Crosshatched Ablation Patterns in Teflon

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The results of an experimental program to investigate the formation of regular ablation patterns of criss-crossed grooves (cross-hatching) are presented. A series of Teflon and filled Teflon ablation materials were exposed to the same gas dynamic environment. The results show that the pattern can be eliminated by grooving or adding a suitable glass filler to the Teflon. The results of the filled Teflon can be correlated in terms of the Reynolds number of the melt layer of ablation material in that the pattern formation is suppressed when the Reynolds number of the melt is sufficiently high.

Introduction

REGULAR patterns of criss-crossed grooves have been observed on the ablated surface of recovered entry vehicles. These grooves give the appearance of a crosshatched, diamond-shaped pattern to the surface. Crosshatched ablation patterns are believed to be a possible cause of dynamic instability of entry vehicles[1] and for this reason have been the focus of considerable attention.[2–5]

An example of crosshatched ablation patterns in Teflon is shown in Fig. 1. This is a close-up view of the ablated surface of a recovered entry vehicle wherein ablation occurred under a supersonic turbulent boundary layer. Even though cross-hatching has only recently been recognized, it is apparently a basic phenomenon in that it has been observed on recovered entry vehicles, hypersonic wind-tunnel models, and ballistic range models. There is also some evidence that the regmaglypt pattern observed on some meteorites is related to the crosshatched pattern.

In early work, Larson and Mateer[2] established a background of knowledge concerning cross-hatching which other investigators have subsequently verified. They established that the flow at the edge of the boundary layer adjacent to the surface has to be supersonic and that a thin turbulent boundary layer is required in order for cross-hatching to occur. Apparently the turbulent boundary layer must be thin enough for the surface response to be coupled to the external supersonic stream.

Many explanations of the cause of the pattern have been attempted. Some investigators have blamed the ablation process, attributing the formation of the pattern to differential ablation arising from disturbances[2] and from gas dynamic effects.[3] An analysis of the response of a liquid film adjacent to a supersonic stream[6] indicated that cross-hatching was the result of an interaction between the film and the supersonic stream and that the interaction was not ablation. Essentially it was the action of supersonic wave drag on a wavy wall (i.e., the surface of the highly viscous melt layer). Likewise, Probstein and Gold[7] did not incorporate ablation in their explanation of the phenomenon, but did incorporate the interaction of the supersonic stream with the surface. Their model of surface behavior was that of an anelastic deformable body. Although others[8,9] have attributed the phenomenon to gas dynamic aspects of the supersonic turbulent boundary layer, it is safe to say that at the present time, no single explanation of the origin of the pattern has been universally accepted.

The fact that there are apparently at least two types of cross-hatching complicates any explanation of its origin. The existence of these two types was pointed out by Larson and Mateer in their discussion of the transient ablation of a Lexan cone and a Lucite wedge,[2] but the distinction has apparently been overlooked by other investigators. It is essential, however, to distinguish between the two types in attempting to understand cross-hatching because the cause of each is apparently different.

The pattern that appears early when the model is exposed to the hot stream is characterized by 1) a fine-grained moving wave pattern, 2) a well-defined wavelength, 3) a deformable or liquid surface, and 4) a pattern angle greater than the Mach angle. The pattern that appears after the model has been exposed for some time and roughness elements have developed is characterized by 1) a coarse-grained stationary wave pattern, 2) no single wavelength, 3) no restriction on surface material, and 4) a pattern angle equal to the Mach angle.

It is conjectured herein that the early pattern is influenced by the properties of the surface material and the later pattern is influenced by what occurs upstream of the pattern. In the latter case, possible upstream influences are roughness elements and spanwise pressure disturbances caused by the steel tips used in the experiments.

Steel tips were used to prevent the nose of the ablation model from blunting during the test and consequently from moving the transition from laminar to turbulent flow off

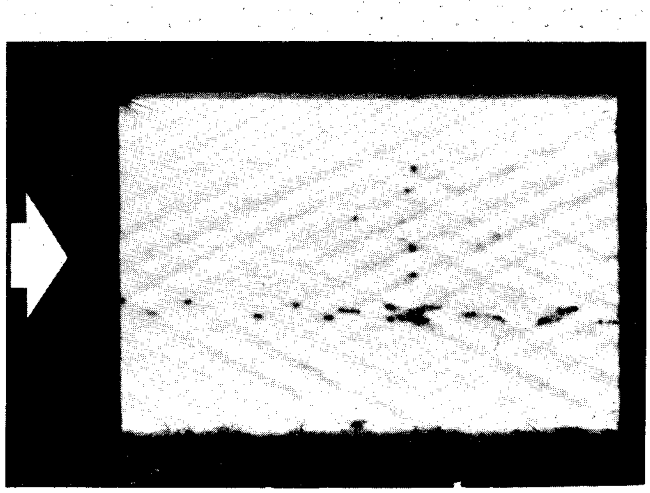

Fig. 1 Teflon surface of recovered ablated entry vehicle.

Presented as Paper 70-769 at the AIAA 3rd Fluid and Plasma Dynamics Conference, Los Angeles, Calif., June 29–July 1, 1970; submitted August 5, 1970; revision received April 26, 1971. The assistance of O. Goetz and L. Thompson of NASA-Marshall Space Flight Center in performing the tests is gratefully acknowledged.
Index Category: Material Ablation.

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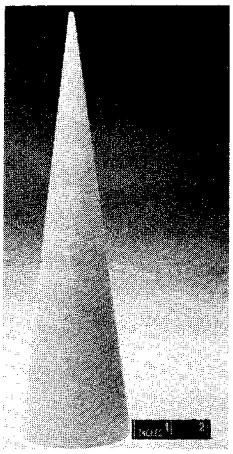


Fig. 2 Representative model in pretest condition.

the base of the model. Because of the increased ablation immediately behind the steel tip, a backward facing step was created early in the run. As is known from the work of Ginoux,[10] a backward-facing step causes a spanwise dynamic pressure variation.

To further substantiate the complexity of the problem it should be emphasized that cross-hatched ablation patterns have been observed in charring materials. This paper deals with ablators that melt, and the classification of patterns made previously is based on the early and late behavior of melting ablators. After drawing attention to the two classes of patterns, the authors have been requested by a reviewer to speculate on the classification of charring ablators. Based mainly on the results of Ref. 3, in which there was an upstream influence in every case involving a charring ablator, the authors speculate that the mechanism leading to cross hatched patterns in charring materials is the same as that present late in time in the case of melting ablators when upstream influences and roughness elements become important. Another way of labeling the classification of the patterns as suggested by the vibrations of a mass-spring system would be to label the early pattern "natural" and the late pattern "forced."

Regarding an explanation of the two different types of patterns that have been observed, the question arises as to whether they are caused by the same phenomenon. Based on the difference in behavior of the patterns during their formation and not exclusively on the final appearance of the

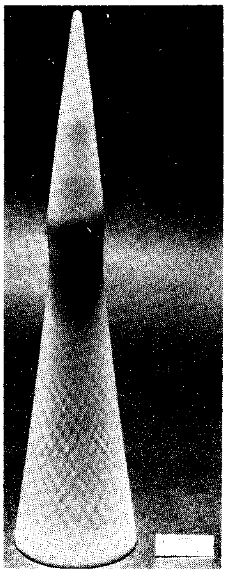


Fig. 3 Typical ablation pattern on Teflon (TFE) surface run in rocket motor facility.

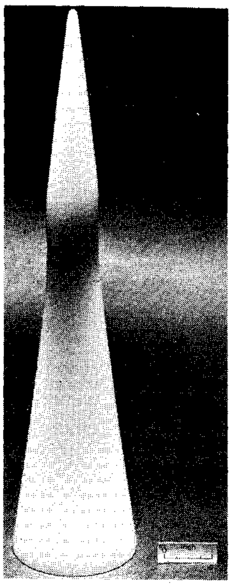


Fig. 4 FEP.

patterns, the authors contend that they are not caused by the same phenomenon. An entirely different point of view would be that a single description applies to both classes of patterns.‡

In order to simulate the smooth ablation and fine-grained formation observed in flight, it was felt that the steel tips should be removed and model surface roughness due to particulate matter in the test stream, avoided. For these reasons the hydrogen-oxygen rocket motor located at the NASA Marshall Space Flight Center was used for the experimental program with the expectation of achieving cross-hatched ablation patterns in Teflon with smooth surfaces upstream of the pattern. Cross-hatching was obtained on slender Teflon cones, and no transition wedges, streamwise grooving or other forms of roughness were observed to influence the results. Therefore, based on the classification given previously, the present tests belong in the class "early patterns."

The objectives of the experimental program were to determine if the surface material influenced the formation of the

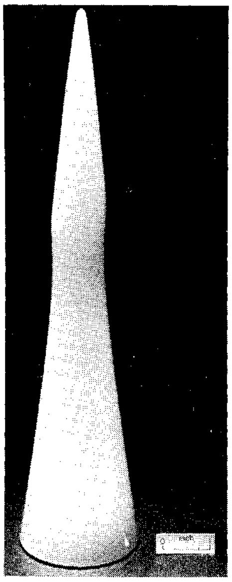


Fig. 5 Kel-F.

‡ A reviewer points out that the modal response analysis of Donaldson (documented in "RVTO Roll Phenomenology—Final Report," CCN-14, GS Doc. 68SD809, July 1968, Vol. 2, U.S. Air Force Contract AF-04(694)914,) could also explain the change in wavelength observed in the tests of Ref. 2.

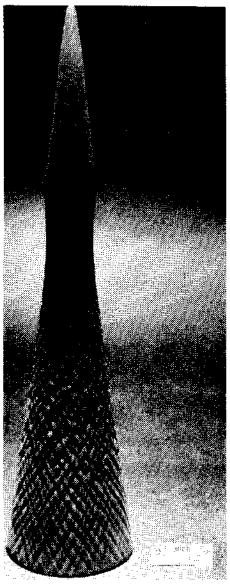


Fig. 6 Graphite (15%) filled TFE.

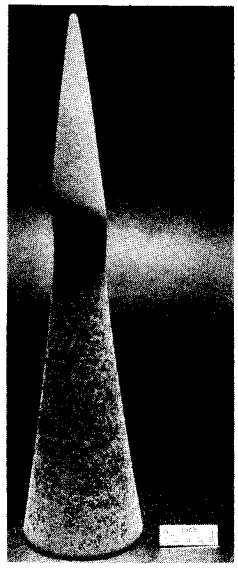


Fig. 8 Glass (25%) filled TFE.

pattern; to develop techniques for suppressing or eliminating the pattern; and to develop an understanding of the origin of the pattern. The scope of the investigation is restricted to Teflon and filled Teflon heat shield materials.

Rocket Motor Facility and Tests

The hydrogen-oxygen rocket motor was operated at a stagnation pressure of 1000 psia and at an oxygen-fuel ratio of 5. The motor had an expansion ratio of 8.5 and the exit diameter of the motor was approximately 5 in. The models were 7° half-angle cones approximately 1-ft long with a $\frac{1}{16}$-in. initial nose radius. Crosshatched ablation patterns were obtained when the average surface recession rate was 0.050 in./sec on a Teflon model. The test stream was free of particulate matter, and ablation upstream of cross-hatching was smooth.

Figure 2 shows a representative model in the pretest condition, and Fig. 3 shows a typical Teflon (TFE) model after being tested in the rocket motor facility. The similarity of the pattern on this model to the pattern on the surface of the flight vehicle shown in Fig. 1 is evident. The necked down appearance of the model in Fig. 3 is due in part to the uneven ablation rates during laminar heating on the forward part of the model and during turbulent heating on the rear of the model. Also, the nonuniform flow in the test stream contributed to uneven ablation.

The influence of the necking down of the models on the formation of the patterns is unknown. However, in view of the fact that this effect was present in every test, the primary objective of determining if the surface material influenced the formation of the pattern could still be achieved.

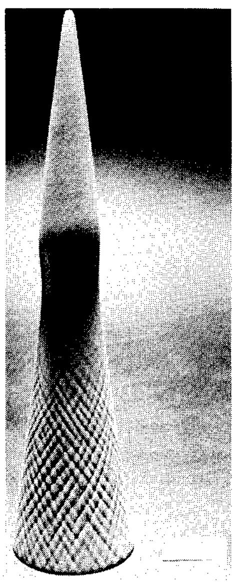


Fig. 7 Glass (7%) filled TFE.

Influence of Material on Pattern Formation

Selection of Material and Initial Screening Tests

Materials were selected from commercially available forms of Teflon and filled Teflon. They were chosen so as to obtain a variation in deformability, surface tension, and viscosity. The fillers for the Teflon were graphite, 15%, and borosilicate glass in various percentages. The forms of Teflon selected were TFE (polytetrafluoroethylene), FEP (a tetrafluoroethylenehexafluoropropylene copolymer), and Kel-F(polychlorotrifluoroethylene).

To ascertain whether the surface material influenced the formation of the pattern at all, models made from the different materials were run under the same conditions. From these preliminary results (which were presented at the Compressible Turbulent Boundary Layer Symposium held at NASA-Langley Research Center[11]), it was apparent that the pattern formation was indeed altered from that shown in Fig. 3. See Figs. 4–8. The subdued appearance of the patterns in Figs. 4 and 5 is due to the light source pointing down on the translucent models.

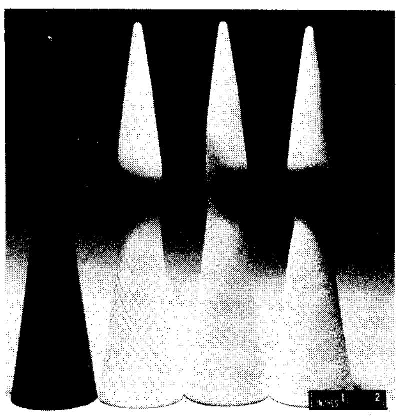


Fig. 9 Glass-filled TFE, 7, 15, 20, and 25% from left to right (test time 3.5 sec).

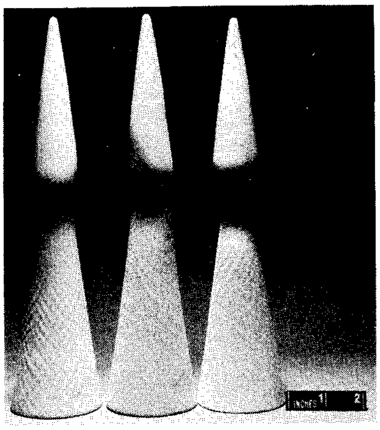


Fig. 10 Glass-filled TFE, 15, 20, and 25% from left to right (test time 5.0 sec).

Viscosity Effect

The most significant result of the initial screening tests was that the model with 25% glass-filled Teflon (Fig. 8) did not develop a crosshatched pattern. After this model had been

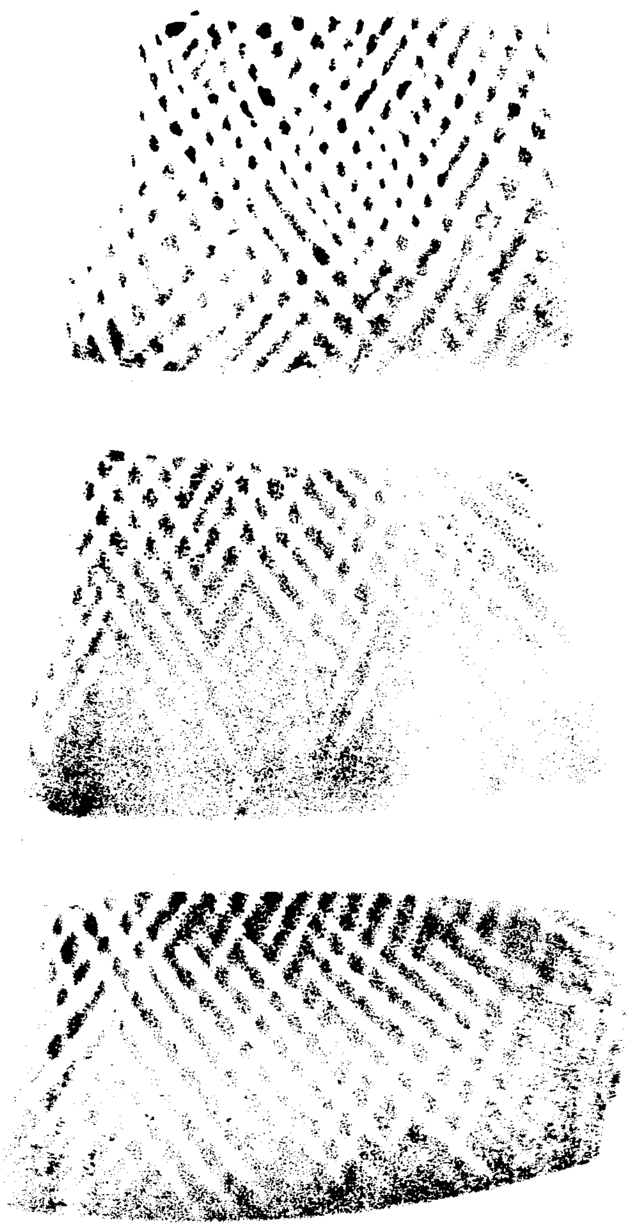


Fig. 11 "Fingerprints" of TFE (lower), FEP (middle), and Kel-F (top) patterns.

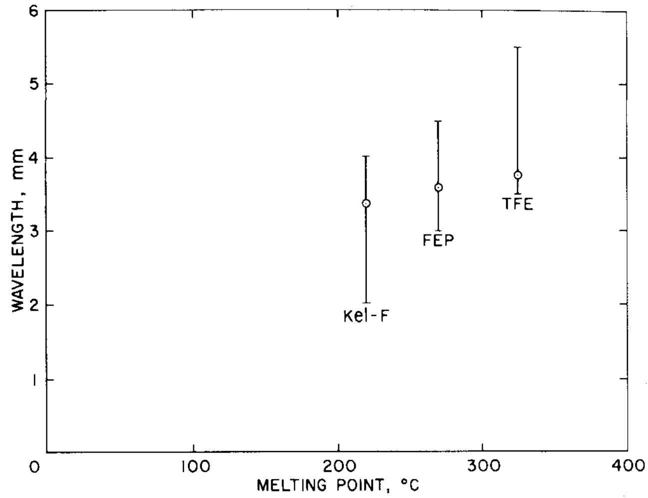


Fig. 12 Correspondence between wavelength and melting point.

tested, the support sting was covered with glass that had resolidified after leaving the base of the models as a melt. Since no melt runoff was observed in the test of the 100-% TFE model (Fig. 3), it was concluded that the runoff for the glass-filled model was a consequence of the lower viscosity of the melt. To investigate the effect of altering the viscosity of the melt layer, the percentage of glass filler was varied.

The results of the tests for 7-, 15-, 20-, and 25-% glass-filled Teflon are shown from left to right, respectively, in Fig. 9. The figure shows that as the percentage of glass increases, the pattern gradually disappears. From the observations of the relative amount of glass deposited on the support sting and from the high-speed movies taken during the tests, it can be inferred that the amount of melt runoff increased as the percentage of glass increased. This result is interpreted to mean that as the percentage of glass increased both the thickness of the melt and the Reynolds number of the melt increased.

The models in Fig. 9 were exposed to the rocket exhaust for 3.5 sec with the same result as for the models in Fig. 10, which were exposed for 5.0 sec. From left to right, the models contain 15-, 20-, and 25-% glass. High-speed movies of these same models showed that the crosshatched pattern moved very slowly. The movement was more evident in the 5-sec than in the 3.5-sec tests.

Influence of Material Properties on Pattern Formation

As pointed out, the variation of the viscosity of the melt markedly influenced the formation of the pattern. This variation cannot be described quantitatively, however, because the physical properties, especially viscosity of the polymers, are unknown during the exposure to the severe environment. The difference between patterns on the different materials was more subtle (a variation in wavelength). The "fingerprints" of the patterns taken at the base of the models are shown in Fig. 11.

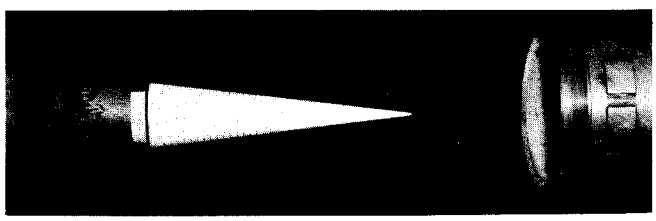


Fig. 13 Exit of rocket motor and sting arrangement supporting a model with grooves.

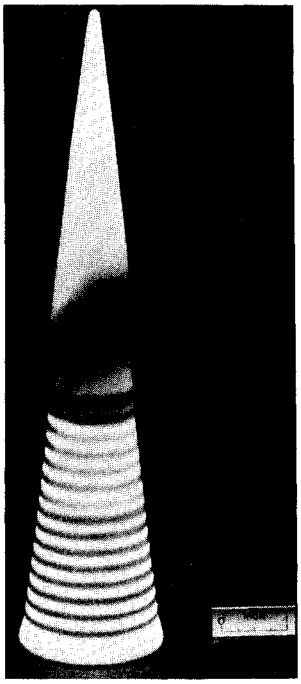


Fig. 14 Grooved model after brief period of ablation.

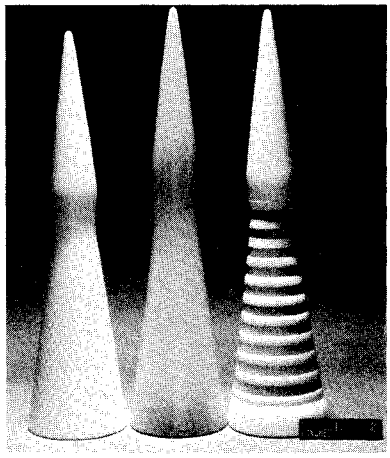


Fig. 16 TFE, Kel-F, and alternate disks of these materials from left to right.

Although the physical properties, such as viscosity, surface tension, and molecular weight, of TFE, TFP, and Kel-F are unknown at the elevated temperatures of the tests, the materials are characterized by their melting points. The difference in the melting points of the chemically similar materials can be attributed to differences in their molecular structure; conversely, the molecular structure reflects differences in physical properties. Hence, the known melting points can be used as a quantitative measure of their physical properties. The correspondence between the wavelength of the patterns and the melting points of the various polymers is given in Fig. 12. This correspondence is significant since it shows a variation in the geometry of the pattern with the physical properties of the materials, that is, the surface material can influence the formation of the pattern.

In Fig. 12, the scatter in the wavelength measurements obtained with a divider is enclosed by the error bars, and the mean value obtained by counting the number per unit length around a circumference is shown by the circled symbols. It is unfortunate that there is so much scatter in the data, but the trend of increasing wavelength with melting point is evident.

Interference Effect

In order to investigate the notion that the formation of the crosshatched pattern originates from an interaction between the supersonic stream and the surface, attempts were made to interfere with the interaction.

One technique was to machine transverse grooves in the surface of the model (see Fig. 13) so that truncated conical shock waves would form that would interfere with the formation of the crosshatched pattern. As can be seen in Fig. 14, the grooves did prevent crosshatching. (Similar results were reported for grooves in TFE tubes.[12]) Eventually, however, ablation eliminated the grooves and cross-hatching reappeared (Fig. 15).

To prevent the grooves from disappearing, models were made of alternate disks of materials with different ablation rates, the idea being that if the difference in ablation rates were great enough, permanent grooves would be established. The model on the left in Fig. 16 is made of Teflon (TFE), the

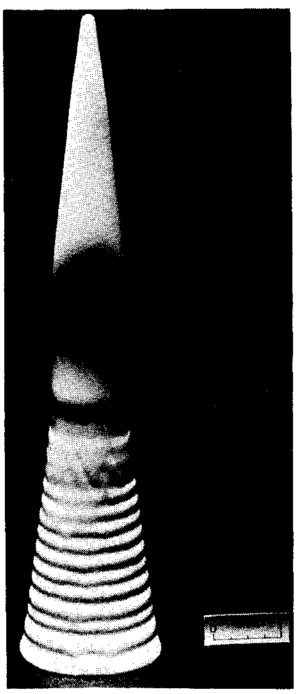


Fig. 15 Pattern development on grooved model once the grooving has disappeared.

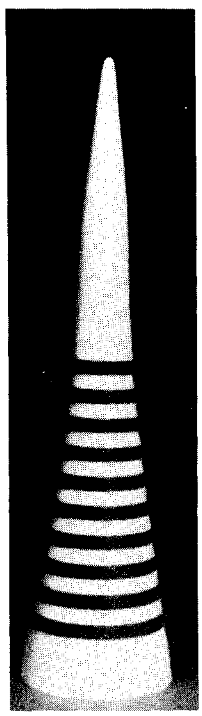


Fig. 17 Alternate disks of glass (25%) and TFE.

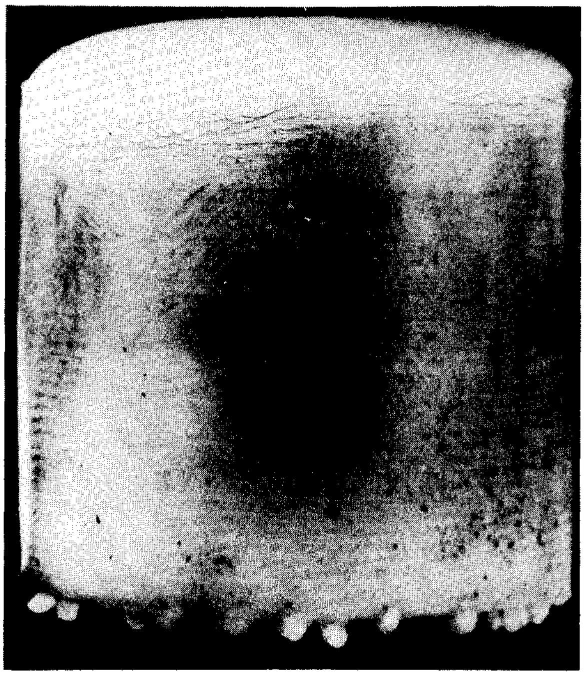


Fig. 18 Teflon model exhibiting molten state of polymer.

center model is made of Kel-F, and that on the right is made of alternate disks of TFE and Kel-F. The ablation rate of TFE was significantly lower than that of Kel-F as determined when the homogeneous models were ablated. Even though both materials exhibited a crosshatched pattern when run separately, the formation of the pattern was suppressed when the materials were interspaced. The grooving was deep enough to interfere with the formation of the pattern, and the relative ablation rates of the two materials when interspaced were the same as when the materials were run as homogeneous models.

Other Teflons (FEP) and filled Teflons (carbon and glass) that exhibited cross-hatching when run individually, but did not have significantly different ablation rates, also exhibited cross-hatching when interspaced.

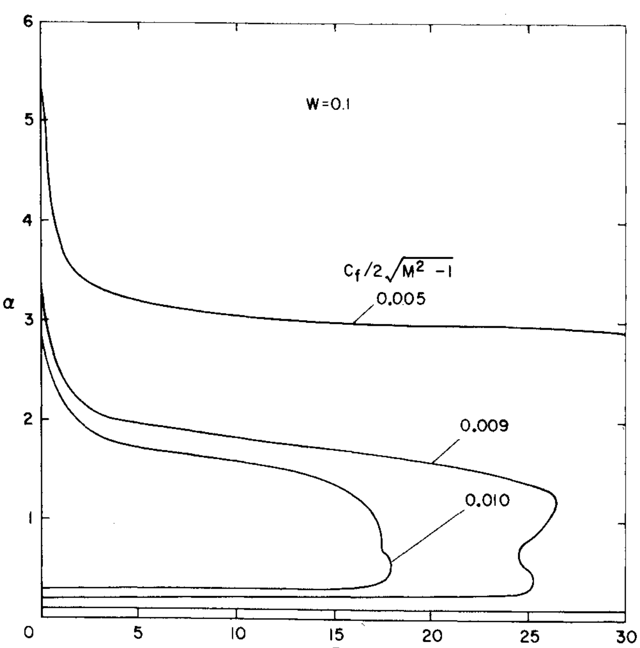


Fig. 19 Neutral stability curves.

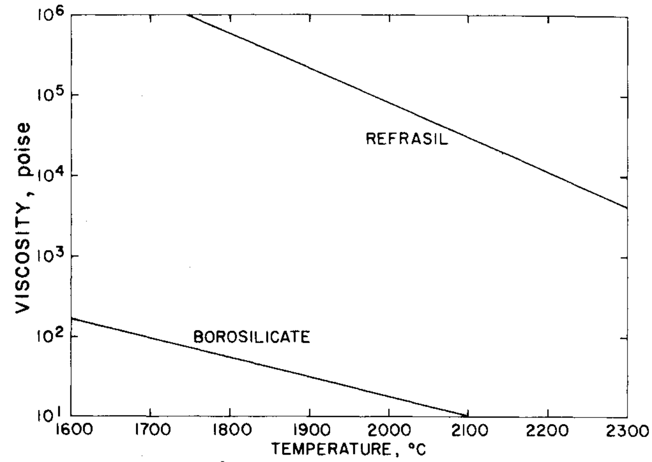


Fig. 20 Melt viscosity vs temperature.

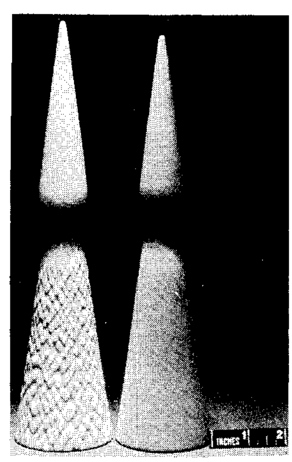
When the 25-% glass-filled Teflon, which did not cross hatch in a homogeneous model, was interspaced with Teflon (TFE), which did, the formation of the pattern was suppressed (see Fig. 17). Curiously, the relative ablation rates of the two materials when run as alternate disks were the reverse of those in homogeneous models. That is, the TFE model had a lower ablation rate than the glass-filled Teflon model (partly because of the melt runoff of the glass), but when interspaced with the glass-filled Teflon, TFE had a higher ablation rate. The high-speed movies showed that the glass which melted at a much higher temperature than TFE and flowed back over the TFE. Hence, the surface temperature of the TFE was higher than it would be if no glass were present. The movies also established that there was a melt layer runoff for each individual disk of glass-filled Teflon.

Interpretation of the Test Results

The interpretation of the test results is based on the results of a stability analysis of a thin liquid film adjacent to a supersonic stream.[6] In order to apply the results of the stability analysis to the present results, it must be remembered that when Teflon is ablated, it is a viscous rubbery melt above 327°C.[13] Teflon is commonly referred to as a sublimer in ablation literature, but strictly speaking, the polymer never sublimes, it vaporizes. Figure 18 illustrates the molten state of a Teflon surface. This photograph, kindly provided by R. Pope, shows the result of an ablation test in an electric heated arc jet located at Ames Research Center. Evidence of the molten state is the fire-polishing in the stagnation region, scalloping at the shoulder, and beading at the base.

Concisely stated, the pertinent result of the stability analysis is that there should be no cross-hatching if the Reynolds

Fig. 21 High silica filled TFE on the left and low on the right.



number of the melt is sufficiently great. As mentioned in the Introduction, the stability analysis postulates an interaction between the supersonic stream and the highly viscous melt layer via supersonic wave drag. The fact that some grooved models exhibited no cross-hatching is consistent with the predictions of the stability analysis since the grooving causes interference and evidently eliminates the interaction.

A typical result obtained from the stability analysis of Ref. 6 is shown in Fig. 19. For given values of the parameters that characterize a liquid film, the diagram delimits regions of dimensionless wave numbers and film Reynolds numbers where disturbances will be amplified. The region enclosed by the closed curves is where the analysis predicts cross hatching will occur.

A note on the notation employed in Fig. 19 is in order. The vertical scale α is a dimensionless wave number made dimensionless with respect to the depth h of the liquid film, that is, $\alpha = 2\pi h/\lambda$, where λ is the wavelength or spacing of the waves measured normal to the wave fronts. The Reynolds number is that of the liquid film, that is, $R = \rho Vh/\mu$, where V is the velocity of the liquid with viscosity coefficient μ at the gas-liquid interface measured in a direction normal to the wave fronts. The Weber number W is defined as follows: $W^2, = V^2\rho h/T$, where ρ is the density of the liquid with surface tension coefficient T. The Mach number M is the normal Mach number (i.e., the Mach number of the external stream measured in the direction of the wave normal). In the formulation of the boundary condition for the disturbance motion at the gas-liquid interface in Ref. 6, the disturbance pressure of the gas is included, and a parameter that enters the stability analysis is the ratio of the dynamic pressure of the gas to the dynamic pressure of the liquid. This parameter is normalized by equating at the interface the shear in the liquid to the shear in the gas, employing a friction coefficient for the gas; that is, for a linear profile in the liquid,

$$\mu(V/h) = (c_f/2)\rho_g V_g^2$$

where the subscript g refers to external flow quantities in the gas. Here again, the velocity of the gas is measured in the direction of the wave normal.

It can be seen by inspecting Fig. 19 that inside the curve, disturbances are amplified, and in the region to the right, disturbances are damped as the Reynolds number of the melt increases. This is the interpretation of the test results obtained with borosilicate glass-filled Teflon; namely, that adding a sufficient percentage of glass caused a melt layer to form, and as the percentage of glass was increased, the Reynolds number of the melt increased and one moved from where disturbances were amplified to where they were damped. The observation that the Reynolds number of the melt increased is based on the fact that there was a melt runoff in the case of the glass-filled Teflon models and there was no such runoff observed in the case of TFE. As the percentage of glass was increased, it was observed that the melt runoff increased.

The effect of altering the viscosity of the melt by adding glass filler was investigated further by means of a special model filled with 20-% Refrasil (trade name of a glass that contains 98.6-% silica). Refrasil is much more viscous than borosilicate. The variation of the viscosity of the two glasses with temperature is shown in Fig. 20.

Aside from altering the viscosity of the melt layer, it might be argued that adding glass to TFE resulted in a less deformable material beneath or in the absence of a melt layer. It is well known that at room temperature the addition of glass to TFE increases its antideformation qualities. In this regard, the antideformation qualities of Refrasil filled TFE should be the same as those of borosilicate filled TFE or higher.

Hence, the Refrasil test should determine whether it is the room temperature antideformation qualities of glass-filled TFE or the viscosity of the melt layer that matters insofar as the formation of the crosshatched pattern in glass-filled TFE is concerned. The result of the Refrasil test is the well-developed crosshatched pattern shown on the left side of Fig. 21. No melt runoff was observed in movies of the test nor was any glass deposited on the sting. The high silica glass fibers were apparently removed as particulate matter. The result of the test for borosilicate filled TFE with the same percentage of Refrasil glass is shown on the right side of Fig. 21 for purposes of comparison. There was a melt runoff in the case of borosilicate filled TFE, and glass was deposited on the sting. This comparison permits one to conclude that the formation of the pattern is influenced not by the antideformation qualities of glass-filled TFE, but by the alteration of the viscosity of the melt layer. That is, pattern formation is eliminated by the establishment of a melt layer of sufficiently high Reynolds number.

Conclusions

1) The surface material can influence the formation of the crosshatched ablation pattern. 2) Crosshatched ablation patterns can result from an interaction between the supersonic stream and the surface, and the formation of the pattern can be prevented by grooving the surface of a model so as to interfere with the coupling between the stream and the surface. 3) An understanding of the formation of the pattern in Teflon has been achieved in that all the test results of this investigation can be interpreted from the point of view that the pattern formation is an interaction of the surface melt layer with the supersonic stream, and that the formation of the pattern can be suppressed if the Reynolds number of the melt is sufficiently great.

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