# 54.0 LUBRICIOUS PVD COATINGS FOR FORGING DIES

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## 54.1 Project Overview and Industrial Relevance

The project aims to determine which surface modification techniques, either permanent coatings or surface texturing, have a larger influence the reduction of the coefficient of friction when applied to forging die surfaces. In the forging industry, lubricants are sprayed on die faces to reduce the friction between the workpiece and dies, thus reducing forging forces. Lubricant also helps metal cavity filling and minimizes the buildup of forged material on die faces. The use of lubricants introduce a few disadvantages, including reduced part quality partly due to inhomogeneous surface lubrication, decreased die life from thermal fatigue, increased cycle time for the required spraying operation, and environmental and cleanliness issues.

An alternative to eliminate or at least minimize the use of lubricants in metal forging is to reduce the coefficient of friction between the workpiece and the forging dies by applying a permanent lubricious coating or a surface texturing technique on the die surface. Ring forge testing (RFT) has been used for decades to determine the coefficient of friction on a set geometry during forging [54.1-54.3]. This is a simple and repeatable test that does not require knowledge of the workpiece's material properties if the initial ring geometry has a specific ratio of the outer diameter (OD), inner diameter (ID), and height. The ideal ratio suggested in the literature [54.1] is of 6:3:2 for the OD:ID:height. The values of the friction factor, "*m*" for the forging die and workpiece are determined by measuring the changes of the ID and height of the forged samples according to analytically derived formulas. These are shown in **Figure 54.1**.

Reducing the coefficient of friction during forging will allow industry to use lower loads to form components, reduce production cycle times, improve part quality, increase die lifetimes, and reduce or eliminate lubricants and their environmental consequences. Consequently, this will lead to significant 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 coefficient of friction between the dies and forged work piece. This work identified and validated the ring forging test [54.1] as a viable experiment to provide a quantitative measurement of the friction coefficient between different die coatings using equipment available at Colorado School of Mines. All tests were performed on Al 6061 T6 samples using a 100-kip hydraulic press at quasi-static displacement rates.

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

Previous experiments showed that pin-on-disk tribometry measurements do not correlate well with real-world forging conditions, as coatings that had low coefficient of friction measured via pin-on-disk had higher values of *m* in the ring forge tests. They also analyzed the effects of temperature on the coatings and showed the coatings with the lowest friction factors suffered performance degradation after high temperature forging. These are two areas that need to be further investigated.

## 54.3 Recent Progress

A baseline study using samples of the 6:3:2 geometry for uncoated and unlubricated dies was used to determine which of either a ball joint fixture or a static parallel fixture for the die holders in the forging press, shown in **Figure 54.2**, would provide the lower variance on sample forged heights at fixed deformation percentages of 30 and 40%. **Figure 54.3** shows the results of the variance in forged height versus deformation percentage of height for both fixtures; the static parallel fixture shows more consistent forged heights compared to the ball joint fixture; therefore, future experiments would be performed using the fixture with the lower variance.

The effects of the sample surface preparation was also investigated to determine if the roughness of the sample to be forged influenced the friction factor values for the same forging conditions. Samples were tested as-cut from a band saw and ground by hand to 1200 grit and forged to 30, 40 and 50% deformations of height. **Figure 54.4** shows that the rougher as cut samples show a slightly lower friction factor and less variation compared to the hand ground samples. It was determined that all samples should have a controlled surface roughness to minimize variation in quantifying the friction factor. A lapping and polishing method was selected that would provide consistent samples with surface roughness of less than 300 nm. 1000 samples have been ordered for the future forging tests with this surface finishing.

Coatings that have shown promise on a lube-free die casting project [54.5] were also obtained on the die inserts. These include AlCrCN, AlTiN-BN and CrN-B;, the first coating was selected because it showed a coefficient of friction value of 0.3 after a break in period in the mentioned project, the other two were selected due to the presence of hexagonal Boron Nitride second phase that should act as a lubricious particle and support higher operating temperatures. These coatings were tested with samples ground to 1200 grit. Three different lubrication conditions were employed for these tests: unlubricated, dry graphite spray, and a commercially available $MoS_2$ lubricant known as Molykote. The resulting values for the friction factor are presented in **Table 54.2**.

Suppliers for new coatings have been contacted and it is expected the following coatings will be obtained in the coming months: i-Kote, i-Kote-BN, ZrOC with a $ZrO_2$ top layer, Si doped DLC, AlCrVN, TiSiVN and CrWN. We will try to replicate the results from the FIERF project [54.4] for i-Kote and tests the new higher temperature version that contains boron nitride, the supplier of the ZrOC with a $ZrO_2$ top layer and Si doped DLC suggests that these coatings will provide a low coefficient of friction and an added oxidation protection due to the additions of $ZrO_2$ top layer and the Si doping. There rest of the coatings were selected to analyze an oxidation study to generate vanadium and tungsten oxides that show a lubricious layered structure similar to graphite, this study will try to determine an optimal oxidation temperature to create these lubricious layers.

There is an ongoing effort to develop the analytical mathematical formulas for the friction factor m that more closely adhere to our testing parameters instead of relying on previous graphs to determine the value of m.

Current research found on literature concentrates mostly on the use of coated dies to minimize wear [54.6] albeit recently some researchers have tried to eliminate the use of lubricants in cold forging with the use of hybrid PVD coatings containing (Cr,Al)N and transition metal dichalcogenides such as molybdenum disulfide and tungsten disulfide [54.7] which have layered microstructures that are bonded by weak van der Waals forces and provide a macroscopic lubricious effect using Pin-on-Disk but have not been tested on the RFT.

## 54.4 Plans for Next Reporting Period

- Perform coating microstructure characterization.
- Develop the analytical mathematical formulas to graph the friction factor *m* curves.
- Repeat the baseline experiments for uncoated dies using the lapped and polished Al rings.
- Perform experiments with uncoated dies of different ground to different grits to understand the effects of die surface effects on *m*.
- Repeat the ring forging tests on current dies using the lapped and polished Al rings.
- Test the selected coatings

- : i-Kote, i-Kote-BN, ZrOC with a ZrO2 top layer, Si doped DLC, AlCrVN, TiSiVN and CrWN.
- Fabricate heated die holders to perform tests with dies at controlled elevated temperatures.
- Design a die holder for the 400-kip press to be able to forge to higher deformation percentages.

## 54.5 References

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**Figures and Tables**

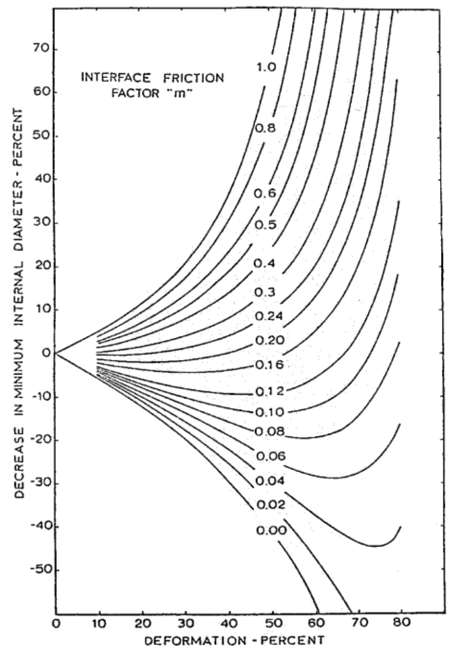
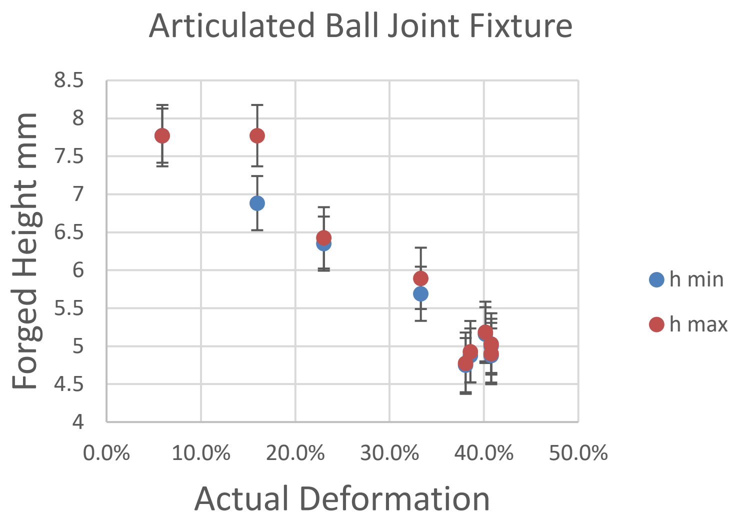


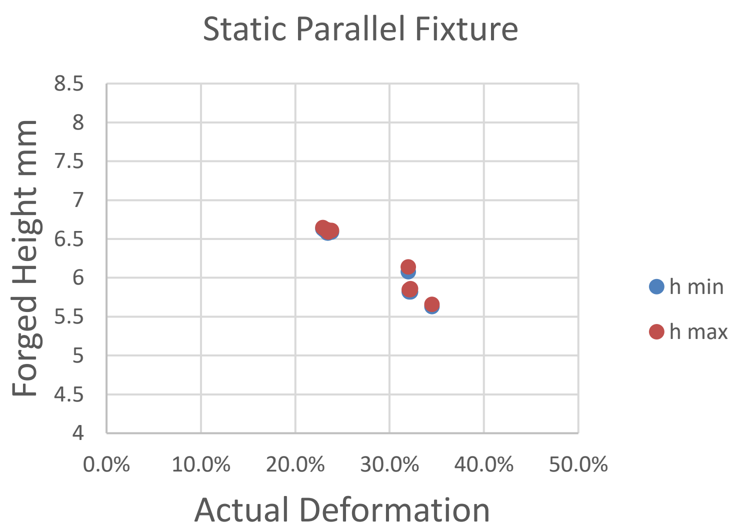

Figure 54.1: Friction factor *m* curves from R. Kohser, PhD. Dissertation, Lehigh University (1975) [54.4].

a) b)

Figure 54.2: Photographs showing two configurations of the six-inch diameter ring forging test fixture with three-inch diameter dies, a) ball joint fixture, b) static parallel fixture.




a)




b)

Figure 54.3: Sample height after forging for different deformation percentages, error bars represent the standard deviation for samples forged using a) ball joint fixture, and b) static parallel fixture. Error bars for b) are smaller than the plot markers.

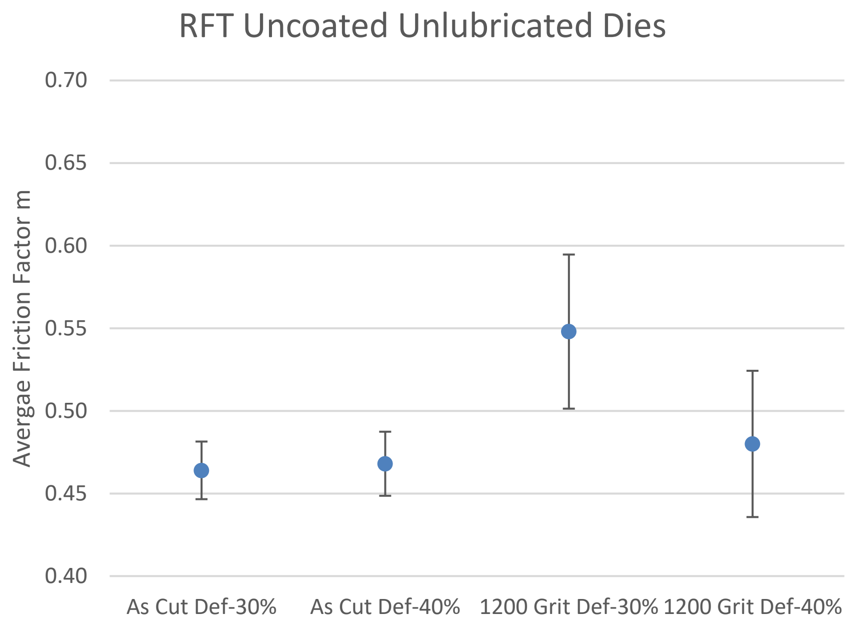



Figure 54.4: Friction factor *m* for samples with different surface preparation, as cut and ground to 1200 grit with 30 and 40% deformation in height.

Table 54.1: Unlubricated friction factor *m* values on dies with indicated coatings tested at room temperature.

| Coating | Lube | Temperature (°C) | No of samples tested | Ave. Friction Factor (m) |
|---|---|---|---|---|
| None | None | RT | 8 | 0.80 |
| i-Kote | None | RT | 18 | 0.35 |
| Super $MoS_2$ | None | RT | 5 | 0.60 |
| TiCN | None | RT | 8 | 0.87 |
| AlCrTiN | None | RT | 1 | 0.80 |
| SiC | None | RT | 3 | 1.00 |
| DLC | None | RT | 3 | 1.00 |

Table 54.2: Friction factor *m* values for indicated coatings tested at room temperature using three different lubrication conditions.

| Coating | Lubricant | Friction Factor m | Std Dev |
|---|---|---|---|
| Uncoated | Molykote | 0.14 | 0.01 |
| Uncoated | Graphite | 0.32 | 0.01 |
| Uncoated | No lubrication | 0.43 | 0.02 |
| AlCrCN | Molykote | 0.18 | 0.00 |
| AlCrCN | Graphite | 0.34 | 0.03 |
| AlCrCN | No lubrication | 0.46 | 0.04 |
| CrN/BN | Molykote | 0.20 | 0.01 |
| CrN/BN | Graphite | 0.29 | 0.05 |
| CrN/BN | No lubrication | 0.78 | - |
| AlTiN/BN | Graphite | 0.33 | 0.01 |
| AlTiN/BN | No lubrication | 0.69 | 0.07 |
| AlTiN-BN (B) CrN/BN(T) | Molykote | 0.19 | 0.01 |