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D. Mark Hoffman, Jeffrey B. Chandler

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Aspects of the Tribology of the Plastic Bonded Explosive LX-04*

D. Mark Hoffman and Jeffrey B. Chandler
High Explosive Applications Facility
Lawrence Livermore National Laboratory
Livermore, CA

Abstract

The coefficient of friction, μ, of the plastic bonded explosive (PBX) LX-04 was measured on stainless steel, aluminum, Teflon and the explosive itself as a function of temperature between ambient and 135°C at a rotational speed of 0.0025 rad/sec^{-1}. An optical profilometer was used to analyze the mean surface roughness, R_a, of the various materials. LX-04 is a composite of the explosive 1,3,5,7- tetranitroazacyclooctane (HMX) and Viton A in an 85/15 weight ratio. The average roughness of the pressed explosive surface was R_a = 0.55 μm. The coefficient of friction for LX-04 on stainless steel of R_a = 0.40 μm decreased from 0.38 at ambient to 0.18 at 95°C. Above this temperature μ was nearly constant to about 125°C, where the coefficient began to increase again. The opposite behavior was observed with aluminum with R_a = 0.31 μm. The coefficient of friction increased from about 0.3 at ambient to 0.46 at 125°C. At this temperature or above, μ tended to increase during the measurement, indicating that the sample may have been sticking to the counter surface. The coefficient of friction against Teflon of R_a = 0.054 μm was nearly constant from ambient to 65°C at 0.43 ± 0.02, then decreased to 0.17 at 100°C and remained there up to 135°C. Against LX-04 itself at temperatures between 35 and 95°C the coefficient of friction averaged 0.64, but tended to increase during the measurement, probably due to adhesion of the Viton to itself. Above 95°C the coefficient dropped off and became nearly constant again at 0.16 from 115 up to 135°C.

Some preliminary measurements on stainless steel with the mock explosive RM-04-BR, a composite of cyanuric acid and Viton A in the same weight ratio as the actual explosive, were made to evaluate the set up procedures and safety of the operation with live explosive. Both pressed, R_a = 0.37 μm, and machined, R_a = 1.7 μm, surfaces were evaluated for the mock. Results compared reasonably well with the explosive itself on steel, indicating that the binder plays a major role in determining the coefficient of friction for these types of composites.

Introduction

Serious explosive accidents have occurred as a result of oblique impact on a surface. Detonation is believed to result from frictional heating during skidding on the surface. Several tests to determine the onset of reaction due to oblique and crushing impact including skid tests [1], Susan tests [2] and Steven tests [3] have been developed by various organizations to evaluate this hazard. A small scale BAM friction test is often used to estimate the sliding force required to produce a reaction in an explosive on a

ceramic plate [4]. Until recently most of these tests were done at ambient. In effort to understand the dominant microscopic mechanism of initiation during impact, Steven tests on LX-04 and PBX 9404 heated to 150 -170°C were compared with ambient results. The results showed that LX-04 was much less sensitive to impact (impact threshold increased significantly: 45 m/s at ambient to > 125 m/s at 150°C) while PBX-9404 impact threshold increased only slightly (35 m/s at ambient to 48 m/s at 150°C) [3]. Models for initiation depend on shear, deformation and friction. Data for the modulus and ultimate properties of LX-04 is available [5-6] as a function of temperature, but friction data is limited to near ambient conditions [7-8]. As a result, this study was undertaken to determine the temperature dependence of the coefficient of friction for LX-04 on four substrates: steel, aluminum, Teflon and the explosive itself.

Experimental

Friction measurements

Parallel plate fixturing for a Rheometrics Mechanical Spectrometer model 800 was modified to measure the torque associated with a given normal force on cylindrical disks of LX-04 explosive 2.528 ± 0.0008 cm in diameter by 0.320 ± 0.003 cm thick. Samples of the explosive or mock were bonded to the removable aluminum plate of the upper fixture with Scotch double stick foam tape. The counter surface, except for LX-04 explosive to itself, was machined into a 5.08 cm diameter disk with a 2.02 cm diameter lower section which was secured into the RMS bottom fixture. The test setup is shown in Figure 1. The test was started with no contact between the LX-04 and counter surface which was rotating. The rotational speed for all testing was 0.0025 rad/s. Once the transducer had auto zeroed, the sample and foam tape were lowered to approximately 0.020 mm below the contact distance. Compression of the foam usually resulted in between 20-90 g normal force, N, being applied to the counter surface which decreased slowly as the foam relaxed. The resulting torque, T, increased slowly for a few seconds and leveled out. The coefficient of friction, μ, was calculated from:

$$\mu = 3T/2NR \qquad (1)$$

where R is the radius of the explosive disk. Occasionally the normal force was increased by increasing the distance by which the upper measuring head was lowered onto the lower to approximately 0.04 or 0.06 mm. Three typical sets of measurements are shown in Figure 2 for the mock explosive RM-04-BR on stainless steel. As can be seen in the figure, the coefficient of friction calculated according to equation 1 quickly becomes nearly constant, even though the normal force and torque may vary slightly. Toward the end of the 1 minute contact time, the sample was raised to a height slightly above the surface to insure that the normal force and torque values return to zero and the temperature was incremented 10°C. A torque and normal force measurement was taken every 0.0375 second. A two-minute hold time was allowed during which time the contact position was redetermined so that approximately the same compression of the fixture could be obtained at the next temperature. After the 2 minute soak time, the next experiment began. All experiments with LX-04 explosive were conducted in a 0.5” thick

remote steel cell to protect the operator from the unlikely possibility of an explosion. The experiments were automated using the Rheometrics Orchestrator program, except for the repositioning of the z-axis, which was accomplished by a remote electronic control switch, instead of the up-down switches on the instrument.

Surface Profiles.

Surface profilometry was preformed on LX-04 and the counter surfaces using a Conoscan 3000 instrument manufactured by Optimet Optical Metrology. This conoscopic holographic technique measures the interference of ordinary and extraordinary rays off the sample through a birefringent crystal against a calibration to produce a surface profile [9, 10]. The roughness R_a is the mean of the z-axis profile calculated from:

$$R_a = (1/L)\ \Sigma_i\ |z(x_i)| \qquad (2).$$

where $z(x_i)$ is the height of the surface at x_i and L is the length over which the measurement was made. A typical example of the results of such measurements is shown in Figure 3 for machined RM-04-BR mock explosive.

Materials:

LX-04 samples from lot # B-924 were compression molded in a cylindrical die at 95ºC and 30,000 psi for 3 three minute dwells with approximately 1 minute relaxation at atmospheric pressure between pressing cycles. The density of LX-04 samples averaged 1.869 ± 0.001 g/cc with an average radius of 1.264 ± 0.005 cm. Stainless steel, aluminum and Teflon plates were machined from stock. The explosive mock RM-04-BR was compression molded as above into a cylinder approximately 2.55 cm diameter x 2.54 cm long of density 1.63 ± 0.01 g/cc with an average radius of 1.275 ± 0.006 cm. This sample was sawed into 0.6 cm lengths and machined flat. Both the compression molded surface and the machined surfaces of disks of mock were used in friction measurements to evaluate the effect of surface roughness.

Results and Discussion

Mock Explosive

Research Mock (RM) explosive RM-04-BR was used to develop and evaluate the procedures used to measure the coefficient of friction on the RMS 800 prior to use with actual explosive. RM-04-BR is an “atomic” mock for the explosive LX-04. It contains 15% Viton A binder, a fluoroelastomer of perfluoropropylene and vinylidene fluoride in a mole ratio of approximately 2:7 [5]. The HMX explosive in LX-04 is replaced in the mock by an equal weight percentage of cyanuric acid. Mock samples identical in shape to LX-04 samples were prepared and tested as described above. The surface profile of machined mock, shown in Figure 3, gave an R_a of 1.7 μm. The surface profile of the

pressed mock (R_a = 0.37 μm) was similar to that measured for LX-04 in Figure 4. The stainless steel plate was used as the counter surface for all mock measurements.

Figure 2 shows 3 different normal force measurements on machined RM-04-BR at 105ºC. As was typical with stainless steel, the sample and foam are compressed rapidly resulting in rapid rise of the normal force followed by slow decay probably associated with creep and set of the foam tape. The torque and coefficient of friction increased slowly for about 5 seconds, probably also associated with the relaxation of the foam tape, and reach almost a constant value. The coefficient of friction decreased from 0.248 at 83.8 g normal force to 0.233 at 142.9 g to 0.224 at 273.1 g, but was quite steady with a standard deviation along the flat portion of the trace in time of about 0.005. No evidence of a static peak in the friction measurements was observed for the mock explosive on stainless steel. Figure 5 shows the coefficient of friction of RM-04-BR as a function of temperature for machined and pressed samples on stainless steel. There is significant scatter at ambient and 35ºC, with the lower values usually associated with the highest normal force. From 45 to 115ºC, the coefficient of friction decreased from about 0.3 to about 0.23. At temperatures above 115ºC the coefficient of friction seemed to level out or increase again. It is known that the Viton binder develops a small amount of crystalliniity over time which melts at about 85ºC [11]. Viton is also known to stress crystallize which increases the crystal melting temperature slightly [12]. At the interface between the mock and the steel, there is probably considerable shear which could prevent the crystallites from melting and keep the coefficient of friction decreasing until 115ºC, as is observed.

LX-04 Explosive on Stainless Steel

LX-04 is an explosive composed of 15% by weight Viton A fluoroelastomer and 85% by weight of a multimodal distribution of HMX explosive [13]. This explosive will not react violently when a ceramic pin is dragged across its surface at a normal pressure of more than 4.5 MPa (650 psi) [4]. The surface roughness (R_a = 0.55 μm) of one of the pressed LX-04 pellets is shown in Figure 4. These measurements were more complicated than surface roughness measurements on the other materials and strips of dark tape had to be used along the line where the laser ran over the surface to reduce optical noise. Figure 6 shows the coefficient of friction calculated from equation 1 as a function of time from about 20 seconds into each test run until just before the normal force was removed. In most cases the friction coefficient was reasonably constant at a given temperature. Only above 125ºC do the coefficients deviate more than a few percent over the time of the measurement. The average torque and normal force for each measurement are plotted in Figure 7. As can be seen from the figure, for a deformation of approximately 0.02 mm, the normal force increased with temperature from about 60 to just slightly over 300 g then leveled out above 95ºC. The torque follows the normal force, varying from 14 g-cm to 46 g-cm. Estimates of the coefficient of friction for LX-04 on stainless steel were made from the average of the traces in Figure 6. The results are plotted along with the mock data in Figure 5. As can be seen from the figure, both LX-04 and mock explosive based on the Viton binder gave similar friction coefficients as a function of temperature. The counter surface was weighed before and after these tests and less than 1 mg of

explosive had been transferred to the stainless steel indicating minimal wear under these conditions.

LX-04 on Aluminum

The dynamic coefficient of friction of LX-04 on aluminum at representative temperatures is shown in Figure 8. Friction at the Aluminum/LX-04 interface increased from about 0.3 to about 0.45 over the temperature range from ambient to 135ºC. Only values of μ at 125 and 135ºC were not nearly constant during the measurement. Figure 9 is a plot of the average friction coefficient for LX-04 on aluminum over the temperature range tested. As can be seen from these figures the coefficient of friction increased with increasing temperature. It is known that most fluoroelastomers will react with aluminum as the oxide layer abrades [14] in frictional applications, so it is not surprising that the coefficient of friction of LX-04 increased against aluminum.

LX-04 on Polytetrafluoroethylene (PTFE)

Teflon (PTFE) is used in shock and impact experiments to mock up the impact characteristics of an explosive [15]. PTFE is well known for its low friction coefficient against metals and hard surfaces [16]. The mechanism of friction reduction on hard surfaces is due to transfer of a thin PTFE film to the hard substrate which serves as a lubricant. However, LX-04 is a relatively soft surface. As seen in Figure 10, PTFE is ineffective as a lubricant for LX-04 at ambient. As the temperature is increased, the coefficient of friction remains relatively constant at 0.44 ± 0.01 until 55ºC. Between this temperature and 115ºC the friction coefficient decreased. From about 115 to 135ºC the Viton A in LX-04 acts as a lubricant between PTFE and the explosive and the friction coefficient drops to 0.15 ± 0.01. Figure 11 shows the average coefficient of friction of LX-04 on PTFE as a function of temperature. PTFE undergoes a solid-solid phase transition at approximately 19ºC [17] which is too low to be responsible for the reduction of the coefficient above 115ºC. The loss of crystalline crosslinks in the Viton binder is the most likely cause of this effect.

LX-04 on itself

Since explosives often fracture and rubblizes on impact [18], the friction behavior of LX-04 explosive against itself is of interest. Since only 2.54 cm diameter samples of LX-04 were available, the lower LX-04 sample was attached to an aluminum insert with double stick tape. The friction coefficient of LX-04 against itself was quite high at ambient. Figure 12 shows the traces of the coefficient of friction of LX-04 on itself. Values of μ were not constant for LX-04 against itself. At 25 and 35ºC, the coefficient of friction was nearly constant, but above this temperature the coefficient increased for almost the entire 60 s of the measurement. This probably indicates that the Viton is adhering to itself across the interface. Above about 95ºC the coefficient begins to drop off dramatically from about 0.6 to below 0.1 at 135ºC. Figure 13 shows the average value of μ as a function of temperature with 3 σ error bars used to approximate the increase in the coefficient between 45 and 105ºC. The reason for the remarkable

reduction in friction above 100ºC is not completely understood, but probably has to do with the melting of small crystallites of Viton binder allowing it to flow. During deformation and rubbilization, the reduction of frictional heating of LX-04 against itself would be expected to reduce the sensitivity of the explosive to this type of initiation mechanism at elevated temperatures.

Conclusions

The parallel plate technique is an effective and simple technique for measuring the coefficient of friction for LX-04 explosive on a variety of substrates as a function of temperature. The decrease in μ of LX-04 on stainless steel, Teflon and the explosive itself as a function of temperature should reduce the contribution of friction to the impact sensitivity of this explosive at high temperatures consistent with results observed at high temperature in the Steven test [3]. The reduction in friction coefficient for these 3 materials begins around 85ºC, approximately where the crystallites in Viton A melt out. This effectively decreases the viscosity of the binder by removing the crosslinking effect of the crystallites. This should substantially increase Vitons ability to transfer material to hard interfaces and enhance lubrication. The anomalous increase in the coefficient of friction of LX-04 on aluminum is consistent with known incompatibilities of these two materials for lubrication applications.

The similarity of frictional behavior between RM-04-BR mock and LX-04 explosive on stainless steel can be attributed to the use of Viton A as a binder for both formulations.

Acknowledgements

Funding for this effort was provided by Steve Chidester of Defense Technologies Engineering Division and was greatly appreciated. The Conoscope 3000 surface profiles were performed by Jerry Benterou and Ron Chanbers. Jerry Benetrou also assistance with their interpretation. PTFE, RM-04-BR and stainless steel samples were machined from stock by Kou Moua with advise from Jeff Wardell. Don Burns modified the electronics on the RMS-800 so that the transducer and upper fixture could be raised and lowered from outside the explosive cell. Discussions with Steve Chidester, Steve DeTeresa, Bruce Cunningham, Joe Zaug, Craig Tarver, and Jonathan Crowherst are greatfully acknowledged.

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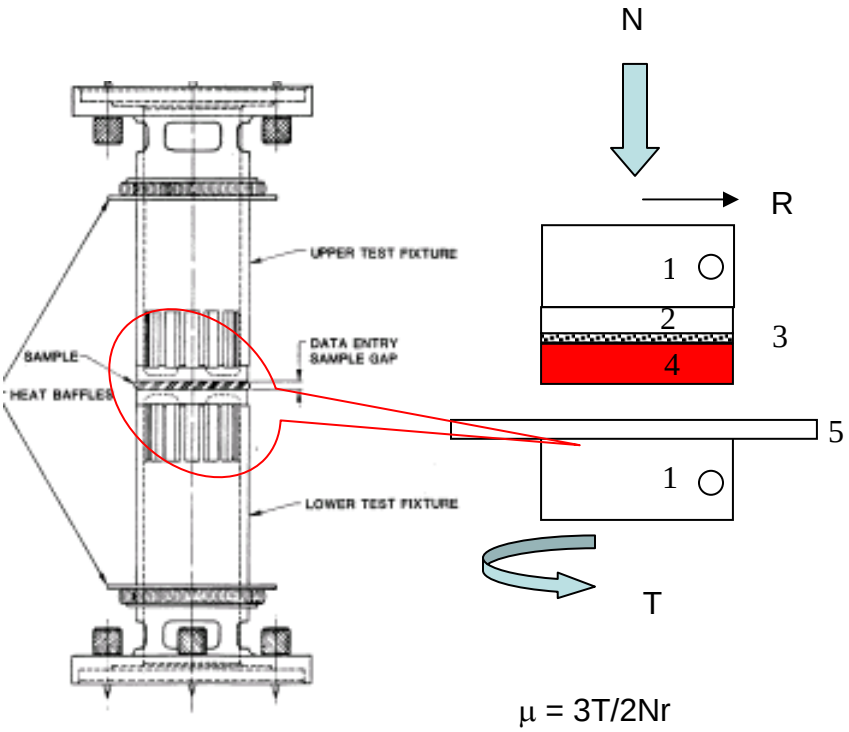

Figure 1. A friction measurement apparatus was developed based on the parallel plate fixtures for the Rheometrics Mechanical Spectrometer Model 800. In the figure 1 = upper and lower test fixture, 2 = removable aluminum plate which is secured into the upper fixture by tightening the screw represented by a circle, 3 = 3M foam adhesive tape to aid in sample (4) /counter surface (5) alignment.

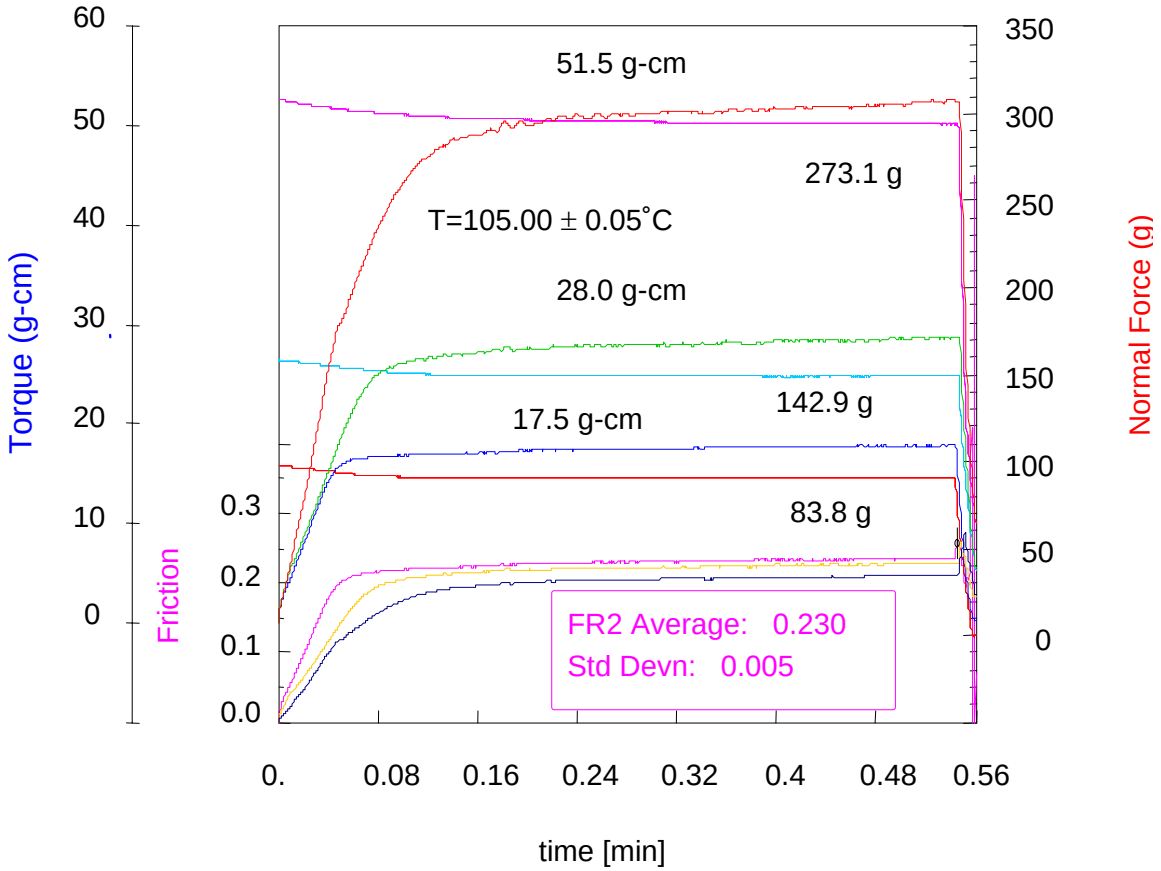

Figure 2. Typical results from torque and normal force measurements show the effect of increasing normal force on the coefficient of friction of mock explosive on stainless steel at 105°C was small but measurable.

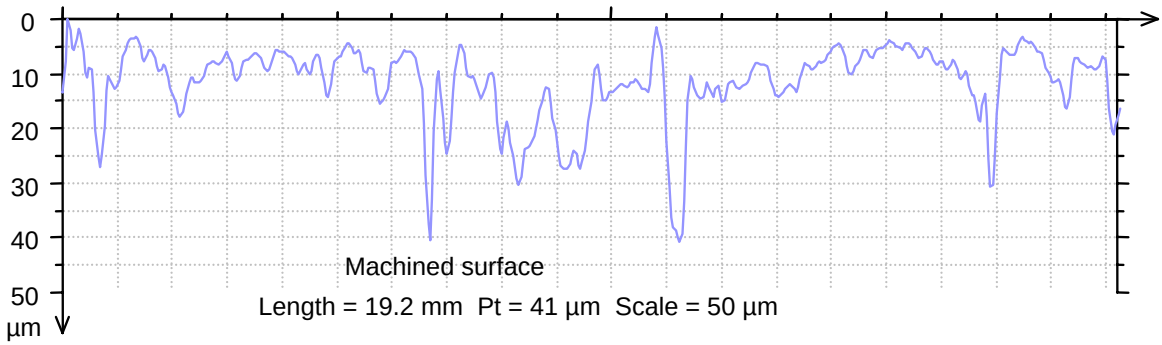

Figure 3. The surface profile of the machined surface of RM-04-BR mock (shown) was rougher than pressed surfaces.

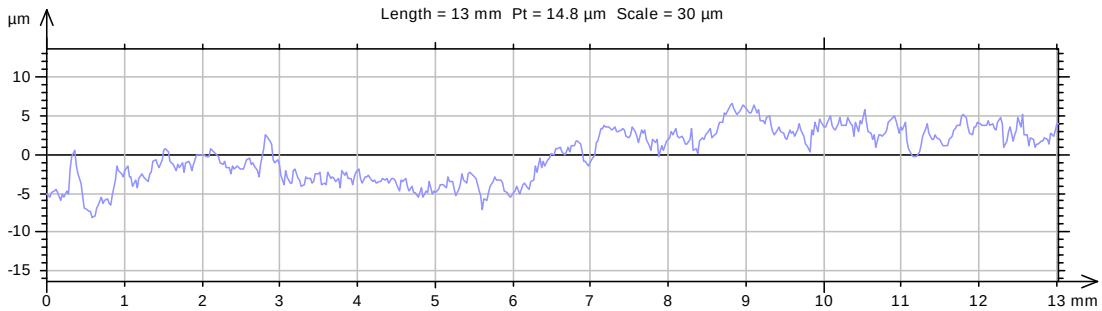

Figure 4. This surface profile of pressed surface of LX-04 explosive gave R_a = 0.55 µm and was similar to pressed surface of mock (not shown; R_a = 0.37 µm).

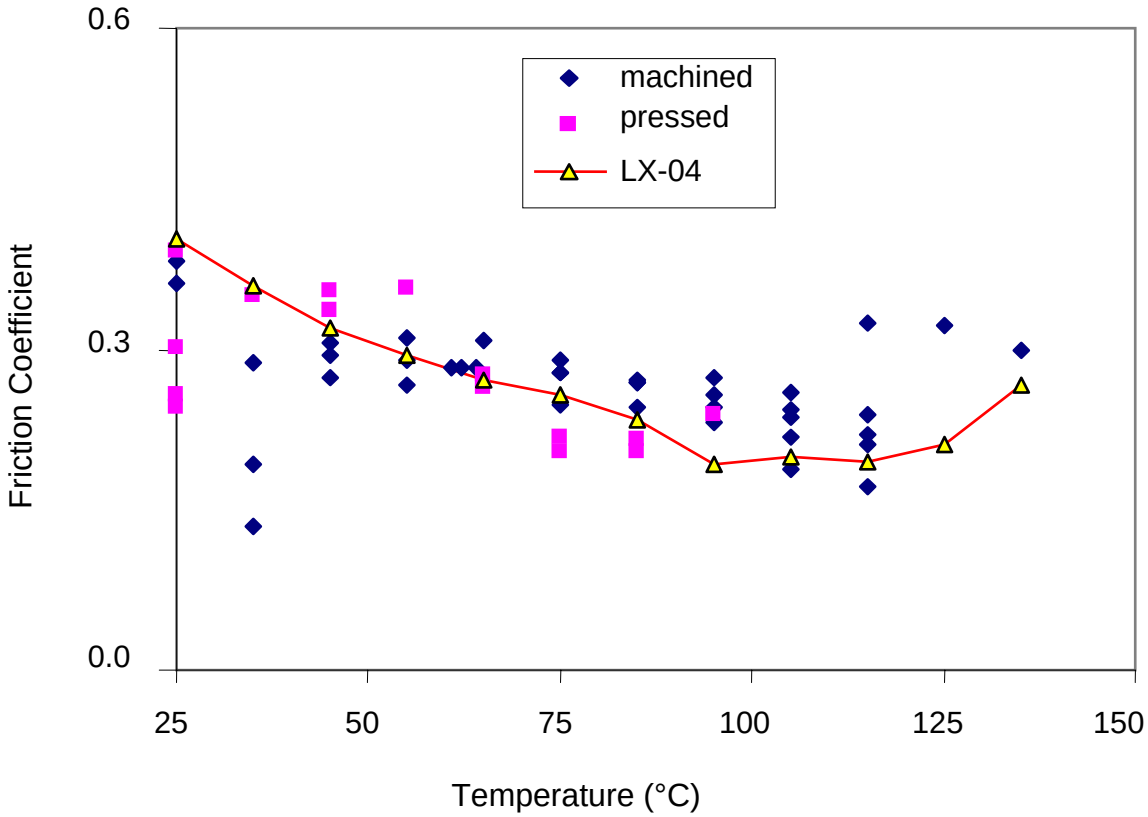

Fig 5. Coefficient of friction from RM-04-BR and LX-04 on stainless steel all decreased with increasing temperature up to approximately 100°C, then increased slightly.

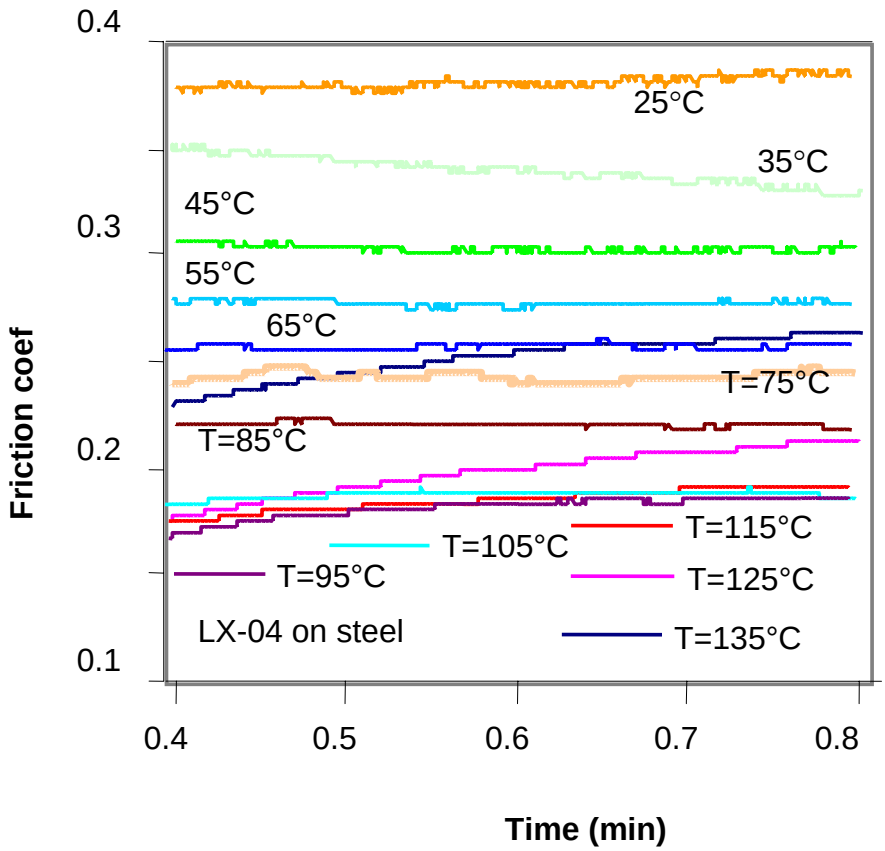

Figure 6. Estimates of the coefficient of friction for LX-04 on steel at each temperature were nearly constant after an initial upswing up to about 125°C.

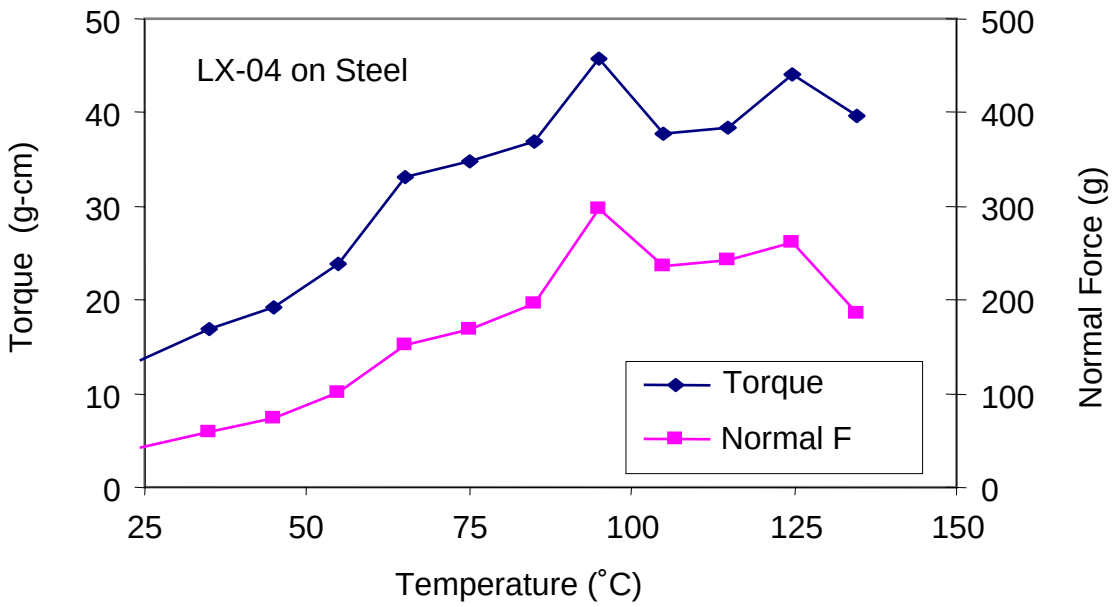

Figure 7. Average torque values followed the normal force for LX-04 on steel in the steady state region of the measurements.

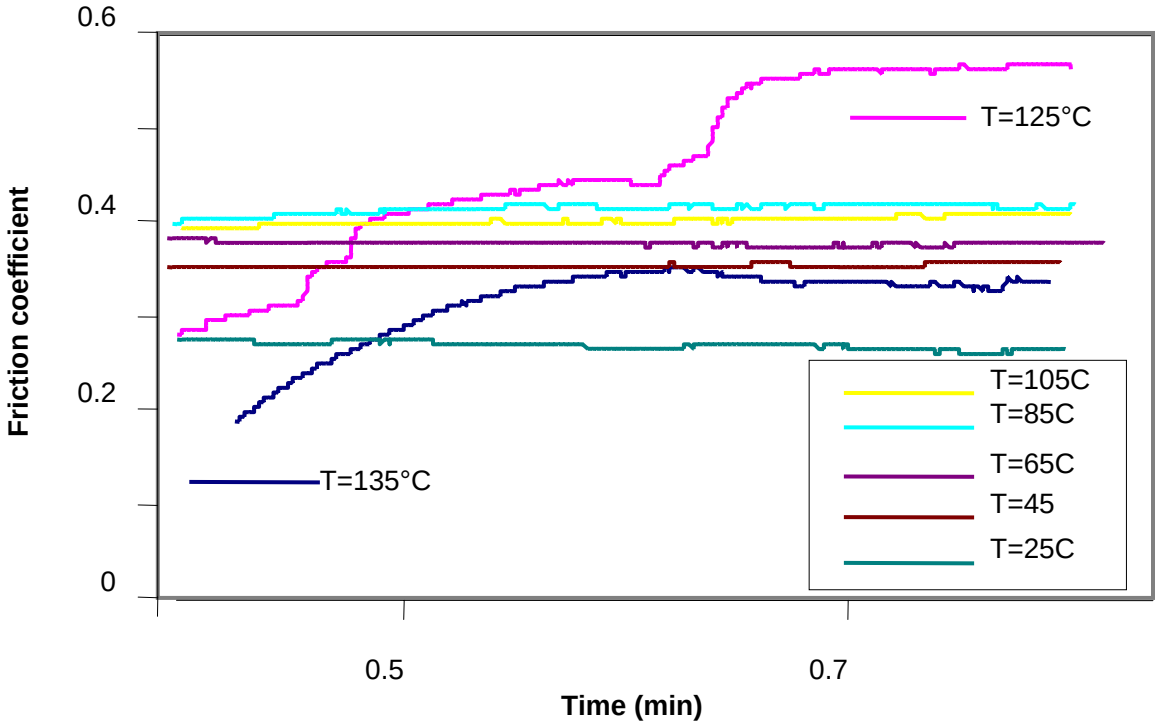

Figure 8. Estimates of the coefficient of friction for LX-04 on aluminum at each temperature were based on the average of the 3T/2Nr calculations and were nearly constant after an initial upswing while the cushion relaxed up to about 125°C.

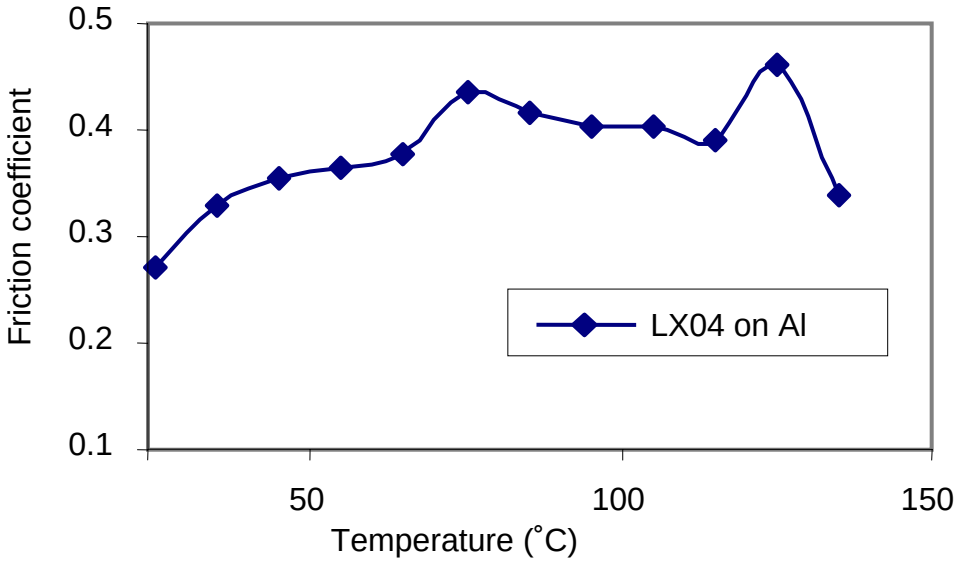

Figure 9. Coefficient of friction as a function of temperature of pressed LX-04 on aluminum increased with temperature. The opposite effect was seen on stainless steel.

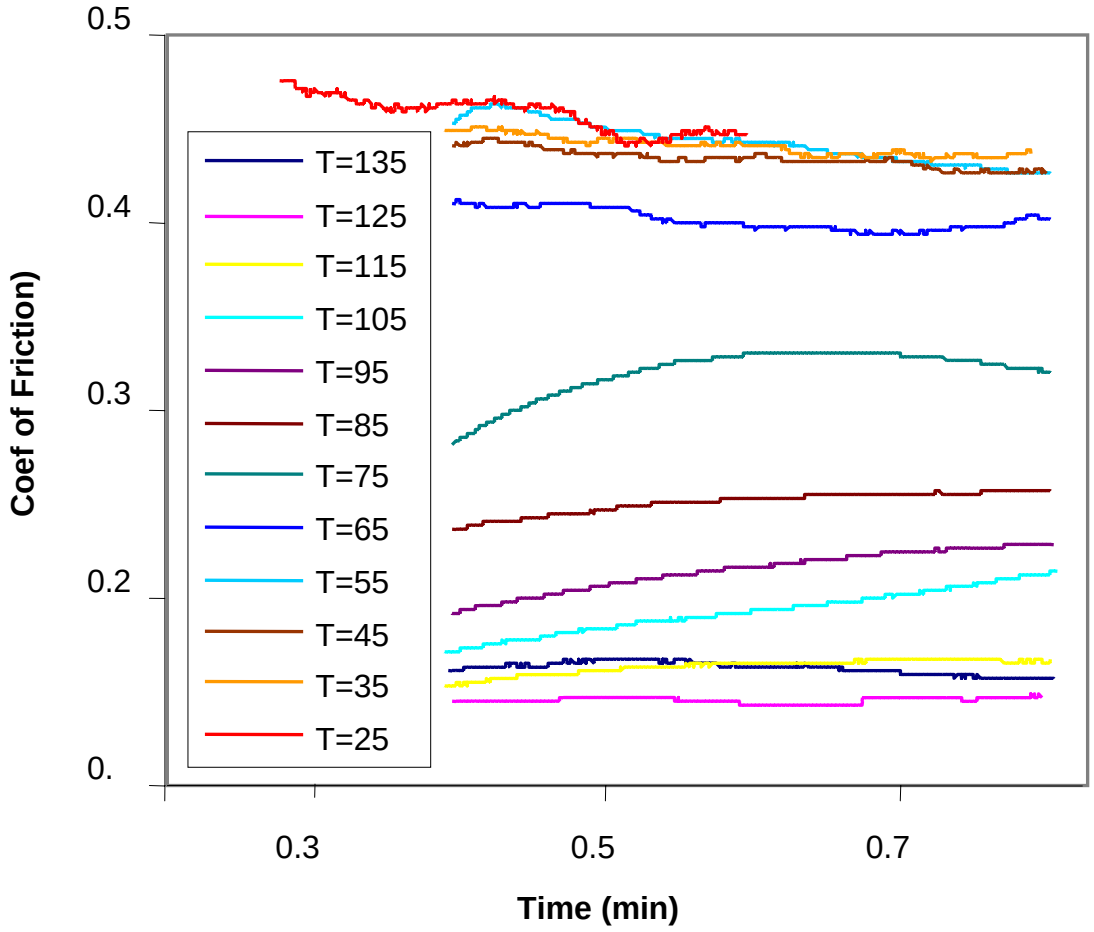

Figure 10. Calculated values of μ for LX-04 on PTFE were reasonably constant except between 75 and 105ºC during the transition from high to low values.

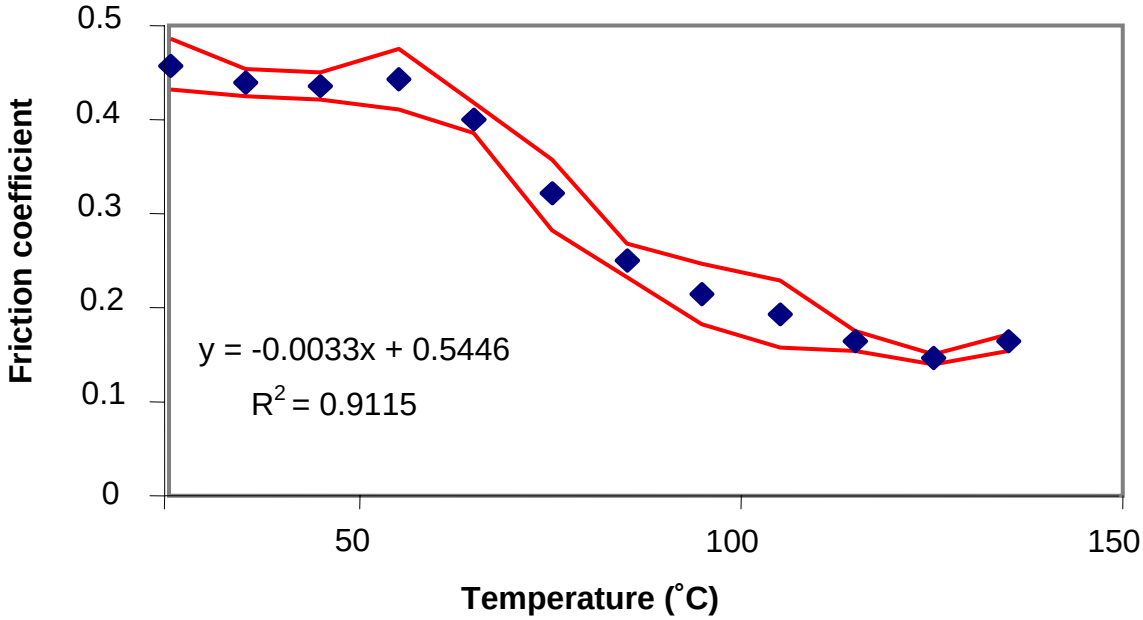

Figure 11. LX-04 on PTFE showed lubrication behavior at elevated temperatures, but not at ambient.

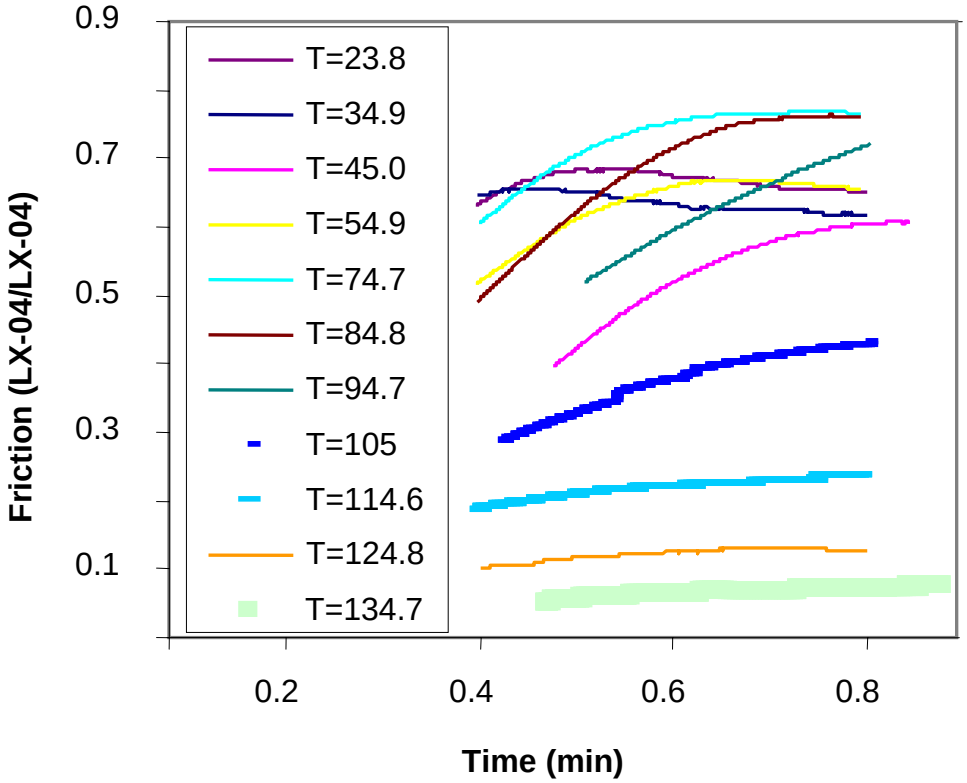

Figure 12. Coefficients of friction estimated for LX-04 on itself did not approach constant values over the 1 minute measurement time at temperatures between 45 < T <95°C.

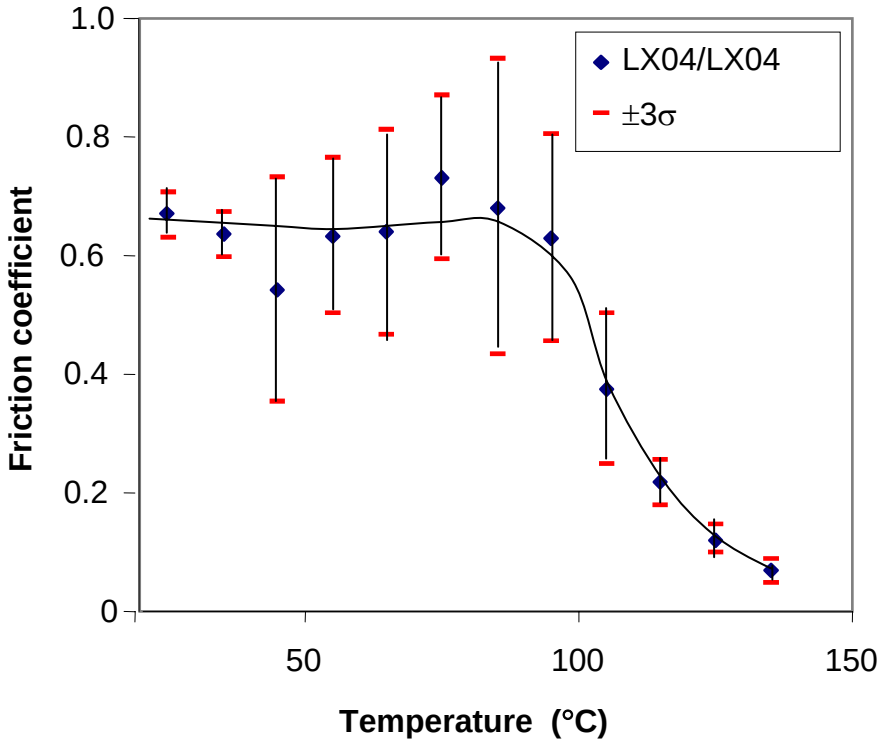

Figure 13. Coefficient of friction estimates for LX-04 on itself dropped off dramatically above about 95°C.

Appendix A – Dynamic coefficient of friction (μ) for LX-04 on different counter surfaces as a function of temperature

Temp(°C) Substrate	Ave μ **Aluminum**	± std.dev. Ra=0.31μm	Ave μ **Stainless**	± std.dev. Ra=0.40μm
25	0.2705	0.0037	0.3808	0.0026
35	0.3297	0.0035	0.3395	0.0061
45	0.3549	0.0017	0.3027	0.0015
55	0.3655	0.0024	0.2772	0.0012
65	0.3786	0.0019	0.2568	0.0011
75	0.4349	0.0020	0.2426	0.0020
85	0.4155	0.0047	0.2204	0.0010
95	0.4017	0.0052	0.1812	0.0046
105	0.403	0.0046	0.1878	0.0017
115	0.3904	0.0156	0.1849	0.0051
125	0.4614	0.0928	0.1982	0.0105
135	0.338	0.0070	0.2512	0.0096

Temp(°C) Substrate	Ave μ **PTFE**	± std.dev. Ra=0.054μm	Ave μ **LX-04**	± std.dev. Ra=0.55μm
25	0.4579	0.0091	0.6667	0.0126
35	0.4408	0.0048	0.6357	0.0129
45	0.4341	0.0048	0.5413	0.0631
55	0.4428	0.0108	0.6321	0.0433
65	0.4016	0.0056	0.6388	0.0572
75	0.3204	0.0125	0.7303	0.0461
85	0.2508	0.0056	0.6817	0.0828
95	0.2145	0.0107	0.6307	0.0582
105	0.1927	0.0116	0.3744	0.0426
115	0.1635	0.0039	0.2175	0.0129
125	0.1453	0.0016	0.1218	0.0085
135	0.1627	0.0031	0.06731	0.0062

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