimize Lubricant Use During Forging: Final Report. CANFSA Report, Project 28, Oct 25, 2019.

### 54.6 Figures and Tables

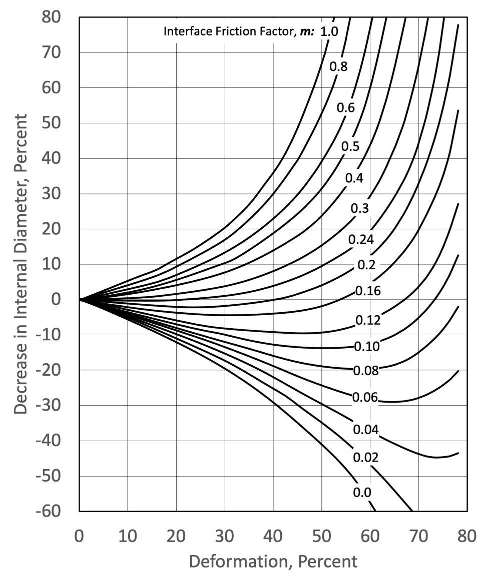


Figure 54.1: Friction factor ***m*** curves adapted from R. Kohser, PhD. Dissertation, Lehigh University (1975).

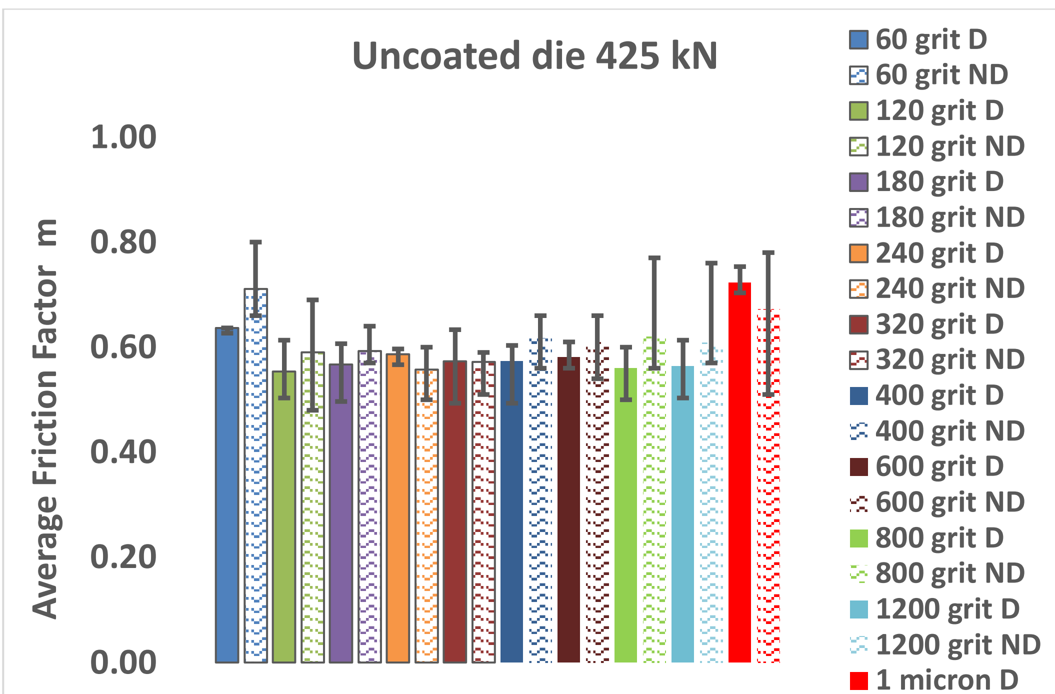


Figure 54.2: Friction factor ***m*** on dies with different surface roughness and grinding marks either directional, D, or non-directional, ND. Friction measured using lapped and polished to Ra<300 nm 6061T6 aluminum samples forged at room temperature to 425 kN for an uncoated die ground from 60 grit SiC grinding papers to polished using 1 μm diamond.

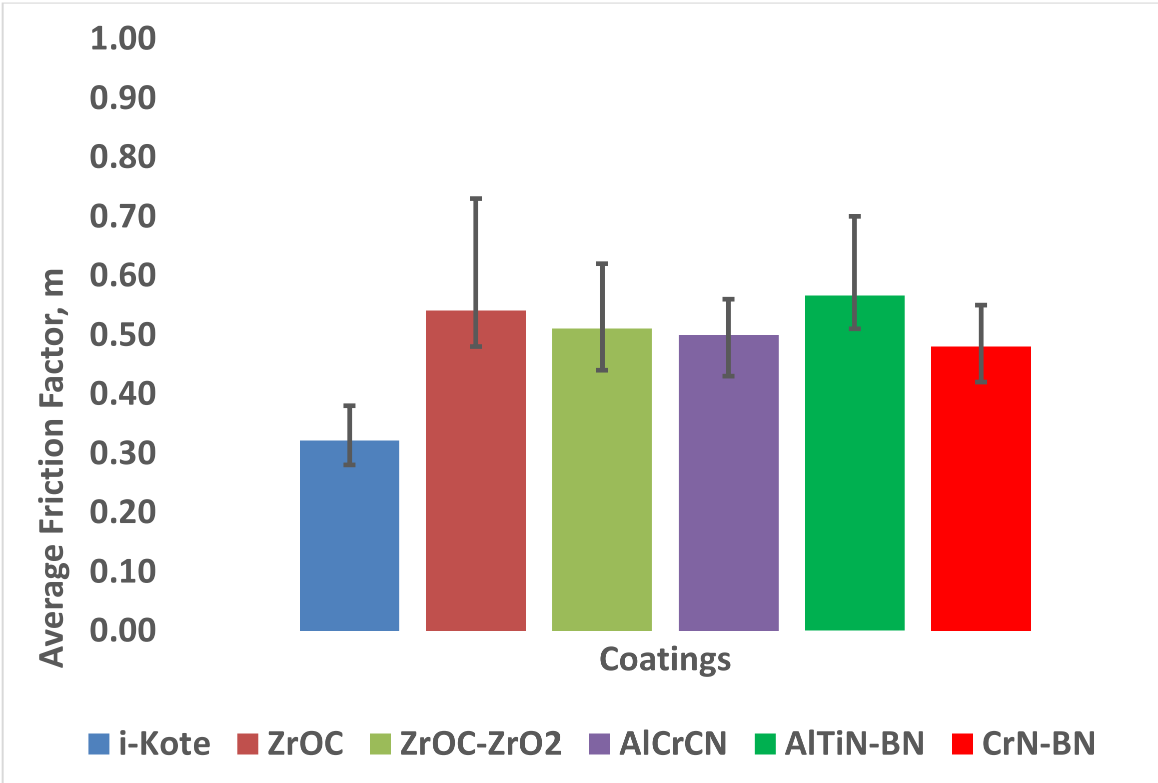


Figure 54.3: Friction factor ***m*** for different coatings tested at room temperature without lubricant to a maximum force of 425 kN using single 6061 aluminum samples lapped and polished to Ra<300 nm.

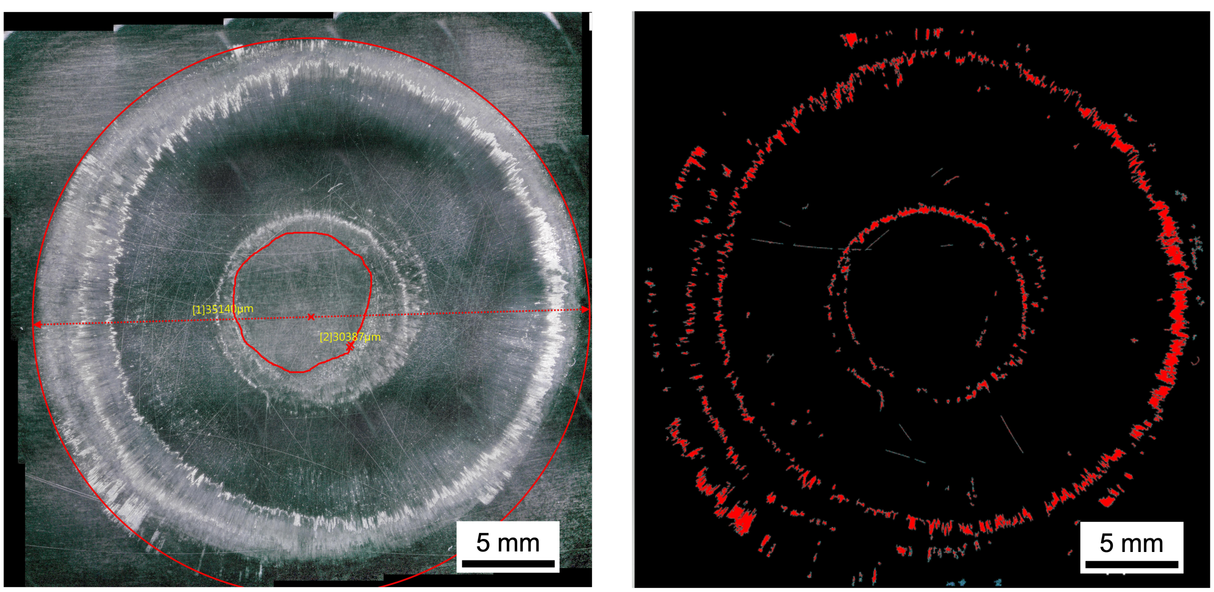


Figure 54.4: CrN-BN die after thirty 6061 aluminum forgings at room temperature to a force of 425kN shows an estimated a 6% of the total forging zone with aluminum build-up.

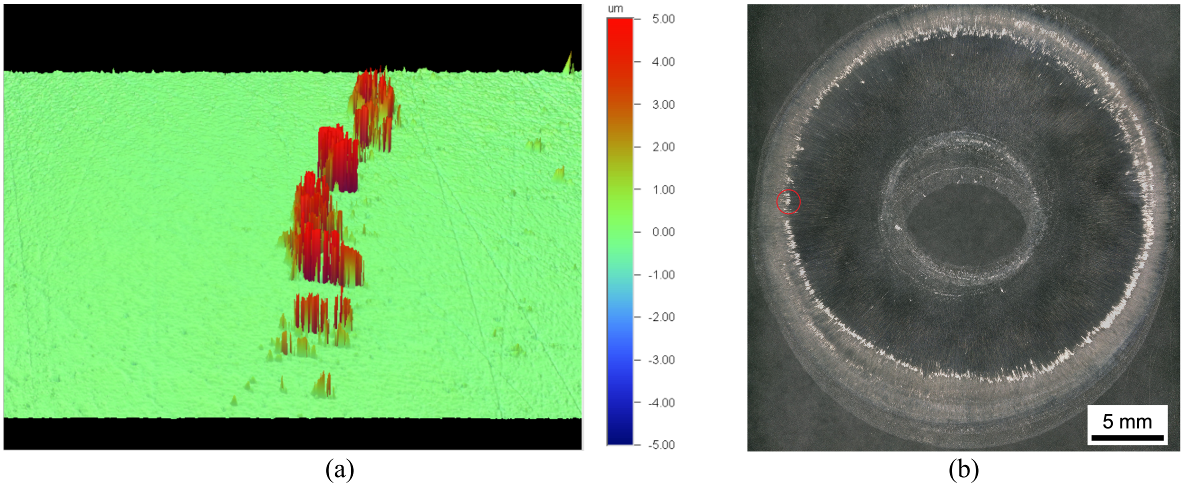


Figure 54.5: (a) 3D surface profilometer measurements (scan width approximately 3 mm) show the height (µm) of the aluminum adhered to the $ZrOC$-$ZrO_2$ coating after 30 unlubricated room temperature forgings to 425kN. (b) Overall forging area where red circle shows the location of the profilometry scan.

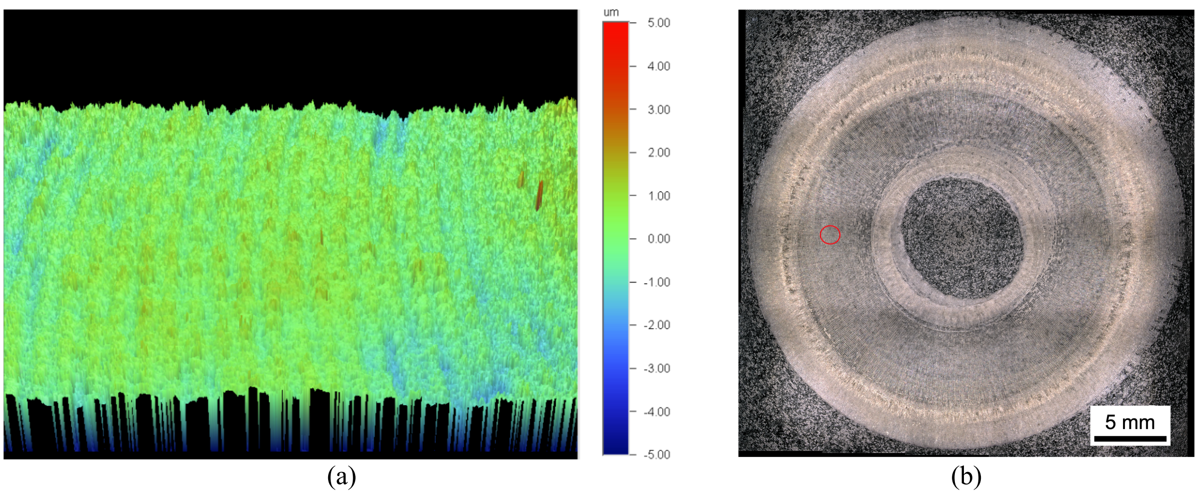


Figure 54.6: (a) 3D surface profilometer measurements (scan width approximately 3 mm) show the surface topography (µm) of the i-Kote coating after ten 6061 unlubricated aluminum room temperature forgings to 425 kN at the middle of the forging zone. (b) Overall forging area where red circle shows the location of the profilometry scan.

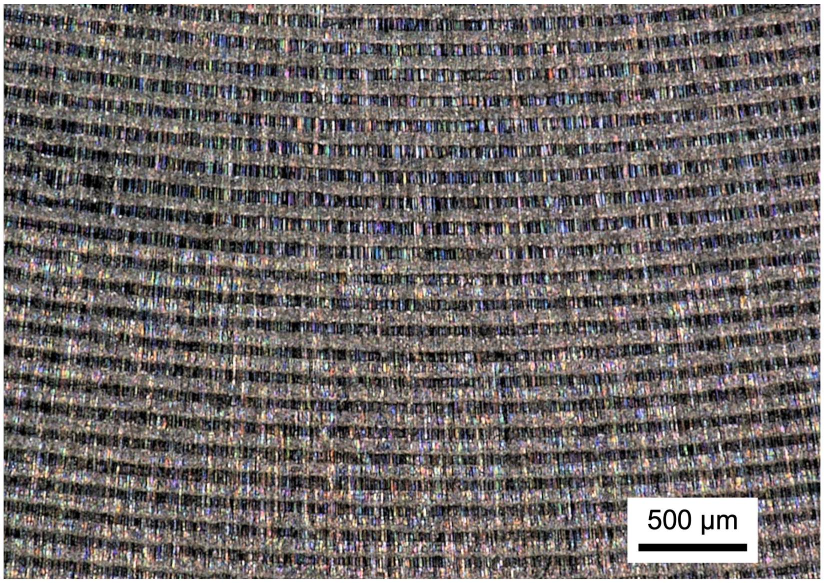


Figure 54.7: Optical micrograph of i-Kote after ten 6061T6 aluminum ring forgings to 425 kN at the middle of the forging zone showing the concentric grooves created due to the ring forging test (RFT).

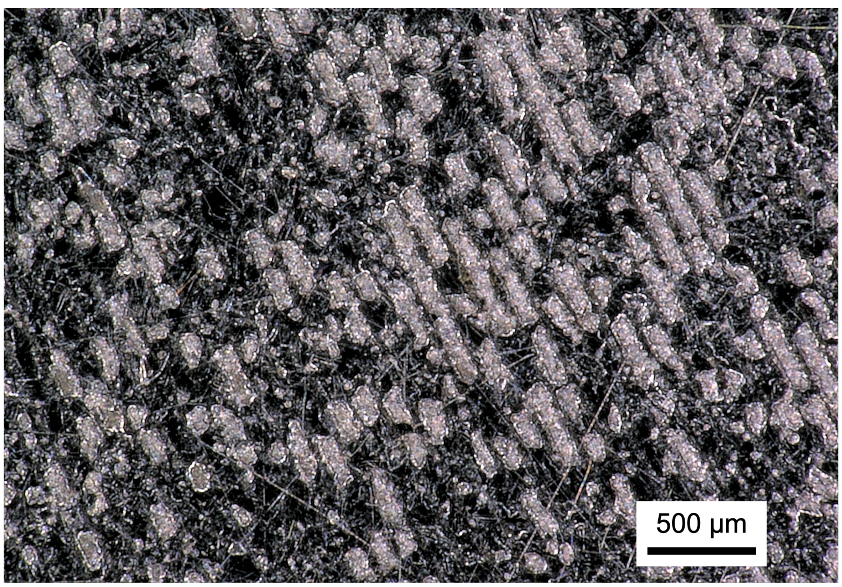


Figure 54.8: Optical micrograph of i-Kote before testing.