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High Speed Measurements of Dry Adhesion as Related to the Friction and Abrasion of Elastomers

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INTRODUCTION

It is well recognized that friction and abrasion of materials are a function of forced sliding, but the mechanism of this action is not too well understood, even in this enlightened age. The traction and wear obtained with automobile tires is a particularly good example of these phenomena but one that has been clouded by the complexities involved in the dynamic behavior of the pneumatic-tired wheel.

The advent of the butyl tire, with its widely recognized high coefficient of friction or road holding traction, has actually been an aid in highlighting the mechanism of friction with elastomers. Samples of butyl, SBR, and natural rubber tire tread stocks exhibit large differences in their coefficient of friction. This has been described as being largely due to their differences in hysteresis.[1] Hysteresis is a physical property involving time, and this, therefore, brings out the importance of velocity in the testing of friction and abrasion of elastomers.

THE RELATION OF ABRASION TO FRICTION

Abrasion is subordinate to friction, for if the frictional resistance is high enough there may be insufficient movement to cause abrasion but if it is low there may be insufficient resistance to cause it. This is particularly true with pneumatic tires, for the tread can deform during its short cyclic rolling contact and reduce the amount of abrasive scrubbing if friction is high, or it can deflect to pass over obstructions if the frictional resistance is low. The rate of abrasion, however, is always greatest under conditions where the frictional resistance is highest and movement is forced. This can be seen with an automobile tire under high torque (Fig. 1). In this case the abrasion occurs at the leading area of the tire-to-road contact patch. Here the tread rubber is being forced down into the road by the rolling wheel. It is then compressed horizontally and forced to slide by the geometric compression of rolling and driving torque.[2] These are the conditions that create a maximum of friction and abrasion. To illustrate this condition, the tread wear on an automobile tire that had been driven in the rear wheel position under high torque obtained by pulling a heavy load is shown in Figure 2. This photograph highlights the abrasion patterns showing that the abrasion was caused by inward and backward movement, as indicated also by the arrows. Such movement can only occur at the leading edge of the contact area, for at the trailing edge the movement is a rapid outward and backward movement.

This concept of the location of wear due to high torque is contrary to the general opinion. It has been stated that under high torque most of the wear occurs at the trailing edge of the contact where the tire tread leaves the road and where most of the slip occurs.[3] However, slip is not necessarily conducive to high wear. In fact, at high slip velocities the wear is usually less than at creep velocities. Furthermore, at the rear end of the contact patch, the tread rubber is being relieved of both its vertical and horizontal compression and is therefore going into a state of relaxation. This causes it to release its grip on the road and to slip with little or no abrasion.

THE IMPORTANCE OF AUTOMOBILE TIRE FRICTION

Without friction we would have no wear, but there would also be no traction between a tire and the road. As frictional resistance to sliding increases, the wear also increases if movement is forced. Fortunately, however, where the frictional resistance between the tire and road is higher the amount of forced movement will be less. This is clearly demonstrated by comparing the amount of slip occurring with butyl and SBR tires. It has been found that under most equivalent driving conditions the butyl tires slip some 20 to 40% less

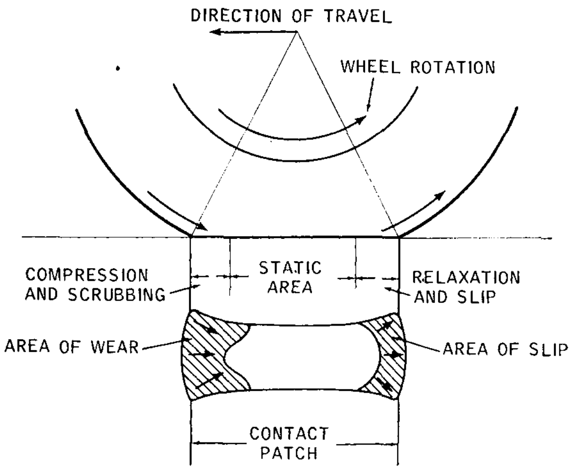

Fig. 1. Tire wear under high torque.

than SBR tires of similar design. This condition maintains for panic stops, high torque hill climbing, or in negotiating sharp corners. The front wheel steering angle required by a 1958 Pontiac to make a 60-ft. diam. circle at speeds of 2 to 20 m.p.h. when equipped with butyl and SBR tires is shown in Figure 3. The curves indicate that control of this vehicle for this radius of turn and road surface would be limited to speeds of about $20^1/_2$ m.p.h. for the SBR tires, but much higher speeds would be possible with the butyl tires. Measurements of the actual slip angles show that the butyl tires were slipping about 20% less than the SBR tires in this circling test.

The actual slip rates for tires during their cyclic contact while cornering and while driving at 60 m.p.h. were also measured, and they were found to be in the order of 20 to 30 in./sec. These are, therefore, the speeds at which friction, abrasion, and the tensile properties of tire tread stocks should be measured.

Fig. 2. Tread abrasion patterns produced by high torque driving.

MECHANISM OF RUBBER ABRASION

In lubricated sliding one of the major parameters in resistance to movement at normal sliding speeds is hysteresis. This is a rate term, and it is influenced quite strongly by velocity and by the frequency of the surface asperities or roughness. However, in dry sliding over reasonably clean surfaces it seems as if adhesion must play a large part.

Adhesion requires static contact and, though it may seem surprising, the maximum of this static or adhesive contact occurs when movement is forced at creep velocities with the one exception being that occurring after long dwell times. As the sliding is continued or the sliding velocities are increased, the surfaces go into a stick-slip contact. Again the stick part of this action would seem to be a short static and adhesive contact or in some cases an interlocking. Many workers argue against the existence of this static contact between moving surfaces.[4] However, in this case static friction is considered to exist where a point of contact, adhesive attachment, or an interlocking is made between the rolling tire and the road which is strong enough to hold and transfer energy from one surface to the other. An example of this concept is that of a bow being drawn across a violin string. In this case intermittent attachments are made between the bow and the string. These are strong enough to energize the string and thus cause it to vibrate at its natural frequency.

RUBBER ADHESION TO THE ROAD

The discussion up to this point has been largely to help show the role of adhesion in the traction and wear of automobile tires. The recognition that dry adhesion could play such an important part in friction, and the realization that when it occurs it may be followed by rupture if the movement is forced, seemed to be a forward step toward a better understanding of the friction and abrasion problem. However, one may ask if a cured tire tread stock really adheres to a surface under conditions such as those existing between a tire and the road.

A road is seldom considered as being very clean. In fact they are usually quite dusty, and the tread of a tire is far from clean also. However, when a tire tread is pressed against a rough and dusty surface the rubber deforms to fit the contour of the surface and envelope the dust particles. In this process it also wipes off the tops of the road asperities that it contacts, and any additional forced

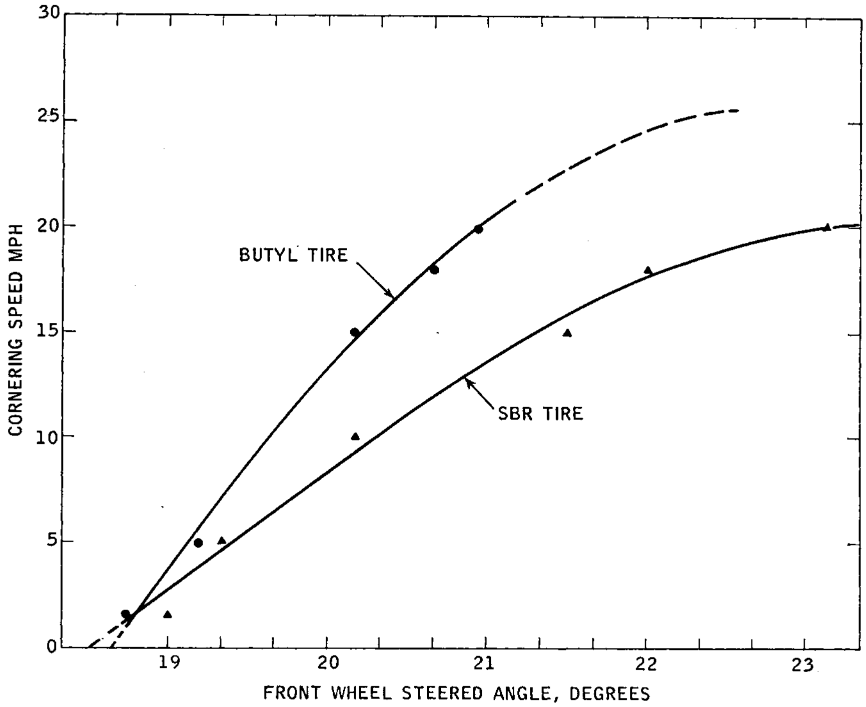

Fig. 3. Steering angle versus speed for 30 ft. radius turn.

movement increases this cleaning action. As the rubber surface is thus deformed, stretched and torn, it also is providing fresh clean rubber surfaces for intimate contact with the very parts of the road that it is wiping clean. This action is actually the same as that used to remove a pencil mark with a pencil eraser.

The abrasion patterns found on a pencil eraser or on a tire tread after use have a profile like that of the teeth on a saw. It is the freshly formed surfaces on the underside of the projections that make contact with the surface being cleaned or, in this case, the road. When a sample of dry cured rubber is pressed against any clean surface, we might concede that there could be some adhesion because it is difficult to make it slide. However, when it is lifted off by hand, there seems to be no adhesion. In this case, the rubber is lifted at a speed less than its recovery rate, and internal forces are helping to release it.

To investigate the phenomenon of dry adhesion we had to lift the sample at rates above the recovery rate of the rubber. Since rubber has a recovery rate in the order of about 1000 in./min., we needed equipment that would load and then separate a sample at rates well above this speed. We were fortunate at this time to have available a Plastechon high speed tensile tester. This machine was capable of pulling tensile samples at rates up to 10,000 in./min. and with some slight modification it was possible to obtain both compression and tension on the Plastechon load cell. With this arrangement samples could be compression loaded up to 50 or more psi and then pulled away at the desired velocities.

HIGH SPEED MEASUREMENT OF DRY ADHESION

The Plastechon is a universal tensile testing machine manufactured by the Plas-Tech Equipment Corp., Natick, Massachusetts. It is capable of measuring stress-strain over a wide range of conditions. This particular model will operate at speeds from 0.2 to 10,000 in./min. Load is measured by a standard load cell and displacement by a transducer on the piston. The load versus elongation, displacement, or time is plotted on an oscilloscope. The piston is operated by a double-acting hydraulic cylinder, servo valve, etc. Its speed is controlled by a servo feedback system and reaches its maximum velocity in a few milliseconds. A photograph of the installation is shown in Figure 4, while Figure 5 is a close-up showing the load cell, rubber test specimen, and styrene contact testing surface.

Figure 6 is a photograph taken from the oscilloscope of the Plastechon showing the loads obtained

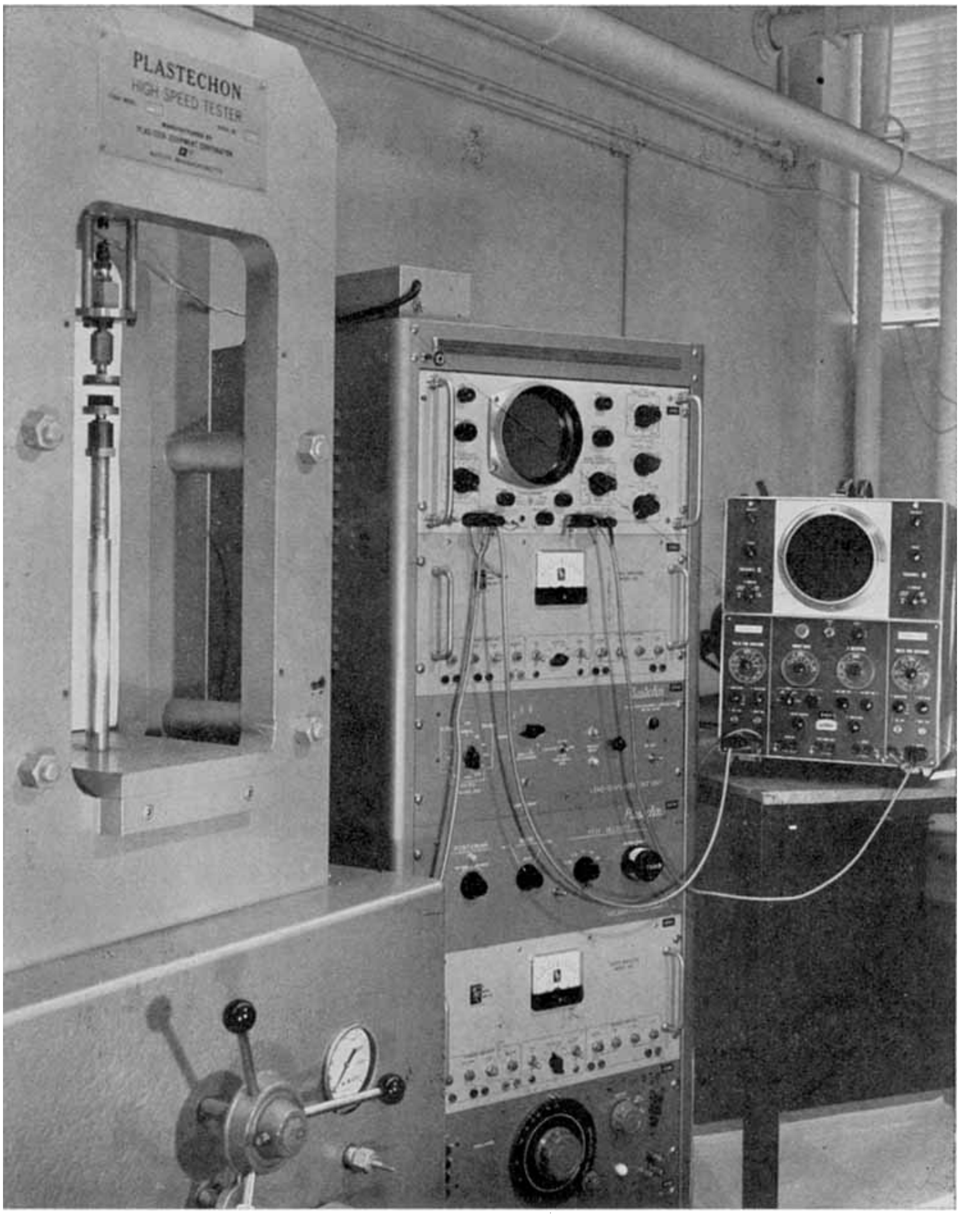

Fig. 4. Adhesion testing equipment.

by pressing a sample of butyl rubber tread stock against a stone-faced plate and pulling it away at about 10,000 in./min. The photograph shows the initial load and the final load or adhesion on the vertical scale, reading below and above the horizontal center line. The scale was calibrated to read 50 lb./cm. In this case the initial load was 150 lb. and the adhesion as shown was about 300 lb. The area of the sample was two square inches. Therefore an adhesion value of about 150 psi was indicated. Since the surface areas were not particularly clean the true contact area must have been only a small fraction of the apparent or measured area. If this 150 psi were increased by a factor to represent only the true contact area, then a force of a few thousand psi may be a more realistic adhesion value for the actual contact area. Such values can easily be above the tensile strength of localized areas in the contacting surfaces, so that rupture and particle loss can occur with forced movement under load.

The data shown in Figure 6 were obtained with a Baldwin SR-4 load cell in the Plastechon and the damped wave following the initial peak load was caused by the ringing of the cell. This ringing was later reduced by changing to a Dynisco load cell

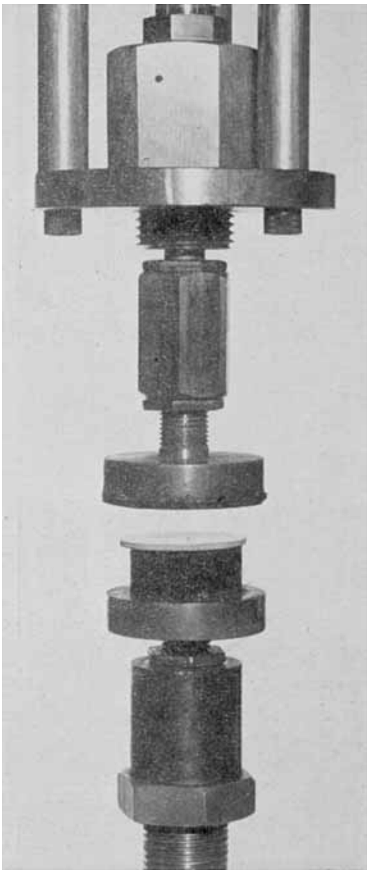

Fig. 5. Detail of load cell and test specimens.

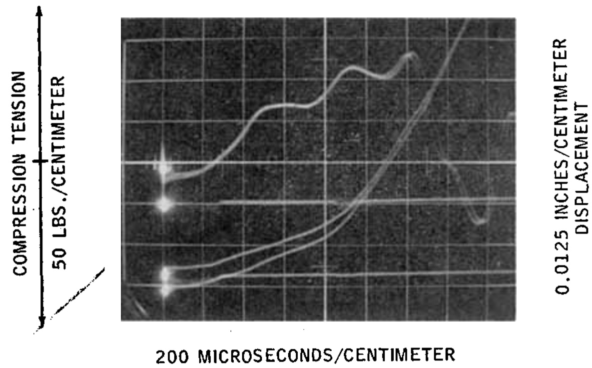

Fig. 7. Double exposure showing reproducibility on repeated test of adhesion and velocity.

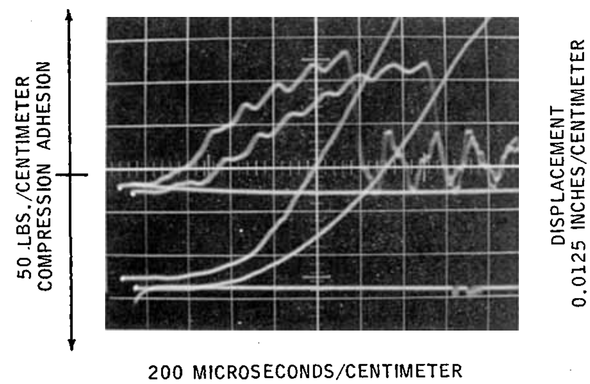

Fig. 8. Double exposure showing effect of velocity on adhesion.

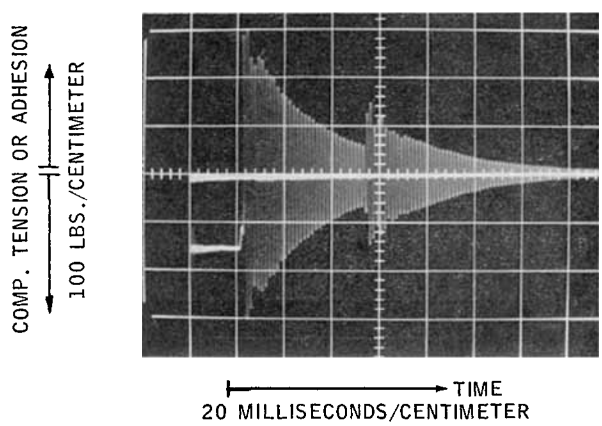

Fig. 6. Adhesion of butyl rubber tread stock to stone surface Separation speed 10,000 in./min.

which has a much higher natural frequency (25,000 c.p.s.) than the SR-4 load cell. The second peak in this figure, some 3 cm. along from the high peak was caused by the piston reaching the end of its 10 in. stroke. This second peak has little meaning except that it does indicate the piston speed, in this case almost 10,000 in./min.

Several hundred tests have now been made covering a great variety of conditions and materials. These have included butyl, natural rubber, and SBR against each other, against metal and stone surfaces, against plastics, and against clean and dusted surfaces over a wide range of velocities. In each case the values for adhesion obtained have had a relation to each other and an order of magnitude that one might expect for the conditions to which they were subjected. In all cases, except where the surfaces were dusted with talc or where Teflon was used, the adhesion forces were surprisingly high.

There was at first some skepticism at the high adhesion values obtained. These values were then checked by installing a shear pin between the piston and the sample holder. The shear pin size was selected so that it would break just before the tensile values obtained in previous tests were reached. In each case where the shear pin was used it broke as expected, proving at least the order of magnitude of the adhesion.

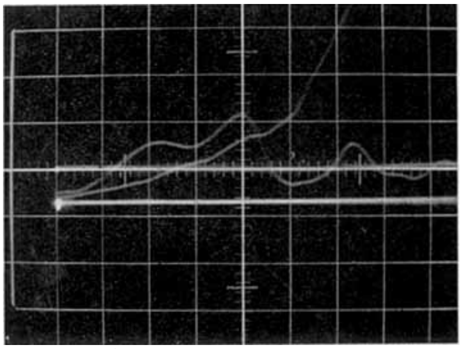

Fig. 9. Butyl on stone.

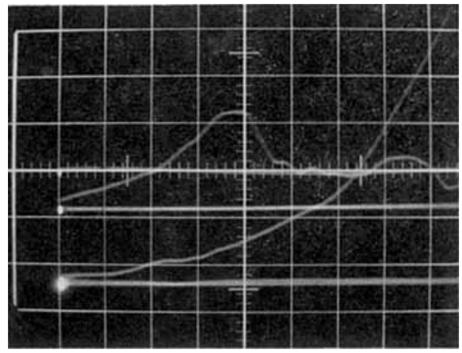

Fig. 11. SBR on styrene.

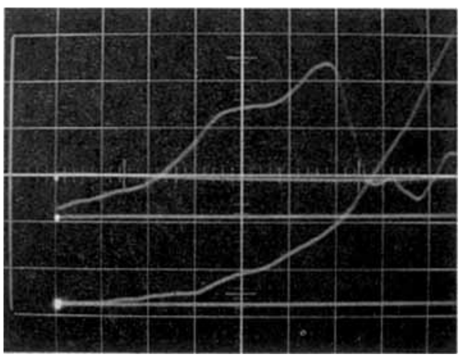

Fig. 10. Butyl on styrene.

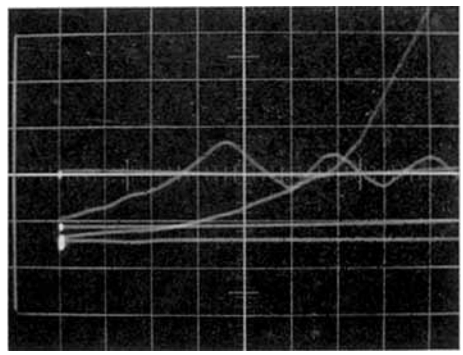

Fig. 12. Natural rubber on styrene.

In those cases where it was necessary to obtain the exact velocity at the time of extension and break, we used a dual beam oscilloscope. On this we could display simultaneously both the load and the displacement against time. These picture recordings gave us the initial load, the load at break, the extension at break, and the piston velocity at break.

One minor difficulty encountered in these tests was in holding the compressive load while the servo valves were being repositioned for their action between compression and tension. This was partially taken care of by providing a $^1/_2$-in. butyl rubber cushion underneath and between the test surface and the piston. The cushion permitted some relaxation without complete loss of the compressive load. The use of this cushion may have slowed down the break-away velocity slightly by its recovery, but this was not considered to be too serious, and placing the cushion on the piston side of the testing surfaces eliminated the effect of its rebound on the load cell.

We were quite surprised at the reproducibility of the data obtained in successive tests. In fact, a test repeated immediately would give an oscilloscope tracing so closely similar to the previous tracing that if a double exposure were made showing the two tests on one film, it would be hard to distinguish the second tracing. Figure 7 illustrates this reproducibility obtained by using a double exposure of two successive tests made on a dual beam oscilloscope.

Figure 8 is a similar double exposure, but in this case the sample was pulled at different velocities, and the oscilloscope beams were moved slightly to avoid overlapping. In this figure the two upper tracings show load versus time, while the lower tracings show displacement versus time, in which the slopes represent the velocity of the piston. The horizontal time scale for both load and velocity is 200 μsec./cm. (0.0002). The vertical load scale was 50 lb./cm., indicating tension above the horizontal center line which represents zero load, and also indicating compression below this center line. The vertical scale for the displacement curves was 0.0125 in./cm.

These tracings show the values obtained for a butyl tire tread stock against the smooth face of impact styrene. The contact surfaces were $1^1/_8$ in. in diameter or one square inch in area. The initial or compressive load, below the horizontal center line, is the starting point of the load curve. The maximum tensile load before the adhesive break is shown by the height of the load tracing above the horizontal center line. The break-away velocity is the slope of the displacement tracing directly below the break point in the load tracing, and the displacement at break is the vertical height of the displacement curve at this point above its original level. From these data it can be seen that the initial compressive load was about 25 psi and the load at break was 135 psi for a break-away velocity of 6000 in./min. and 120 psi for a break-away velocity of 5600 in./min.

While identical data could be obtained in tests immediately repeated as shown by our double exposures, it should not be considered that this test method is that infallible. Humidity and dirt or foreign material would play a large part, just as in friction testing. We were also bothered by noise in the electronics at our more sensitive oscilloscope settings and this gave us difficulty in triggering the action.

The cleanliness of the test samples was perhaps the most important point, and we needed some standard degree of cleanliness. For this we simply washed the contact surfaces with soap and water until they were hydrophobic or would repel water from their surfaces. If any patch of water remained, we would rewash that area until the entire surface would shed the water equally well.

Figure 9 shows the adhesion obtained by pressing butyl against a rough grindstone surface. The figure shows an adhesion value of about 60 psi with an initial compression load of 25 psi. Figure 10 is for butyl under similar conditions except that this opposing surface was smooth impact styrene. Figures 11 and 12 are for SBR and natural rubber, respectively, on styrene. The compounds used for all of these tests were typical tread compounds similar to those used on passenger car tires. The length of dwell time before pulling the samples apart is also an important variable, but in these cases it was kept at about 40 sec., this being the minimum time necessary for the operation of the servo valves.

THE EFFECT OF DWELL TIME AND BREAK-AWAY VELOCITY

The length of dwell time that the sample is kept under load before being pulled apart has quite an effect on the adhesion values obtained. This is

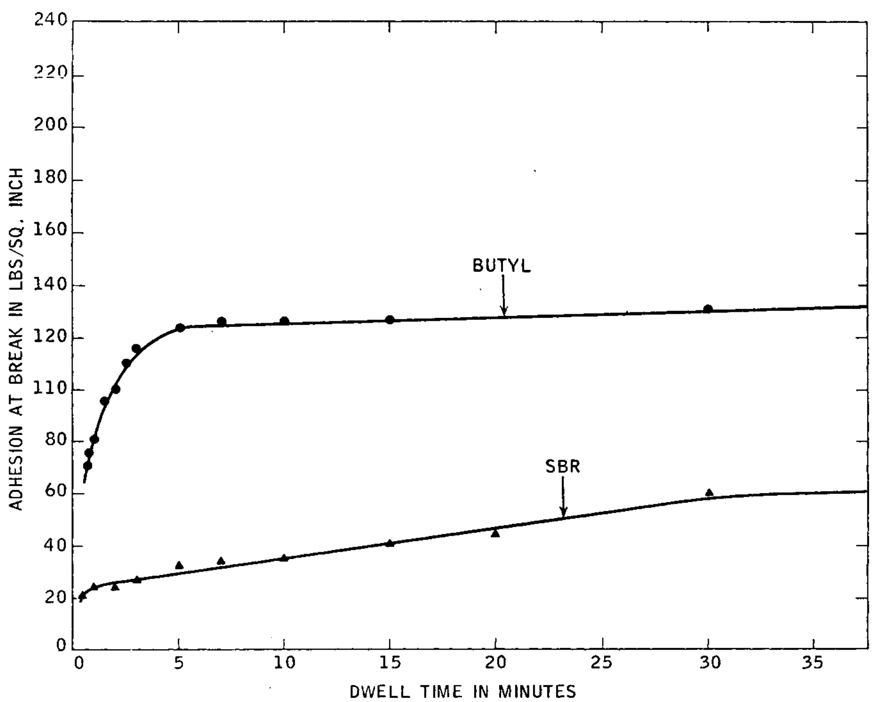

Fig. 13. Increase in adhesion with time. Butyl and SBR on styrene.

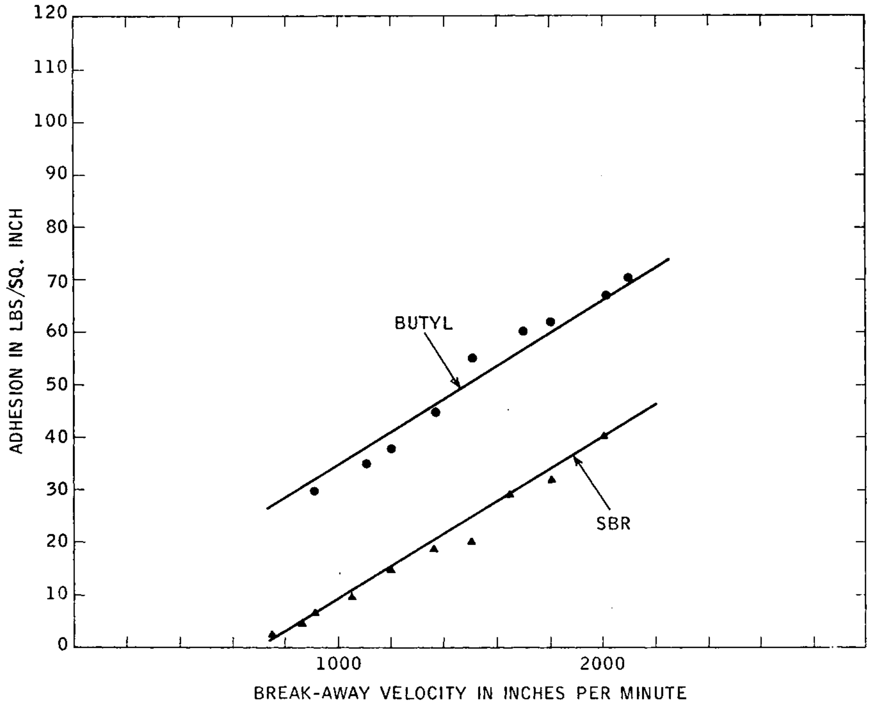

Fig. 14. Adhesion versus velocity at break.

shown in Figure 13. The adhesion values increase quite rapidly, as would be expected, with the first seconds or minutes of dwell, particularly with butyl rubber. After that there is little change with time.

It appears, from Figure 13, that the adhesive value would approach zero with very short dwell times, such as those with a tire rolling at high speed. However, forced movement as well as time enhances intimate contact and produces the effect of that of a longer dwell time.

The velocity of the piston in pulling the samples apart is also important, and Figure 14 shows the relation of adhesion to the actual velocity at the time of break. The velocity increases quite rapidly at the start of the operation, but due to the very short extension before break, the break-away velocities are much less than the maximum velocity attained by the piston a millisecond later.

THE EFFECT OF INITIAL LOAD

The initial load or compression obtained before pulling the surfaces apart has a very definite influence on the adhesion. Higher initial loads will enhance the intimate contact between the surfaces and increase the adhesion obtained. However, the values obtained did not have exactly the same linear relationship with load as one gets with friction. Apparently the initial dry tack between clean surfaces has a slight effect at low loads, and the recovery of the elastomer may be reducing the adhesion at higher loading since the internal stresses will be higher. Figure 15 shows this relationship between adhesion and initial load.

THE EFFECT OF HYSTERESIS

Hysteresis is perhaps the most important variable of dry adhesion, because load, time, and speed are factors beyond the role of the rubber chemist.

Our first studies into the effect of hysteresis on adhesion made by increasing the temperature were not too successful. The adhesion of butyl to styrene was found to drop quite rapidly with increasing temperature. We could not, however, attribute this drop in adhesion to the change in hysteresis alone, because of surface changes that also occurred due to the heating. We found, for instance, that on heating the sample from 80 to 120°F. that the adhesion values would be reduced to about one-half. However, when we let the sample cool down again, it would not recover its high adhesion until after it had been well cleaned with an abrasive soap. Apparently there had been some bleeding of oil or other lubricant that

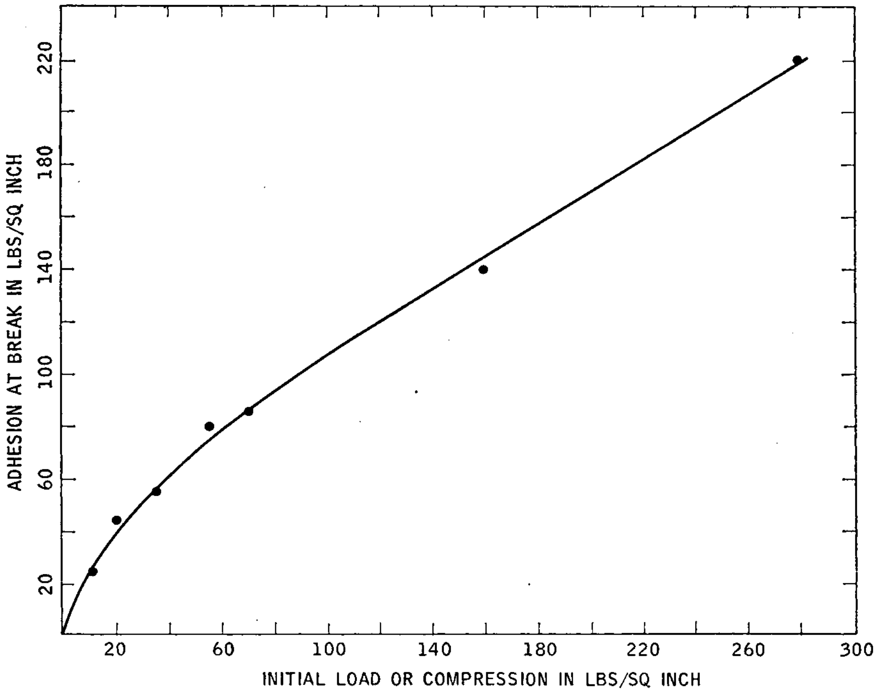

Fig. 15. Effect of initial load on adhesion.

contaminated the surface. This effect would not appear in tire friction because here the surfaces are being constantly cleaned.

Our second attempt to study the effects of hysteresis was a little more successful. This time we used butyl against a rough grindstone surface. In this case there is some scrubbing action as the rubber specimen deforms over the asperities of the grindstone. We also applied the heat faster so as to reduce the time for any possible bleeding. The data obtained are shown in Figure 16, and plotted

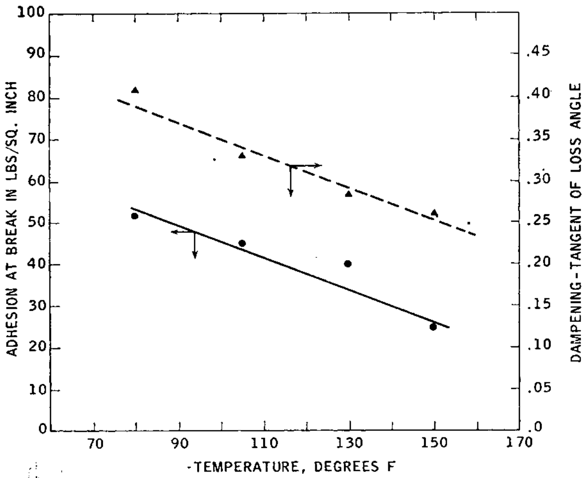

Fig. 16. Relation of adhesion to temperature and dampening.

with them are data on the relative dampening of the butyl sample, expressed as loss tangent. The similarity or close relation of these two curves is obvious. The different values obtained between butyl, SBR, and natural rubber also bring out the influence of hysteresis on adhesion.

CONCLUSIONS

Much more work still needs to be done before any firm conclusions can be drawn from these preliminary studies. This work may help to bring out the importance of hysteresis in tire traction and would seem to confirm the suggestions that others have made in studying friction, "that adhesion must play a large part in sliding resistance." It is possible also that some of the tire tread damage and road damage, particularly that type of damage that looks as if sections had been plucked or torn out, could have been due to adhesion between the tire and the road.

As a tire rolls, the tire tread is peeled off the road at the trailing edge in line contact. This line of breaking contact has almost no area and therefore requires little energy to peel the surfaces. This is similar to peeling a strip of Scotch tape. However, where tire treads carry a design pattern of individual buttons, the buttons may not peel off the road as a strip but can deform to be plucked off as separate identities. At turnpike driving speeds the lift rate can be several thousand inches per minute, which could easily produce high adhesive values and result in damage to either the tire or the road.

The author hopes that this study will stimulate someone else into thinking along these lines, but would warn them that a study of dry adhesion is just about as difficult as studying friction. Some time back he thought that the easy way to study friction would be to study adhesion. Now he thinks that perhaps the best way to study adhesion would be to study friction.

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Synopsis

Studies of friction and abrasion of elastomers have indicated that static friction or adhesion may be one of the important parameters in the traction and wear obtained with automobile tires. In this case static friction is considered to exist where a point of contact, adhesive attachment, or an interlocking is made between the rolling tire and the road which is strong enough to hold and transfer energy from one surface to the other. To investigate the magnitude of adhesion between tire tread rubber and the road, a test was developed that would measure the dry adhesion of rubber to other materials at break-away speeds above the recovery rate of the rubber. By using clean dry surfaces and break-away speeds of 2000 in./min., adhesive values in the order of 100 psi were measured with butyl tread stocks against impact styrene or against a rough stone surface. Much lower values were obtained for SBR and natural rubber. The influence of surface contamination, break-away velocity, and hysteresis was also studied. The equipment used and the procedures for these tests are described in this paper.

Résumé

Des études sur la friction et l'abrasion des élastomères ont indiqué que la friction statique ou l'adhésion peut être l'un des paramètres importants dans la traction et l'usure obtenues avec les pneus d'automobile. Dans ce cas, on considère que la friction statique existe là ou il y a, entre le pneu qui roule et la route, un point de contact, une adhésion ou une interpénétration suffisamment forte pour tenir et transférér l'énergie d'une surface à l'autre. Pour rechercher la grandeur de l'adhésion entre le caoutchouc du pneu et la route, on a réalisé un test qui mesure l'adhésion sèche du caoutchouc aux autres matériaux à des vitesses d'arrachement supérieures à la vitesse de récupération du caoutchouc. En utilisant des surfaces sèches et propres et des vitesses d'arrachement de 2000 pouces par minute, on a mesuré des valeurs de l'adhésion de l'ordre de 100 psi avec des caoutchoucs butyliques sur du styrène à impact ou contre une surface de pierre rugueuse. Des valeurs beaucoup plus basses ont été obtenues pour du SBR et du caoutchouc naturel. L'influence de la contamination de la surface, de la rapidité de l'arrachement et de l'hystérésis, ont également été étudiées. On décrit dans cet article l'équipement utilisé et la manière de procéder à ces essais.

Zusammenfassung

Reibungs- und Abrasionsuntersuchungen an Elastomeren haben gezeigt, dass die statische Reibung oder Adhäsion einer der wichtigen Parameter bei der Abnützung von Autoreifen ist. In diesem Fall wird angenommen, dass statische Reibung dort vorhanden ist, wo ein Kontaktpunkt, eine Adhäsionsberührung oder ein Ineinandergreifen zwischen dem rollenden Reifen und der Strasse besteht, der stark genug ist, um Energie zu speichern und von einer Oberfläche auf die andere zu übertragen. Um die Grösse der Adhäsion zwischen der Gummilauffläche des Reifens und der Strasse zu bestimmen, wurde ein Test zur Messung der Trockenadhäsion zwischen Gummi und anderen Materialien bei Abreissgeschwindigkeiten oberhalb der Rückstellgeschwindigkeit des Kautschuks entwickelt. Unter Benützung von reinen, trockenen Oberflächen und Abreissgeschwindigkeiten von 2000 inches pro Minute, wurden Adhäsionswerte in der Grössenordnung von 100 psi mit Butyllaufflächen gegen schlagfestes Polystyrol oder gegen eine rauhe Steinoberfläche gemessen. Für SBR und Naturkautschuk wurden viel niedrigere Werte erhalten. Weiters wurde der Einfluss von Oberflächenverunreinigung, Abreissgeschwindigkeit und Hysteresis untersucht. Prüfapparatur und -verfahren werden in der Arbeit beschrieben.

Discussion

Question: At what frequency did you measure your hysteresis, and with what type of equipment?

Answer: The hysteresis values were obtained on a modified Goodrich flexometer at 17 cycles/sec.

Question: If I understand your arrangements correctly, what you have been measuring is simply the exposure of two mating surfaces to the atmosphere. You say that when you separate two parallel plates, air has to move in. It is the rate of the exposure to air that has been discovered by Sturm, whose work has been repeated many times since. I think this has nothing to do with adhesion, but is, rather, the overcoming of atmospheric pressure.

Answer: It very likely has been studied, but the forces and effects are there even if it is only due to the viscosity and resistance of air coming in. A lot of people have asked whether this were a vacuum effect. I say we get much higher values here than you get with a vacuum. Notice, also, the great difference in the adhesive values obtained with natural rubber and butyl against styrene when measured in the same atmosphere. It does not really matter at this time what the mechanism is; as long as the rubber holds to the roadway, the forces and effects are important.

Question: Was there any wear—for example, scuffing—on your rubber when you pulled it away?

Answer: No, there was not much opportunity for scuffing and other wear. For wear you need lateral motion under load, while this adhesion was measured normal to the surface. If you just push down and pull up without sliding friction, the rubber is being relieved and there should not be much sign of wear. Of course, we were working on clean surfaces, but did not see much evidence of wear.

Question: What would be the speed at which the rubber would be pulled from the road in the case of a car traveling at, say, 60 m.p.h.?

Answer: It is about a quarter or so of the speed of the car. An approximation of the tread lift rate with respect to the car's velocity can be obtained by multiplying the speed of the automobile by the sine of the angle formed by the road and a line drawn tangent to the tread and normal to the wheel radius at the trailing edge of contact.

Question: Is the speed fast enough to make the adhesion you speak of?

Answer: At 60 m.p.h. or 88 ft./sec. the break-away speed would be about a quarter of that, or 22 ft./sec., while the adhesion forces obtained here were measured at 3–15 ft./sec.

Question: I should like to make a comment on an earlier question. How can you measure this force? What you are proposing is that the rubber is in tension when you are pulling it up from the plate; it seems that you have not established that yet, that it is actually at that point in tension.

Answer: What you are referring to is my term "adhesion." I am not certain whether it is actually adhesion or not, but it seems to be and agrees with my theory for abrasion. But these are the data I obtained and the actual forces that I measured normal to the surface.

Question: I think the point must be established of whether, when you have two plates separating, they are in effect in adhesion when you pull them apart.

Answer: We did at times actually rupture the cement bond between the sample and the piston and, as mentioned before, we also obtained enough tension across the sample to break a specially designed shear pin.

Question: Did you test any substance other than those mentioned in the paper?

Answer: Yes, we tested various other materials and got various values; in some cases we got still higher values than shown in these slides. Butyl-to-butyl gave the highest value of the materials tested.

Question: It does appear that you have used two different types of material and got two different stress magnitudes; and, after all, air is still air.

Answer: Yes. We pressed rubber against metals, against plastic, against everything we could think of, with clean surfaces, dirty surfaces, oily surfaces, and we always obtained adhesive values that were about what we expected for the particular case. We obtained the lowest values with dry metal-to-metal surfaces and rubber-to-Teflon.

Question: To explain this a little differently: the reason dry materials give different rates of adhesion is simply the rate at which the separation occurs, and the given stress is inversely proportional to the square of the distance. I believe that at least in one instance you have a place which is easily proportional and you have a high adhesion. If it is not proportional to the square of the original distance you will have a big effect. This is a theory that is about ninety years old, and originally came from Sturm. It has been proved again and again.

Answer: The cleaner the surfaces, the higher the sliding friction and the higher this apparent adhesion, possibly because the surfaces are in closer contact.

Question: To return to the commercial aspects of this butyl rubber; have you the same frictional advantages on a wet surface—for example, does butyl have the same frictional advantages on a wet street as it does on a dry street?

Answer: Yes, on a wet street there are the advantages of hysteresis, while on the dry surface there is the advantage of what I am calling "adhesion." On a wet surface butyl has an advantage over a material like natural rubber because of its high hysteresis.

Question: It is difficult for me to see any connection between hysteresis and adhesion.

Answer: I placed the hysteresis curve on the slide to show its possible relation to the change in adhesion with temperatures. The lower-hysteresis rubbers gave lower adhesive values than butyl, and lowering the hysteresis of butyl by heating gave progressively lower adhesion values through the range tested. This I think is the reverse of the Stefan effect in relation to the viscosity of the intermediary air.

Question: What happens when one puts a joint between the two surfaces? This is a rather high viscosity material.

Answer: If there were a very thin film of water, I don't know what would happen. When we wet the surfaces or added a little grease we always obtained a lower value.

Question: Did the adhesion force reduce under high viscosity?

Answer: Yes, with water or grease on the juncture, which would displace air. However, a very careful study would have to be made with a very thin film of water: in this case one might get a different picture. A reduction in the atmospheric humidity seemed to reduce the adhesive force.

Question: Your chart shows the effect of time of initial contact, and it shows both humidity and adhesive force going down possibly to zero at very small times. Does this indicate that the results are significant only in the case of a parked car; or, when the adhesion force is going to be zero for the actual case of a car running, is this a possibility?

Answer: No, the tread stays on the ground a little longer than zero time. It is a pretty short length of time but if you get near zero time of contact I wouldn't expect much from this adhesion.

Question: Perhaps not zero time, but both curves seemed to be getting down to zero even for a very short time.

Answer: The procedure wasn't fast enough for us to obtain data near zero time. However, the tire tread is on the road for some measurable time and it does suffer some scrubbing action that enhances intimate contact, which is all that is needed for adhesion. Apparently, it is the intimacy of contact, rather than time, that governs.

Question: Could you run this test in a vacuum and resolve this question?

Answer: We probably could.

Question: When you press two things together in water you have high viscosity; and when you apply the force at the same time you don't have the original distance you have in air. The original distance (in air) is much greater and when you separate the materials in water you may have lower results because the load is proportional to the square of the distance. You must separate the effects of adhesive force, if present, versus the damping effect of the medium. If you want to compare the rate of separation in a vacuum versus in water, you have to measure the force in the initial separation since the initial separation is significant. You have to press them together in water about 100 or ten times as long.

Answer: This is all correct. But the point is that when you bring the two materials close together it does not matter what the mechanism is that makes them hard to pull apart, but they do have this tenacity for each other. So that when rubber is on the road under load and forced movement, you have small portions of the two faces in contact that cling together. This need not be for long, but if they hold together while gross movement is being forced, it can result in the extension, tearing, and rupture of small particles. This is a mechanism of abrasion, and whether the points of contact that resist movement are called adhesive attachments or called something else does not affect the issue. The important thing is that they transfer energy and can result in particle loss. Apparently, this adhesion can also support a normal force for a short length of time.

Question: I think that is possibly true, but if this problem cannot be approached from the viscosity point of view then probably one should pull materials apart to study what happens when there is adhesion. Did you actually get any physical evidence of adhesion or rupture?

Answer: I looked for that but could not definitely say there was any. It might have been very small and hard to see, because in most of my tests there was no scrubbing. In some cases there were signs of wear, but they were due to lateral motion. I had used a thick piece of rubber and would get some lateral movement due to spreading of the sample, and then scrubbing. The evidence of wear in those cases was not due entirely to the vertical pull. In any sliding friction there is wear, and whenever there is a material with a high coefficient of friction and this higher apparent adhesion there is always more wear. With higher adhesion and friction it seems that far larger particles are pulled out and the surfaces wear fast as movement is forced.

Chairman Eirich: This is a very fascinating topic. I agree with Mr. Vickers that the actual nature of the forces which hold rubber to the surface do not matter for this particular purpose. All that matters is that there are such forces and they may participate in some form of wear of the rubber. Viscosity may indeed play a very important part. As a matter of fact, if I remember the formula correctly, it is the fourth power of the distance, not the square of the distance.

However, there may be other factors as well. Notwithstanding what has been said, rubber under the circumstances described may begin to act like a pressure-sensitive material, causing a certain amount of flow of rubber into the surface; there may be a pressure-sensitive effect there too.

The question of hysteresis was brought up. Hysteresis probably will not matter very much in the actual forces developed, but the hysteresis means a deterioration of energy and therefore a heating of the rubber. Certain people in the rubber field go as far as to maintain that actual wear of the tire is not at all due to mechanical abrasion but due to oxidation, and that the oxidated losses are due to the heat that is developed in the rubber. However that may be, I think that these very elegant experiments have shown that there are very substantial forces even in dry adhesion without any slip and wear, and that we have to count now at least on three factors in rubber wear or, let us say, oxidation: heating effect, actual abrasion (loss of slip stick processes, as Dr. Taber has shown us), and dry adhesion.