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PROJECTILE LUBRICATION BY MELTING ROTATING BANDS

April 1976

US ARMY ARMAMENT COMMAND

BENET WEAPONS LABORATORY
WATERVLIET ARSENAL
WATERVLIET, N.Y. 12189

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Sliding experiments carried out in the laboratory with a pin-on-disk machine produced appreciably higher coefficients of friction than the actual values measured for projectiles sliding down cannon bores. Although the pin surface melted, the coefficient of friction was at least an order of magnitude higher than expected for liquid film lubrication. The sliders in the laboratory experiments were, of course, much smaller than actual rotating bands and the bearing pressure was limited by distortion of the sliding pin. A recently

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20. published theoretical study of lubrication by a melting slider can account for the disparity on this basis.

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TABLE OF CONTENTS

APPENDIX

TABLE

FIGURES

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Projectile Lubrication by Melting Rotating Bands

The lowest coefficients of friction for all the metals investigated in the fast-sliding wear study made by the Franklin Institute in the period 1947-1956 (1) were in the range of 0.15 to 0.20. This was despite the fact that the abrupt drop in both the frictions and the wear rates at the same point leaves little doubt that the sliding was lubricated by a molten surface film at the higher sliding velocities and bearing pressures. An appreciably lower coefficient of friction would be expected for hydrodynamic lubrication and the coefficients of friction for actual projectiles sliding down cannon bores are known to be considerably below this value. For example, the values for projectiles fired in the 155mm M185 howitzer were as low as 0.015 after only ten to twenty inches of travel. (2)

It was suspected that this disparity resulted because the laboratory experiments were made using a small slider and relatively low bearing pressures as well as other differences. The laboratory slider was a pin just 0.080 in. in diameter while a rotating band is usually an inch to an inch and a half wide and the laboratory bearing pressures did not exceed 20,000 psi while the average band pressure during engraving is on the order of 50,000 psi. It certainly was not an effect of sliding velocity because the laboratory experiments were made at velocities as high as 1800 fps while the 155mm projectiles in ref. 2 had not reached 400 fps when the coefficient of friction was as low as 0.015. While these factors were suspected to be the causes of the disparity, the reasons were not clear until the recent publication by Wilson of a theoretical study on lubrication by a melting solid (3). From his analysis, the coefficient of friction is proportional to the square root of the non-dimensional sliding speed, S. This speed is defined as:

$$S \equiv \mu U / x_2 L \qquad (1)$$

where: μ = liquid viscosity

U = sliding velocity

x_2 = length of slider

L = volumetric latent heat

Therefore, the coefficient of friction is inversely proportional to the square root of the length of the slider for any particular sliding velocity. This could account for a portion of the disparity in the coefficients of friction.

In Wilson's study it was also shown that, in the case of a melting slider, the system is not self-sustaining until very high values of non-dimensional bearing pressure. Specifically, the system does not develop its own lubricant supply for complete liquid film lubrication until the non-dimensional bearing pressure, W^*, is greater than about 0.2. W^* is defined as:

$$W^* \equiv w / L x_2 \qquad (2)$$

where: w = load per unit width

Below this value, the leading edge of the slider would not be lubricated by the liquid metal and, consequently, the coefficient of friction would be much greater. The value of W^* for the gilding metal bands on the 155mm M107 projectile would be about 0.20 during engraving for an engraving pressure of 50,000 psi and assuming the latent heats of zinc and copper in the alloy are additive. (See Appendix) It would be 0.19 for the copper bands on the 155mm M483 projectile during engraving for the same pressure. Therefore, in this case, lubrication by surface melting of the rotating bands would be self-sustaining or close to it. On the other hand, the maximum W* for copper or gilding metal in the laboratory experiments was only about 0.07. The high coefficients of friction measured in the laboratory pin-on-disk experiments could easily be accounted for by the small slider size and low bearing pressures.

After a short distance of sliding, the coefficient of friction becomes low but not as low as predicted by Wilson. This is apparent from Fig. 1 where the 155mm howitzer friction data from ref. 2 is plotted as a function of non-dimensional speed on Wilson's graph. This may be a result of the complex geometries and bearing pressure patterns of the rotating bands. The bearing pressure at the entering ramp at the leading edge is considerably less and the cannelures, in the grooves of the rifling at least, break the sliding surface into shorter segments. Furthermore, the experimentally measured engraving pressure is an average pressure; the actual bearing pressure is significantly greater at the lands and less in the grooves of the rifling.

It is interesting to note that, from this analysis, the material of the rotating bands has an appreciable effect on the bearing pressure required for the lubrication to be self-sustaining through the volumetric latent heat. While the required bearing pressure is

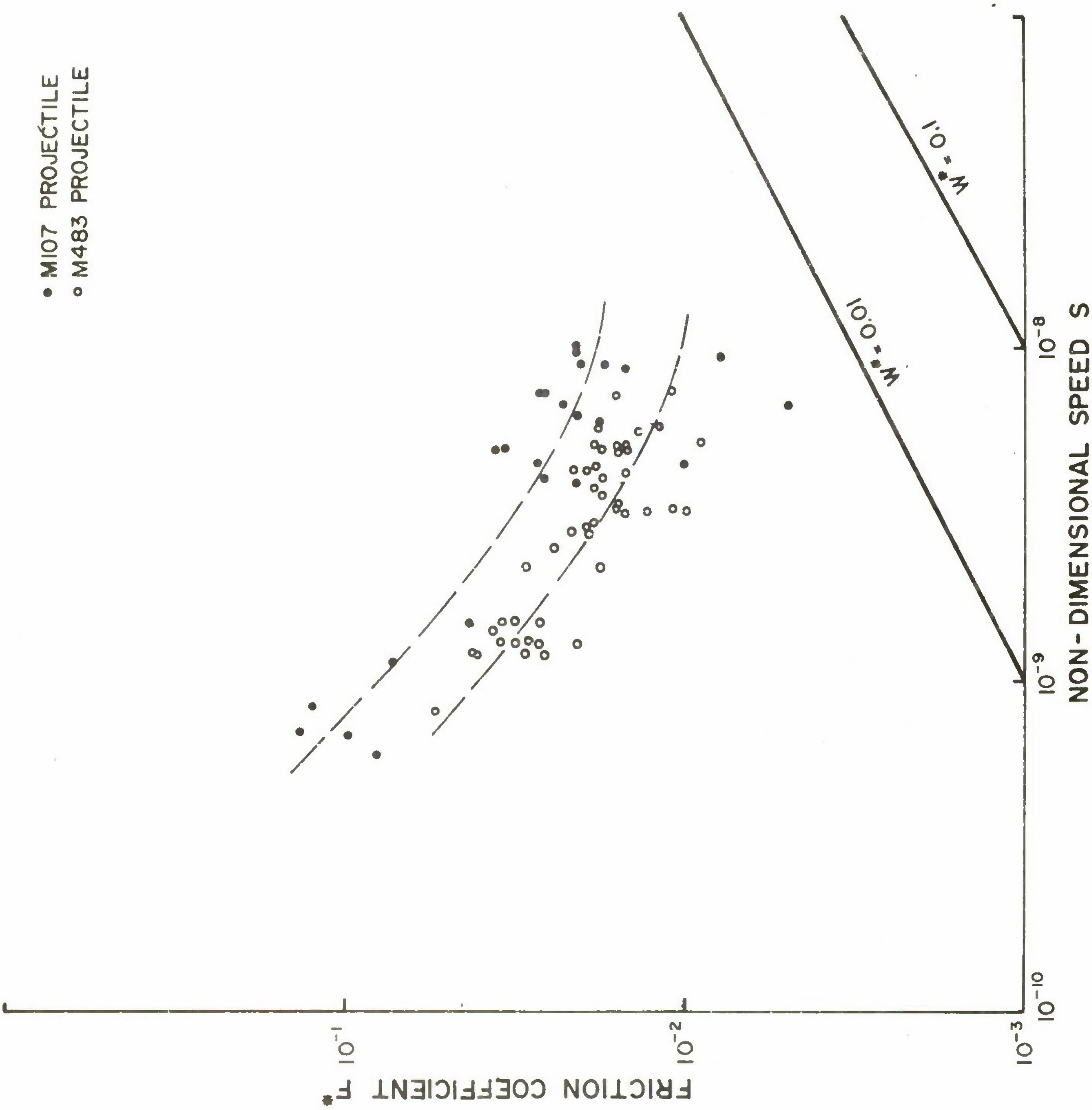


Fig. 1 155mm M185 Howitzer Friction Data as a Function of Non-dimensional Speed. The data is from Ref. (2) and the lines of constant non-dimensional bearing pressure, W*, from Ref. (3).

about 50,000, 53,000, and 56,000 psi for gilding metal, copper, and iron bands respectively, it would only be about 30,000 psi for aluminum bands. The required bearing pressure would even be less for the plastic band materials. This would have a significant effect on the friction of the bands during the initial engraving process.

References

(1) Montgomery, R.S., Friction and Wear at High Sliding Speeds, Watervliet Arsenal Technical Report 75028; WEAR 36, 275-298 (1976)

(2) Bubb, Gary, Determination of In-bore Resistance Forces, Second International Symposium on Ballistics and Warhead Mechanisms, Daytona, Florida, 8-11 March 1976; Montgomery, R.S., Surface Melting of Rotating Bands, Watervliet Arsenal Technical Report 75060; WEAR To be published

(3) Wilson, W.R.D., Lubrication by a Melting Solid, Am. Soc. Mech. Engr., Paper No. 75-Lub-26 (1975)

TABLE I

155MM M185 HOWITZER FIRING DATA (FROM REF. 2)

Rd. No.		316	318	319	320	330	331	313	314	315	324
Proj.		M107	M107	M107	M107	M107	M107	M483A1	M483A1	M483A1	M483A1
1.0 in.	U	700	310	510	368	264	298	-	-	-	-
Travel	$S \times 10^9$	1.5	0.68	1.1	0.81	0.58	0.66	-	-	-	-
	f	0.42	0.138	0.073	0.126	0.082	0.099	-	-	-	-
2.0 in.	U	-	-	-	-	-	-	912	968	996	892
Travel	$S \times 10^9$	-	-	-	-	-	-	1.2	1.3	1.3	1.2
	f	-	-	-	-	-	-	0.043	0.032	0.021	0.030
5.0 in.	U	2100	2080	2280	2300	1800	1900	2080	2140	-	1900
Travel	$S \times 10^9$	4.6	4.6	5.0	5.1	4.0	4.2	2.8	2.8	-	2.5
	f	0.027	0.010	0.036	0.034	0.021	0.026	0.022	0.020	-	0.025
10.0 in.	U	3200	3200	3380	3340	2820	2900	3100	3180	-	2840
Travel	$S \times 10^9$	17.0	7.0	7.4	7.3	6.2	6.4	4.1	4.2	-	3.8
	f	0.023	0.005	0.027	0.026	0.018	0.021	0.018	0.015	-	0.019
20.0 in.	U	4100	4460	4600	4600	4040	4100	4240	4320	-	3940
Travel	$S \times 10^9$	9.0	9.8	10	10	8.9	9.0	5.6	5.7	-	5.2
	f	0.020	0.008	0.021	0.021	0.015	0.017	0.014	0.012	-	0.019

337	338	339	340	341	342	345	346	347	360
M483A1	M483A1	M483A1	M483A1	M483A1	M483A1	M483A1	M483A1	M483A1	M483A1
-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-
1096	1008	1120	968	936	932	980	1040	1120	600
1.5	1.3	1.5	1.3	1.2	1.2	1.3	1.4	1.5	8.0
0.032	0.029	0.027	0.027	0.026	0.042	0.035	0.037	0.035	0.055
2260	2160	2280	2460	2400	2400	2420	2500	2560	1680
3.0	2.9	3.0	3.3	3.2	3.2	3.2	3.3	3.4	2.2
0.022	0.020	0.019	0.016	0.013	0.010	0.015	0.011	0.016	0.018
3240	3200	3300	3600	3660	-	3860	3920	3860	2700
4.3	4.3	4.4	4.8	4.9	-	5.1	5.2	5.1	3.6
0.022	0.020	0.019	0.016	0.015	-	0.015	0.009	0.016	0.018
4460	-	-			-		5580	5440	3800
5.9	-	-			-		7.4	7.2	5.1
0.018	-	-			-		0.011	0.016	0.018

Appendix 1

Estimation of Effective Width of Rotating Bands, x_2.

M107 Projectile

Contact with rifling grooves

Assume 50% of cannelure in contact -

Contact begins about 0.26 in. behind leading edge.

Contact length = 1.00 - 0.26 - 0.05 = 0.69 in.

Contact with rifling lands

Assume all of cannelure in contact -

Contact length = 1.00

Av. length of contact

$$\frac{1.00\ (0.15) + 0.69\ (0.249)}{0.15 + 0.249} = 0.81 \text{ in.}$$

M483 Projectile

Contact with rifling grooves

Assume 70% of first cannelure in contact and 90% of second cannelure in contact.

Contact begins about 0.26 in. behind leading edge.

Contact length = 1.49 - 0.07 - 0.01 - 0.26

= 1.15 in.

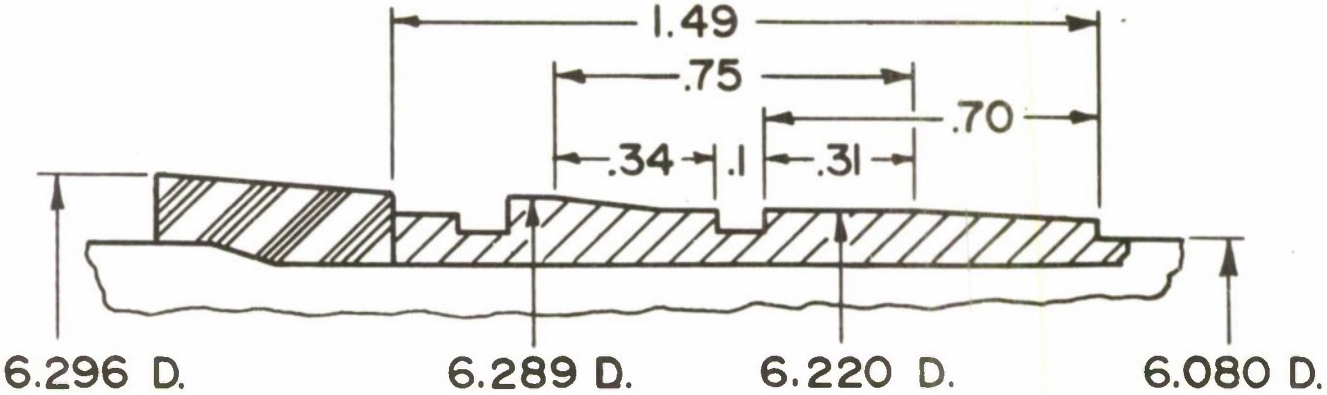
Contact with rifling lands

Assume all of cannelure in contact.

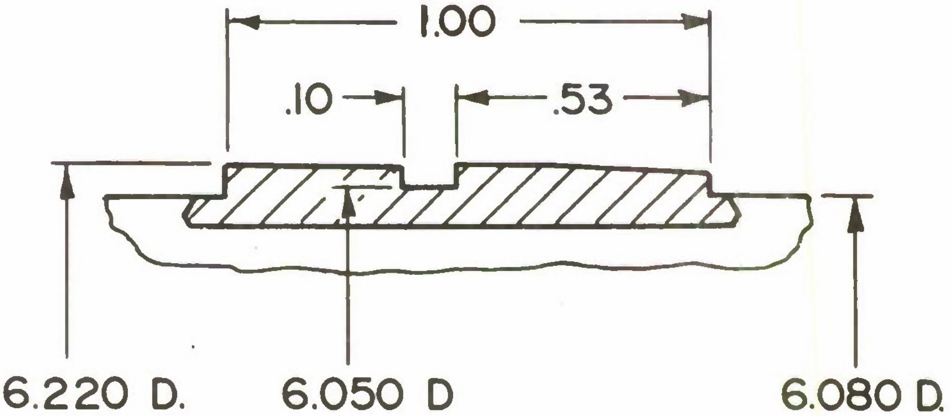
Contact length = 1.49 in.

Av. length of contact

$$\frac{1.49\ (0.15) + 1.15\ (0.249)}{0.15 + 0.249} = 1.28 \text{ in}$$



M483



M107

Fig. 2 Rotating Band Configurations of the Projectiles.

Appendix 2

Calculation of Volumetric Latent Heat, L

Heats of Fusion (gcal/g) from Kubaschewski and Alcock, Metallurgical Thermochemie (1967)

Al = 92.7 ± 1.1

Cu = 48.8 ± 1.6

gilding metal (90 Cu-10Zn) = 46.6

(assuming additive)

Fe = 59.1 ± 3.6

Ni = 69.9 ± 1.4

Zn = 26.6 ± 0.5

Densities (g/cm^3)

Al = 2.71

Cu = 8.91

gilding metal = 8.80

Fe = 7.86

Ni = 8.86

Zn = 7.14

$$L = \frac{(\text{Heat of Fusion, gcal/g})(\text{Density, g/cm}^3)(3087,\ \text{ft-lbs/Kcal})(12,\ {}^{\text{in}}/\text{ft})}{(1000,\ \text{gcal/Kcal})(0.06102,\ \text{in}^3/\text{cm}^3)}$$

Volumetric Latent Heat (in-lbs/in^3)

Al = 152,000

Cu = 264,000

Gilding Metal = 249,000

Fe = 282,000

Ni = 376,000

Zn = 115,000

Calculation of Non-Dimensional Speed, S, For Gilding Metal Bands of M107 Projectile

Assume viscosity, μ, is the same as liquid copper at its melting point. (3.1 centipoises)

$$S = \mu U/x_2 L = \frac{(0.031\ \text{dyne-sec/cm}^2)(2.248 \times 10^{-6}\ \text{lb/dyne})(U\ \text{in/sec})}{(0.1550\ \text{in}^2/\text{cm}^2)(0.81\ \text{in})(249{,}000\ \text{in-lbs/in}^3)}$$

$$= 2.2 \times 10^{-12}\ U(\text{in/sec})$$

Calculation of Non-Dimensional Speed, S, For Copper Bands of M483 Projectile

$$S = \frac{(0.031)(2.248 \times 10^{-6})(U\ \text{in/sec})}{(0.1550)(1.28)(264{,}000)}$$

$$= 1.3\dot{3} \times 10^{-12}\ U\ (\text{in/sec})$$

Appendix 3

Calculation of Maximum Non-Dimensional Load Support, W*, For Laboratory Experiments With Gilding Metal

The slider had a circular contact area of 0.080 in diameter.

x_2 was estimated as 0.071 in.

$$W^* = \frac{\text{(max. load)}}{\text{(slider Diameter) } Lx_2} = \frac{98.5}{(0.080)(249{,}000)(0.071)}$$

$$= 0.07$$

Calculation of W* for Gilding Metal During Engraving of M107 Projectile

$$W^* = \frac{w}{Lx_2} = \frac{\text{bearing pressure}}{L}$$

$$= \frac{50{,}000}{249{,}000} = 0.20$$

Calculation of W* for Copper During Engraving of M483 Projectile

$$W^* = \frac{50{,}000}{264{,}000} = 0.19$$

Calculation of Bearing Pressure Required for Self-Sustaining Liquid Film Lubrication

$$\frac{w}{x_2} = W^*L$$

$P = 0.2\ L$

Al = 30,000 psi

Cu = 53,000 psi

gilding metal = 50,000 psi

Fe = 56,000 psi

Ni = 75,000 psi

Zn = 23,000 psi

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