Contrails

FRICTIONAL FORCES AND LUBRICATION OF TEXTILE FABRICS AT HIGH SLIDING VELOCITIES

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Introduction

The study of the frictional properties of fabrics has never received much attention in textile research, although some work has been done on the frictional properties of fabrics and their relation to hand. It is true that increasing research, especially in England and Sweden, has been directed toward a study of frictional properties of textile materials, but almost all of this work has been concerned with fibers and yarns, for these are of great importance in the textile processing of fabrics. However, the lack of an adequate basic knowledge concerning the friction of fabrics is not serious, as there is a good understanding of friction per se based on research performed upon metallic, non-metallic objects and fibers. This knowledge has been applied in our particular investigation.

Our investigation of fabric to fabric friction has been initiated and supported by the United States Air Force, Wright Air Development Center, Materials Laboratory, because of the damage caused to parachute materials by rubbing and the resulting frictional heat. In particular, the so called "line burn" phenomenon appearing on canopy cloth after its use.

The damage to the cloth appears as torn and melted fabric and is caused by the rubbing of two fabric surfaces under load and moving at a high velocity. Since the surfaces are nylon, which has a melting point of 480°F., the result of rubbing is that often while in use the fabric surface may reach this temperature at points of contact. If this temperature is attained, then fusion of the nylon occurs and the fabric surface is destroyed as indicated by the appearance of holes (see Figures 107 and 108). This is, of course, extremely serious and must, if possible, be prevented.

Basic information indicates that frictional heat can be lowered by reducing the coefficient of sliding friction, and this can be effectively done by the use of lubricants. In addition, lubricants generally possess low coefficients of thermal conductivity. That is, heat produced by friction will not pass through the layer of lubricant quickly (in effect, an insulating layer is present); hence, the temperature build-up on the fabric surface is lessened and the melting temperature of the nylon fabric may not be reached.

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Therefore, it was decided early in this project to construct a machine which would be capable of attaining the high speeds, estimated to be between 60 and 140 feet per second, encountered by parachute materials. This apparatus was so devised as to rub the canopy cloth against shroud line in such a manner that the frictional forces and the effects of lubricants upon these forces could be measured. The apparatus is described in the following section.

Description of the Apparatus

The apparatus is designed to utilize the belt-friction formula $\frac{T_2}{T_1} = e^{\mu\theta}$ where T_2 is the tight and T_1 is the slack tension of the cord, μ is the static or the sliding coefficient of friction, and θ is the angle of contact or wrap of the cord about the pulley. By means of this apparatus, it is possible to study sliding coefficients of friction.

The apparatus shown in Figure 109 was designed in the following manner: A cast iron pully A, five inches in diameter and two and one-half inches in width, has a slit across its width which is wide enough to accomodate a double thickness of nylon fabric. A strip of fabric cut parallel to the warp yarns two and one-half inches wide and about 2 feet in length is tightly wrapped around the pulley, and the ends fastened securely to the underside of the pulley with masking tape. The shroud line F is attached to the strain gauge B drawn around the frictionless pulley C and wrapped around the pulley A for in this instance an angle of wrap of 360°. The shroud line then passes over the frictionless pulley D, and a weight W is suspended from its end. It can be seen that it is easy enough to vary the angle of wrap.

The pulley A is attached to a shaft G which is driven by a motor. The pulley is capable of being driven at four different peripheral linear speeds (24.0, 35, 52.0 and 76 feet per second) by a multiple pulley arrangement. The output of the strain gauge B is fed through an electronic system and the forces registered on a Brown "Electronik" potentiometer strip chart recorder.

It has been established in our investigation that the coefficient of sliding friction can be calculated through the use of the belt friction formula,

$$\frac{T_2}{T_1} = e^{\mu_k \theta}$$

The tight tension, T_2, is found by reading the minimum force at sliding on the Brown recorder and subtracting from this force the weight of the line from the frictionless pulley to the strain gauge. The slack tension, T_1, is found by determining the weight of the line from the frictionless pulley to the known attached weight and adding the weight of the

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line to the known weight suspended from the end of the line. The angle of wrap or contact, θ , can be easily found by use of a protractor; therefore, the sliding coefficient of friction, μ_k, can be calculated by substituting the experimentally determined values of T_1, T_2 and θ into the belt friction formula.

The Relationship of Frictional Forces and Fusion to Fabric Finish

Once preliminary results had indicated that the apparatus was capable of reproducing "line burns" (see Figure 110), and that the apparatus could also measure the frictional forces involved, tests were run on scoured cloth and line, as well as cloth and line as received from the manufacturer.

The study of lubrication was also begun on a greater number of possible commercial lubricants, as well as some pure chemical compounds.

Results

Scoured line and cloth (cut parallel to the warp yarns)* were tested in order to establish a basis for comparison with lubricated material. Table 1 shows the tensions involved and the resulting *sliding coefficient* of friction. It will be observed that the angle of contact, load and speed are all of a low value; whereas the coefficient of sliding friction increases to a higher value with increasing load. Any values higher than the last values of slack tension, T_1, cause instantaneous fusion and tearing. In addition, samples with the cloth cut on a 45° bias to the warp yarns, were tested and the results are also given in Table 4. This was done in order to establish whether or not the angle of sliding, using the warp yarns as a reference point, causes any significant difference in μ_k with respect to T_1. It may be seen that the significance is slight.

Unscoured cloth and shroud line as received from the manufacturer was also tested. The cloth, in addition to a small amount of spinning oil, contained an anti-tear agent. It was found that 0.5% of extractables was present on the cloth. The line contained only the spinning oils as received from the throwster and had 0.60% extractables. Table 2 shows that a higher order of speed, angle of contact and load can be reached before the onset of fusion and tearing, if this relatively small amount of surface finish is present.

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* Unless otherwise noted, this is the normal method of cutting cloth samples.

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For rapid characterization of lubricants, it was decided after preliminary investigations to run two samples of lubricated shroud line against scoured cloth. It was found that if an effective lubricant is present, a still higher degree of protection is afforded the lubricated sample against fusion than untreated samples, as demonstrated by the increase in speed (to 76 feet per second) and load withstood by the fabric.

(A summary of these findings, covered in the previous sections, is given in Table 3)

Furthermore, it has been possible to separate good from poor lubricants upon a basis of slack tension, at a constant angle of wrap, 360°, and speed, 76 feet per second. The lubricant is considered to have failed to have fulfilled its proper role of preventing fusion if fusion occurs at an experimentally determined slack tension, with the standard conditions of speed and wrap mentioned above. Therefore, by determining at which slack tension fusion results, the lubricants may be arbitrarily arranged into four classes. These classes are as follows:

Class I - lubricants which allow the nylon to fuse immediately at a slack tension of 22 grams under standard conditions of speed and wrap.

Class II - lubricants which allow the nylon to fuse in the slack tension range of 23 - 52 grams.

Class III - as in Class II, only the slack tension range is from 53 - 102 grams.

Class IV - as in Class II, only the slack tension range is from 103 - 200 grams.

Those lubricants which are in Class IV are considered best. Those in Class III, next best, and so on until Class I is reached, and this class of lubricants is considered to have little value in the prevention of fusion. A Table (4) is shown of such a classification of lubricants.

An interesting aspect of our continuing study of lubrication is the tentative results indicated upon relating lubrication, as it is understood in the prevention of fusion, to the polarity or non-polarity of the lubricant. Preliminary results from a study of approximately seventy possible lubricants appear to show that those lubricants which are essentially of the non-polar type, e.g., methyl stearate, stearic acid,

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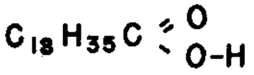
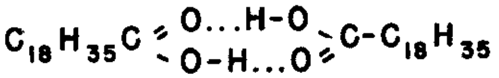
butyl stearate, and those which, in the surface-active nomenclature, are called nonionics, are in the better class according to our aforementioned classification. In contrast, materials which are more polar in nature, e.g., perfluoroctanoic acid, lauric acid, capric acid and dodecyl alcohol, and materials which are anionics or cationics, are poor lubricants, falling in Class I of our arbitrary designation.

Commercial samples of trifluorovinyl chloride appear to be an exception to the above. None of three samples in the m.w. range of 500 to 1000 of trifluorovinyl chloride were able to prevent fusion at a slack tension of 22 grams and, therefore, were placed in Class I. From a cursory glance at the structure of the polymer, one would expect that the fluorolubes ought to be non-polar in nature. However, because of the presence of the very strong electro-negative element fluorine in the structure, the carbon to fluorine bond is shortened as well as the carbon to chlorine bond. This makes for a compact, chemically inert structure. On the other hand, it may be that the fluorine confers a high degree of polarity to sections of the structure, resulting in strong dipoles. Perhaps, then, the polymers of trifluorovinyl chloride may be qualitatively classified as other polar compounds.

Consequently, upon the basis of our experimental results, the separation of good and poor lubricants may be possible by a study of their nature as surface-active agents, or as polar or non-polar types of materials. If these general results are shown to be valid by further investigations, then the study of fabric lubrication will be somewhat simplified. That is, no longer will it be necessary to operate on a trial and error basis in our study of a large number of lubricants, but, instead, it will be possible to winnow those which may be effective from those which may not be effective on the basis of polarity or non-polarity.

In addition, a study of such compounds as myristic, n-capric, palmitic, oleic, linoleic, and ricinoleic acids indicates that molecular weight may be one of the factors in lubrication. For example, myristic acid (Class I) has a m.w. of 228, and because of association through hydrogen bonding, its m.w. increases to approximately 456, while stearic acid (Class II) has a m.w. of 284, and again through association its m.w. is increased to approximately 578. Generally, it is found that in the case of the fatty acids those possessing molecular weight below 500 are not good lubricants. Not only does association tend to increase the molecular weight to a more desirable value, but association also appears to cause the molecule to become of a more "nonionic" type. Thus, stearic acid,  $C_{18}H_{35}C\begin{array}{l}=O\\ -O\text{-}H\end{array}$, would presumably be of the "anion" type, but, as it possesses a double molecule, thus


$$C_{18}H_{35}C\begin{array}{l}=O\ldots H\text{-}O\\ -O\text{-}H\ldots O\end{array}\begin{array}{l}-\\ =\end{array}C\text{-}C_{18}H_{35}$$

This results in the molecule being longer and more "neutral."

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Relative Humidity and Frictional Forces (Figure 111)

A study of relative humidity and frictional forces was made at 11%, 60% and 71% levels under standard conditions of slack tension, 103 grams, angle of wrap (360°) and speed (17 feet per second). It was found that the forces, in all cases studied, rose initially to a maximum and then decayed in approximately two minutes to a constant value. The initial values for the frictional forces are high, but after approximately two minutes, no significant difference exists between the forces for each humidity. The difference between the initial reading and the decline to a constant value can be accounted for if one assumes that the heat of friction is drying the fabric, and that dry nylon has a lower coefficient of friction than nylon containing moisture. It is seen then that this assumption can be justified by the following: (1)from the initial differences in forces, (2) from the shapes of the curves, and (3) from the fact that under constant conditions, after two minutes running, no differences exist in frictional force at different values of relative humidity.

Results

The sliding coefficient of friction

From the calculation of the sliding coefficient of friction in all instances studied, it was observed that the coefficient of sliding friction is not always constant with respect to the slack tension. In the case of scoured material, the coefficient of sliding friction tends to rise. In the case of the unscoured material, it generally tends to remain at a constant value within the range of slack tensions studied; while for those materials which are good lubricants, i. e., are effective in preventing fusion at high speeds (76 feet per second) and loads, preliminary results indicate that as the load increases at constant speed, the sliding coefficient of friction tends to decrease, e. g., for butyl stearate from 0.14 to 0.12. It is believed that this is a significant decrease as all lubricated material in Classes II, III, and IV show this same general trend. Table 5 shows a summary of these general results.

It is therefore obvious that our study indicates that Amonton's Law, $F = \mu R$ where F is the frictional force, R is the load and μ is the coefficient of friction does not apply. (Such a failure of Amonton's Law also has been found in studies of fibers and yarns.) Consequently, $\frac{T_2}{T_1} = e^{\mu\theta}$ is not valid for our work as μ is the constant which appears in the relationship of Amonton's. The use of μ can only be justified if this failure is kept in mind, and the "μ" calculated is used to indicate increasing or decreasing ratios of T_1 and T_2.

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Summary

To summarize our work up to the present: An apparatus has been constructed through which it is believed frictional forces, fusion and the effects of lubricants may be studied at relatively high speeds. Preliminary results indicate that proper surface finishes are effective in the prevention of fusion under conditions of high loads and speed. Relative humidity undoubtedly plays an important part in the frictional process, as high relative humidities seem to increase the frictional force. Lastly, Amonton's Law is not apparently valid, as indicated by the variability of the sliding coefficient of friction.

It is obvious that many questions still remain to be answered, and further work will be pursued in an effort to clarify these questions.

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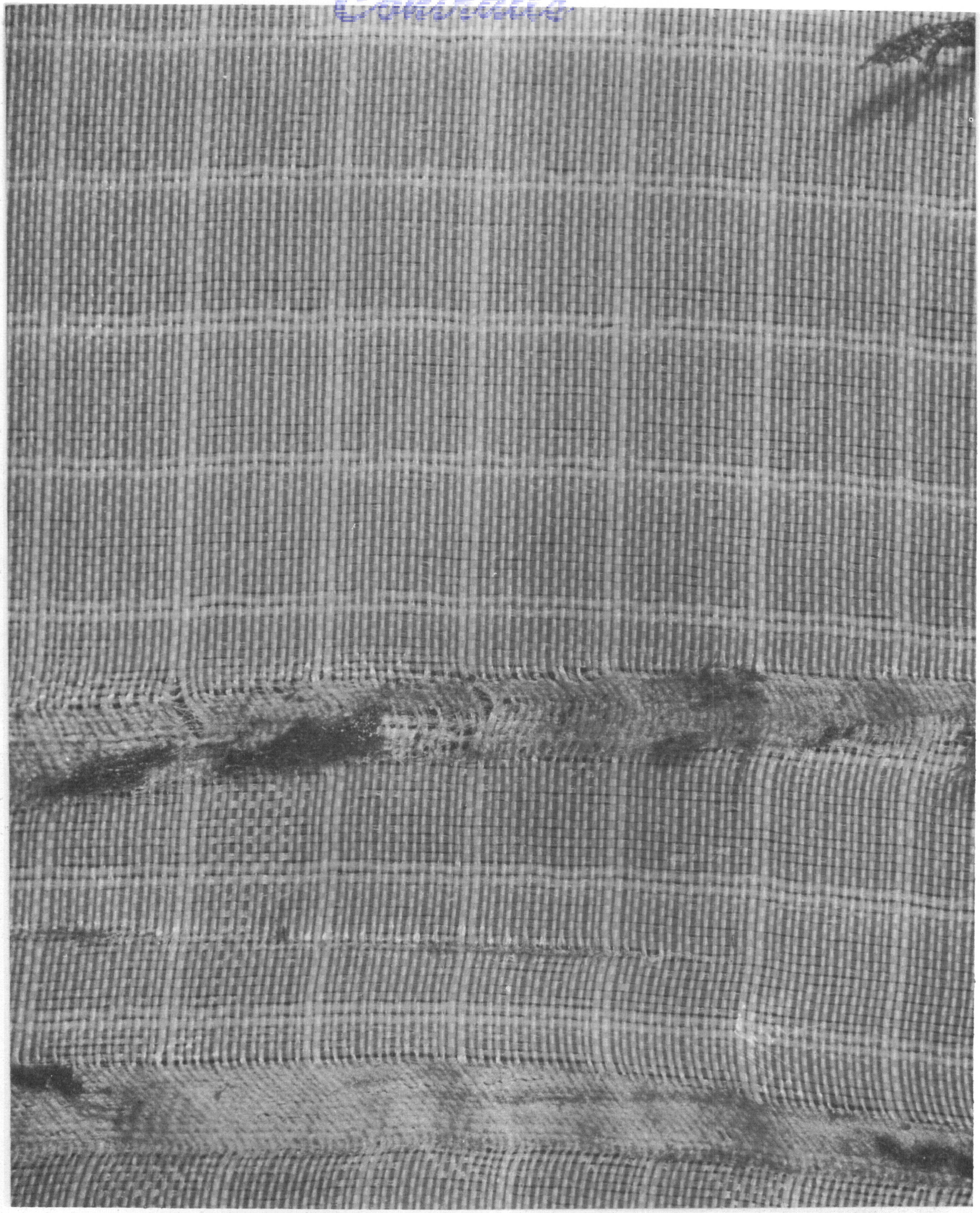

Figure 107. Damaged Fabric Due to Rubbing.

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Figure 108. Damaged Fabric Due to Rubbing.

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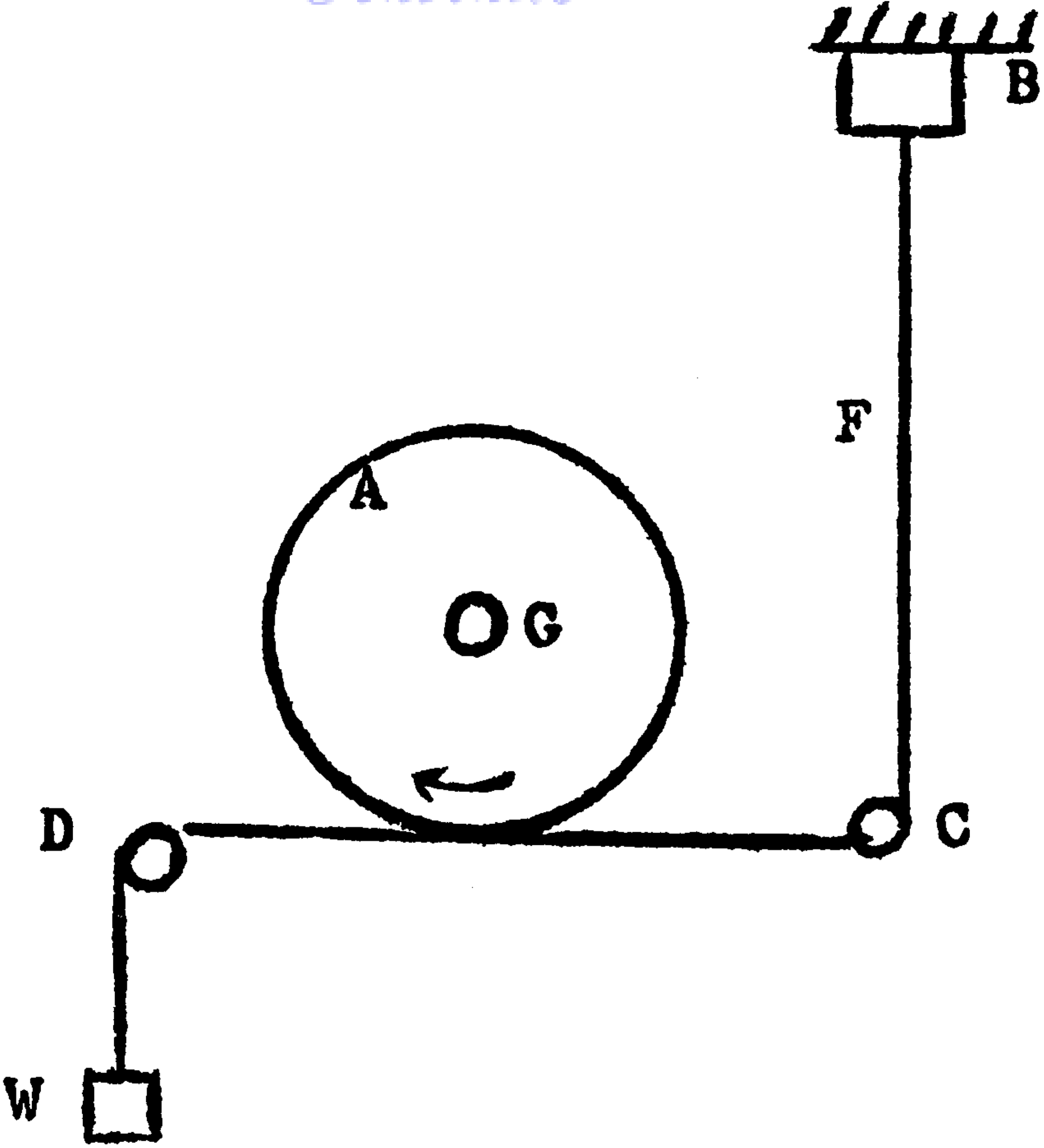

Figure 109. High Speed Friction Apparatus.

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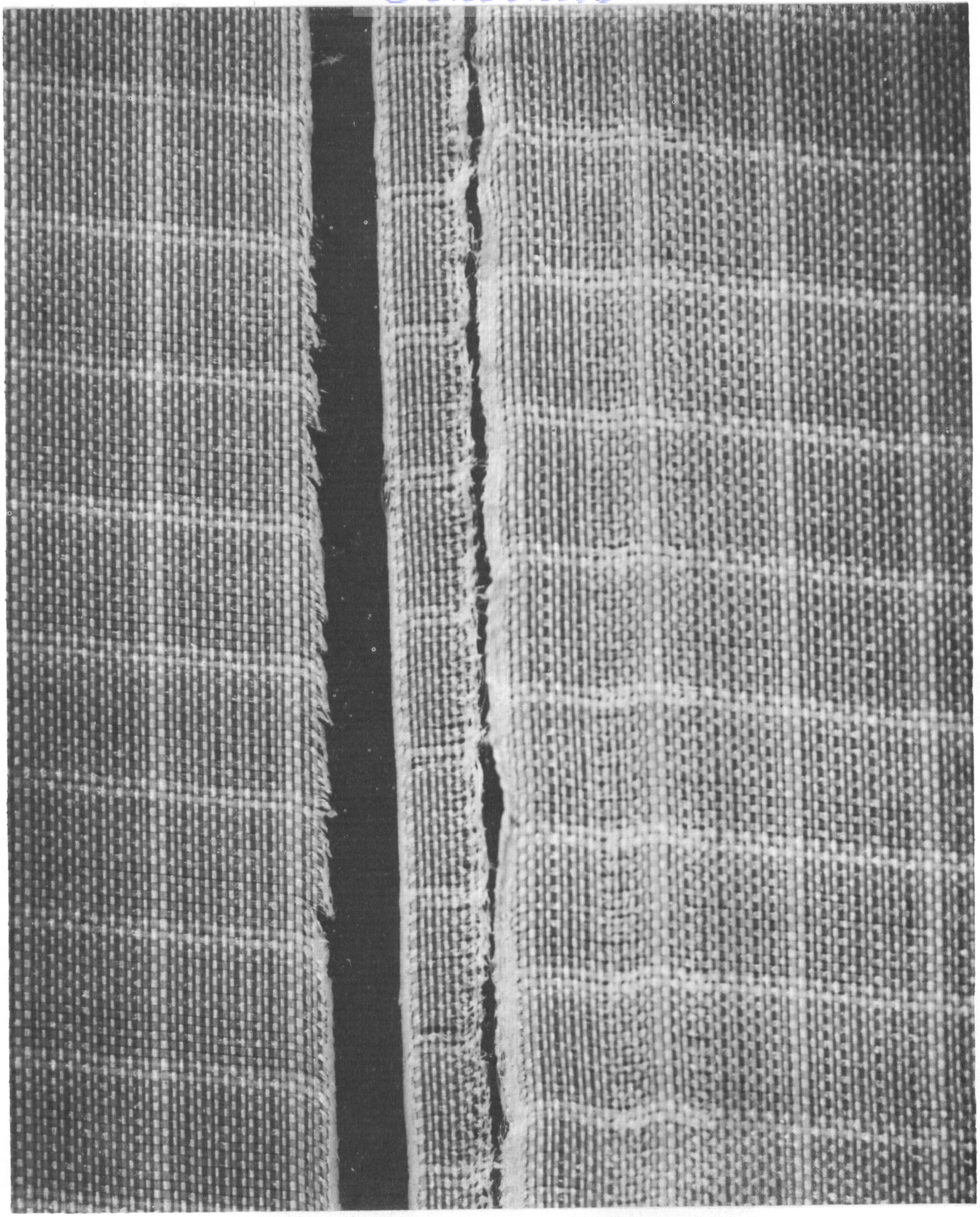

Figure 110. Line Burns.

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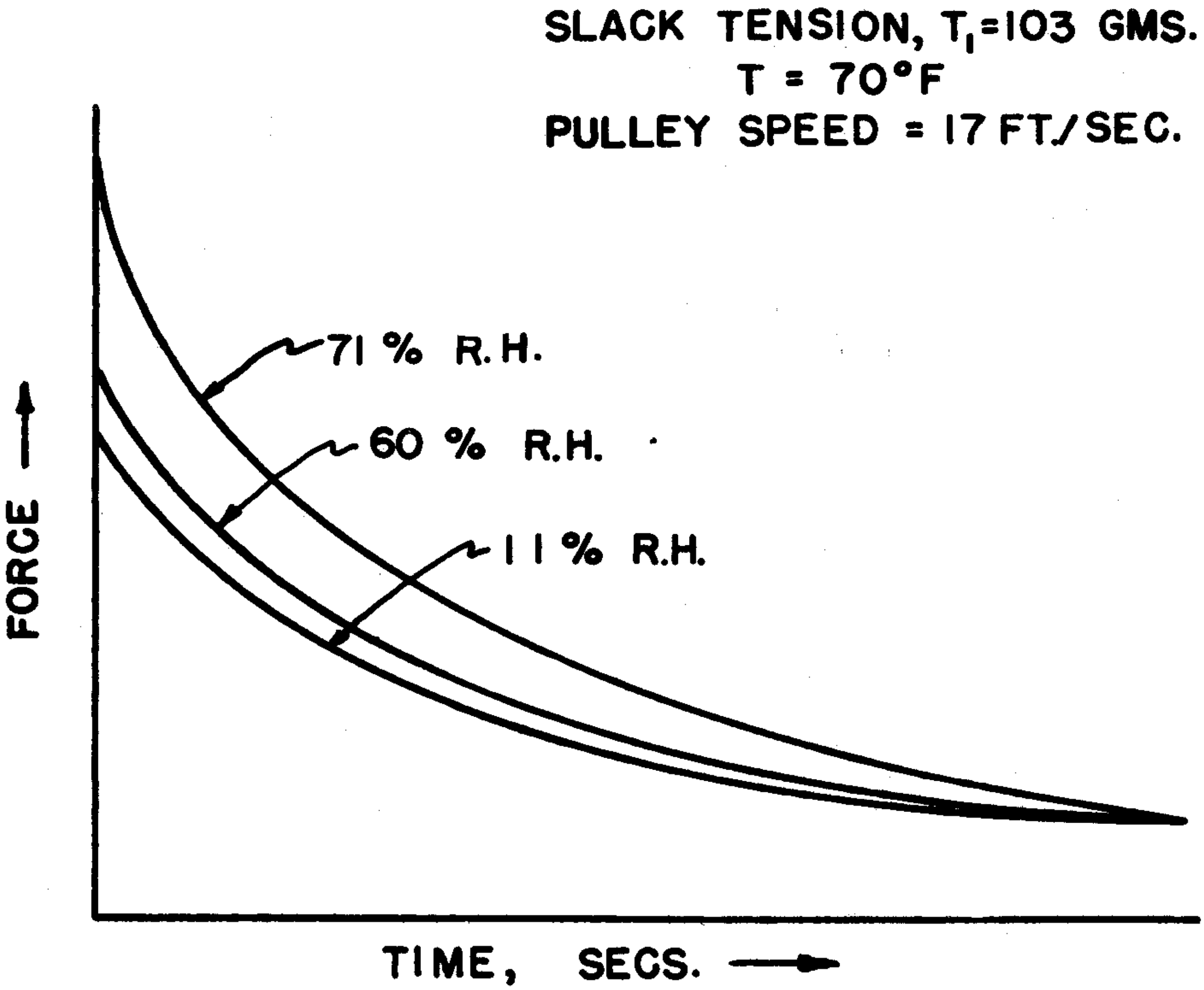

Figure 111. The Effect of Relative Humidity on Frictional Force.

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	Scoured Cloth and Line Angle of Wrap 360°				Scoured Cloth (cut on a 45° bias) and Line Angle of Wrap - 90°			
	24 ft/sec		35 ft/sec		24 ft/sec		35 ft/sec	
$\bar{T}_1$, Grams	$\bar{T}_2$, Grams	μ_k	$\bar{T}_2$, Grams	μ_k	$\bar{T}_2$, Grams	μ_k	$\bar{T}_2$, Grams	μ_k
8	10	0.14	11	0.21	10	0.14	12	0.25
13	18	0.21	25	0.42	18	0.21	23	0.36
18	—	—	33	0.38	—	—	34	0.40
23	35	0.27	39	0.34	—	—	52	0.52
33	66	0.44	Fusion		49	0.25	Fusion	
43	81	0.40			—	—		
53	Fusion				97	0.38		
					Fusion			

Table 1. The Effect of Slack Tension, T_1, upon the Tight Tension, T_2, and the Sliding Coefficient of Friction, u_k, Using Scoured Cloth and Line.

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Linear Speed = 52 ft/sec Angle of Wrap = 360°			
	T_1, grams	T_2, grams	μ_K
1.	13	41	0.18
2.	18	59	0.19
3.	23	75	0.19
4.	28	93	0.19
5.	33	108	0.19

Table 2. The Effect of Slack Tension, T_1, on Tight Tension, T_2, and Sliding Coefficient of Friction, u_k, using Cloth and Line as Received from the Manufacturer.

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	Scoured Cloth and Line	Cloth and Line as received from Manufacturer	Lubricated Line—Scoured Cloth
Angle of Wrap of Line, θ	90°	360°	360°
Speed (max), ft/sec	35	52	76
Slack Tension, T_1 (max) grams	23	32	203

Table 3. The Effect of Increasing Surface Finish upon Angle of Wrap, Speed and Slack Tension.

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Pulley Speed = 76 ft/sec **Angle of Wrap = 360°**		
CLASS I **(Fusion at a Slack Tension of 22 Grams)**		
Myristic Acid		Molecular Weight
M-Capric Acid		2 x 228 ≅ 456
Lauric Acid		2 x 172 ≅ 344
Dodecyl Alcohol		2 x 200 ≅ 400
Cyclohexyl Maleate		N x 186 ≅ 186N
		198
10 Commercial Samples	Anionic or Cationic	
CLASS II **(Fusion at a Slack Tension of 23 to 52 Grams)**		
Palmitic Acid		2 x 256 ≅ 512
Stearic Acid		2 x 284 ≅ 578
Ricinoleic Acid		2 x 298 ≅ 596
Myristyl Alcohol		N x 214 ≅ 214N
0 Commercial Samples	Nonionic	
CLASS III **(Fusion at a Slack Tension of 53 to 102 Grams)**		
Linoleic Acid		280 x 2 ≅ 560
Oleic Acid		282 x 2 ≅ 564
Methyl Stearate		312
Butyl Stearate		340
5 Commercial Samples	Nonionic	
CLASS IV **(Fusion at a Slack Tension of 103 to 200 Grams)**		
Butyl Stearate		340
Butyl Cellosolve Stearate		362
Methyl Cellosolve Stearate		368
8 Commercial Samples	Nonionic	

Table 4. Lubricants.

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T_1 Grams	Scoured Cloth & Line (24 ft/sec)	Cloth & Line as Received from Manufacturers (52 ft/sec)	Lubricated Line (Methyl Stearate - Scoured Line (76 ft/sec)
8	0.14		
13	0.21	0.18	
23	0.26	0.19	0.16
33	0.44	0.19	0.14
43	0.40		0.14
52			0.14
62			0.13
72			0.13
82			0.12

Table 5. The Effect of Surface Finish and T_1 on the Sliding Coefficient of Friction, u_k.

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