CONVERSION OF HIGH MODULUS MATERIALS INTO FLEXIBLE FABRIC STRUCTURES

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ABSTRACT

The designs of numerous re-entry drag or lift-drag devices incorporate a flexible, low porosity, thermally durable membrane. The missions anticipate temperatures in the range of 1500-2500°F and strengths of 20-50 pounds per inch width. The necessity of being able to package and subsequently deploy these devices demands a membrane with good bending recovery.

The possible flow patterns over and heat transfer to a porous, fibrous structure in a re-entry environment were examined. The expressions for a theoretical estimate of the heat transfer increase to the structure were developed. Unqualified statements of the precise heat transfer increase as a function of structure are not possible in light of the obvious need for experimental verification. However, the theoretical investigation indicates that a moderate porosity can be tolerated under some flight conditions without a significant temperature increase.

The feasibility of stranding and plying into yarns metal filaments as fine as 0.5 mil and subsequently weaving the yarns has been shown. The fabrics obtained were flexible, thermally durable and had very low porosities.

A possible application of the metamorphic principle was demonstrated by the high temperature exposure of a fabric woven from a composite yarn composed of a chemically treated organic yarn and 0.5 mil metal filaments.

At the present time further investigations leading to the development of high temperature durable, flexible, strong, "fabric-like" structures utilizing high modulus of elasticity materials in both filamentous form and other configurations are being carried out.

SYMBOLS

M = Mach number

$\gamma = \frac{c_p}{c_v}$ = ratio of specific heats

s = filament spacing

d = filament diameter

D = over-all body diameter

V_∞ = free-stream velocity

$P = \left(\frac{s-d}{s}\right)^2$ = line-of-sight porosity

θ = angular coordinate on a cylinder, measured from the stagnation point

δ = boundary layer thickness
ρ_s = post-shock density
V_s = post-shock velocity
μ = viscosity
Re = Reynolds number
$\bar{\delta}$ = displacement thickness
B = blowing parameter
e = distribution through the boundary layer of $\rho\mu$, the product of density and viscosity
σ = Prandtl number
β = effect of free-stream pressure gradient
ρ_w = density of the air at the wall
V_w = suction velocity
H_s = air enthalpy at stagnation
H_w = air enthalpy at the wall
$\dot{m}$ = mass flow rate
p_w = pressure at the wall
T_w = wall temperature, °R
R = gas constant for air
A_{open} = pore area
C_w = nozzle coefficient
φ = critical porosity for "starting", $\varphi = 0.65$ for $\gamma = 1.4$
Nu = Nusselt number

INTRODUCTION

Successful performance of a manned space vehicle depends not only on successful launching but also on safe recovery. The present operational U. S. program, the Mercury program, utilizes a blunt nose cone and retro-rockets for re-entry deceleration and a semi-conventional parachute for soft landing. The vehicle alone does not generate a particularly high drag-to-weight ratio and therefore the deceleration takes place at a relatively low altitude, i.e., in a dense atmosphere.

The heat transfer rate to a vehicle is approximately proportional to the square root of the product of the air density and vehicle velocity. Hence, the lower the altitude through which a vehicle travels at high speed, the greater the heat transfer rate to it. The Mercury capsule requires a large heat shield at the front end to cope with this high heat flux. The heat shield and retro-rocket assembly is heavy and thus represents a considerable portion of the pay load.

The obvious conclusion from the above is that it would be advantageous to have a re-entry vehicle with a higher drag-to-weight ratio than that of the Mercury capsule. Retro-rockets could be done away with and the vehicle would decelerate at a high altitude because of its inherent drag. The heat transfer rate would thereby be moderated since the product of density and velocity would be lower.

A variety of schemes have been proposed for attaining a higher drag-to-weight ratio. In general they contemplate the use of an expandable or inflatable membrane-like structure to generate drag, or a combination of lift and drag, during the re-entry maneuver. A simple drag device could conceivably resemble a parachute trailed behind the vehicle. However, if the anticipated deployment occurs when the vehicle is traveling at supersonic speeds, inflation instability and oscillation problems must be overcome. Another drag device, originally proposed by Avco and since abandoned, consisted of a fabric covered "umbrella" attached to and opened at the front of the vehicle. Inflated balloon-like trailing systems, "ballutes", proposed by Goodyear Aircraft have also been under consideration. More sophisticated vehicle designs contemplate use of lift surfaces; for example, the Dyna-Soar program. These have at one time or another been visualized as inflatable lift surfaces. Another lift-drag device, the "para-glider" or "Rogallo Wing", is being considered for re-entry applications, recovery of first stage rockets and numerous subsonic applications. It is constructed of triangular fabric panels stretched between three struts joined at one end. Currently some interest is being directed to the use of inflatable fabric struts for this scheme.

Textile fabrics comprise a class of materials possessing many of the characteristics desired for the membranes required by the above re-entry decelerator schemes. In general, they are easily folded, packaged, and deployed without suffering damage. Upon release of deformation forces they exhibit some degree of spontaneous recovery or at least respond readily to external recovery forces. The principal objection to conventional textiles for re-entry drag systems is, of course, their low thermal durability. Most conventional textile fibers will either be melted or seriously degraded by exposures above 500°F.

The actual re-entry time-temperature specifications vary with the general characteristics of the device or mission. For a parachute type re-entry decelerator Ross[10,11] has given the operational temperature conditions as 1500°F for 30 seconds, 1200°F for 7-10 minutes. Other re-entry schemes contemplate a temperature of over 2000°F for a short length of time. It is therefore obvious that conventional textile fibers are not in themselves useful. The decelerator material must also be resistant to oxidation at the temperatures encountered.

Although numerous materials are capable of surviving 1500°F to 2000°F for a short time in an oxidative environment, the added requirements of flexibility, bending recovery (i.e., small permanent deformation) and compactability (i.e., ability to be packed into a small container) make the problem more difficult. These requirements demand a material with a low rigidity and a high extension to yield. However, most thermally durable materials have a high modulus and low extension to yield. Therefore, a structural design must be utilized which results in a flexible, compactable membrane made from high modulus, low yield extension materials.

Contrary to what intuition might suggest, a re-entry decelerator does not necessarily require a fabric of great strength. For example, to exert a deceleration of 10g (which is approximately the maximum desired if an astronaut is aboard the capsule) on a two-ton vehicle requires a total force of 40,000 pounds. If the decelerator is a 30 foot diameter hemispherical parachute and the load is distributed uniformly and tangentially around the hemisphere perimeter, the deceleration force results in a stress of only 40 pounds per inch. The loading

on lift surface fabrics can be considerably less.

The range of potentially useful materials available in fiber form may be arbitrarily classified as metallic, ceramic, or carbonaceous. Ceramic fibers, particularly continuous filament fused silica, are available as yarns and are suitable for the flexibility requirements. The capabilities of fused silica yarns in parachute-like systems are currently being investigated by Fabric Research Laboratories under U. S. Government Contract No. AF 33(616)-7557. Graphite and carbon cloths, leached glass cloths, and non-woven and woven fibers of a variety of oxides are also available. However, each of these has either low flexibility, poor abrasion resistance or low tensile strength. This leaves the super alloys and the refractory metals and their alloys as the most suitable candidate materials at the present time.

Flexibility implies low bending rigidity. The bending rigidity G of a single filament of circular cross-section is given by

$$G = \frac{E\pi d^4}{64}$$

where E is Young's modulus of elasticity and d is the filament diameter. Metallic filaments, as a class, are 10-20 times more rigid than organic fibers of equal tensile strength. This difficulty can be overcome by decreasing the diameter of the metal filaments and increasing the number in the yarn so that the total tensile strength of the yarn remains constant. Such a structural design results in the yarn rigidity being proportional to the square of the filament diameter(2). This indicates that metallic filaments would have to be drawn to less than one-fourth the diameter of organic filaments to achieve equal yarn rigidity at equal strength, assuming complete freedom of filaments to bend individually.

The diameter of a typical organic filament is approximately 0.5 to 1.0 mil. The diameter of metallic filaments necessary to achieve equal yarn rigidity at equal strength would, therefore, be in the order 0.1 to 0.25 mil. Also, in yarns of comparable strength and stiffness there must be about 700 to 1400 metal filaments per yarn compared to 50 to 100 organic fibers. Half mil wire is the finest that is commercially available in quantity at the present time. Although 0.5 mil wire is available, no known successful attempts have been made in stranding and weaving such wire commercially. Current industry capabilities appear to be limited to 1.0 mil monofilament cloth and fabric woven from multifilament yarn assembled from 1.5 mil filaments.

HEAT TRANSFER TO POROUS, FILAMENTOUS STRUCTURES IN A SUPERSONIC AIR STREAM

Few experimental or theoretical investigations appear to have been carried out on the heat transfer to porous filamentous structures in a supersonic air stream. Assuming a continuous shock over the structure, the problem can be approached from two directions.(1)

(1) A porous filamentous structure may be considered to approximate an array of cylinders. The heat transfer to the structure may be found by summing the heat transfer to each single filament of the structure.

(2) A porous filamentous structure may be considered to approximate an ablating body with negative mass flow. The heat transfer to the structure may be calculated with ablation theory by reversing the sign of the mass flow. When the boundary layer thickness on the filaments is a small percent of the filament spacing, the single body theory may be applied. When the boundary layer fills the pores of the filamentous structure and forms a continuous layer displaced from the surface, the suction-ablation theory is applicable.

The boundary layer equations of continuity, momentum, and energy have been solved for the case of two-dimensional steady laminar flow with mass-transfer cooling of an incompressible fluid with constant properties and negligible dissipation.(5) The results were extended to the case of suction. The effect of air mass suction on the heat transfer from a partially dissociated laminar boundary layer in thermodynamic equilibrium has also been investigated by reversing the sign of the mass flow in the ablation theory.(7)

When these theories are applied to the suction case, they are only valid as long as the boundary layer remains of the same approximate shape as the boundary layer for the ablation case and has a finite displacement from the surface. They do not apply when the suction is large and the boundary layer is sucked through.

The transition point from single body heat transfer (separate boundary layers on each filament) to diffuse permeation heat transfer (continuous boundary layer over all filaments) is where the boundary layers on adjacent walls of the pores of the porous surface merge. It is probably more appropriate to define the transition point as the merging of the displacement boundary layer thickness since it is the amount by which the body dimension must be increased for the flow field around the body to approximate potential flow. The merging of the displacement boundary layers implies that the porous body has become solid. The displacement thickness referred to is the displacement thickness at $\theta = 90°$ on a single cylinder in a flow field.

The boundary layer and displacement thickness in the pore of a porous surface will differ from the boundary layer and displacement thickness at $\theta = 90°$ on a single cylinder. The flow velocity immediately in front of a porous body varies with the porosity of the body, decreasing as the porosity decreases. Thus, the stagnation point boundary layer thickness increases with decreasing porosity.

Since the pressure ratio across the porous body is always large, the pore or nozzle throat velocity is always sonic. Thus, as the porosity decreases the acceleration of the flow around the cylinders that make up the porous surface increases. The boundary layer does not grow as fast around a body when the acceleration of the flow is increased.

The two effects of decreasing porosity, the increasing stagnation boundary layer thickness and increasing acceleration, counteract each other. It was therefore assumed that the ratio of the pore boundary layer thickness to the stagnation point boundary layer thickness is constant regardless of the surface porosity.

The porous surface was assumed to be approximated by a crossed-rod matrix. The stagnation point boundary layer thickness is therefore given approximately

by[12]

$$\delta_{st} = \frac{1.2\ d}{\sqrt{\frac{\rho_s V_s d}{\mu}}} \tag{1}$$

where ρ_s, V_s and μ are post-shock values. The boundary layer thickness at $\theta = 90°$ on a single cylinder is approximately twice the stagnation thickness and the displacement thickness is approximately one-third the boundary layer thickness.[12] Thus,

$$\bar{\delta}_{90°} = \frac{0.8\ d}{\sqrt{\frac{\rho_s V_s d}{\mu}}} \tag{2}$$

Therefore, transition occurs when

$$\frac{0.8\ d}{\sqrt{Re_d}} = \left(\frac{s-d}{2} \right) \tag{3}$$

Thus the suction-ablation theory is applicable when

$$\frac{0.8\ d}{\sqrt{Re_d}} \geq \left(\frac{s-d}{2} \right) \tag{4}$$

It may be seen from this expression that for small Reynolds numbers the suction-ablation theory is applicable up to large porosities.

The Reynolds number that is appropriate when using Equations (3) and (4) is the pore entrance Reynolds number. This Reynolds number differs from the post-shock Reynolds number. The procedure used to calculate it in a specific flow case assumes that the pressure ratio across the porous surface is large enough to insure that the nozzle throat velocity (i.e., pore velocity) is sonic ($M = 1.0$). Knowing the pore contraction ratio (surface porosity) and assuming isentropic pore flow, the entering Mach number can be calculated.[13] Knowing the free-stream conditions and assuming the shock over the surface is approximately normal, the post-shock flow, i.e., density, velocity, temperature, and thus the post-shock Reynolds number, can also be calculated. Then assuming the flow from post-shock to pore entrance is isentropic, the entrance density ρ_e, velocity V_e, temperature T_e, and thus the entrance Reynolds number can be calculated.

Suction-Ablation Heat Transfer

Assuming a Reynolds number-porosity combination less than critical, the ratio of the heat transfer to a surface with suction to that to an impermeable surface (of the same over-all dimensions) is given by the following equation.[7]

$$\frac{q_{suc}}{q_{imp}} = 1 + 0.58\, e^{0.04}\, \sigma^{-0.18}\, B\, \frac{1 + 0.096\sqrt{\beta}}{1.068} \tag{5}$$

where B, the blowing parameter, is given by

$$B = \frac{\rho_w V_w}{q_{imp}} (H_s - H_w) \tag{6}$$

The suction mass flow per unit frontal area, $\rho_w V_w$, assuming that the pressure ratio across the porous body is large enough (i.e., greater than two) to assure sonic flow at the minimum pore area, is given by[13]

$$\frac{\dot{m}}{A_{open}} = \sqrt{\gamma \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}\ \frac{P_w}{\sqrt{R\, T_w}} \tag{7}$$

Thus,

$$\rho_w V_w = \frac{\dot{m}}{A_{open}} \frac{A_{open}}{A_{frontal}} C_w = \sqrt{\gamma \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}}\ \frac{P\, p_w\, C_w}{\sqrt{R\, T_w}} \tag{8}$$

Values for nozzle coefficients as low as 0.1 have been obtained for 200 mesh screens woven from 2 mil diameter wire.[4]

In Equation (5) $e^{0.04}$ may be taken as equal to 0.71, $\gamma = 1.4$, $\sigma = 0.71$ and $\frac{1 + 0.096\sqrt{\beta}}{1.068} = 1$. Therefore, Equation (5) reduces to

$$\frac{q_{suc}}{q_{imp}} = 1 + 0.424\, \frac{C_w\, P\, p_w}{q_{imp}\sqrt{R\, T_w}} (H_s - H_w) \tag{9}$$

In the continuum flow region the heat transfer to an impermeable surface is given by

$$q_{imp} = h\, \Delta T = 0.5\, k_m \sqrt{\frac{\rho_\infty V_\infty}{\mu_m D}}\ (T_r - T_w) \tag{10}$$

If T_r, the recovery temperature, is approximated by the stagnation temperature (i.e., assuming a recovery factor of one)

$$q_{imp} = 0.5\ k_m \sqrt{\frac{\rho_\infty V_\infty}{\mu_m D}}\ (T_{st} - T_w) \tag{11}$$

where subscript m denotes that the gas properties are evaluated at the mean boundary layer temperature. The enthalpy difference between air at stagnation and at the wall may be approximated by

$$(H_s - H_w) = C_{pm}(T_{st} - T_w) \tag{12}$$

Substituting Equations (11) and (12) into (9)

$$\frac{q_{suc}}{q_{imp}} = 1 + 0.848\ \frac{C_w\ P\ C_{pm}\ p_w}{k_m\ \sqrt{R\ T_w}}\ \sqrt{\frac{\mu_m D}{\rho_\infty V_\infty}} \tag{13}$$

This equation does not contain a term that accounts for the reduction in heat transfer area with increasing porosity. This is justified by the fact that the heat transfer takes place through the boundary layer and the whole surface is assumed to be covered with a continuous boundary layer in order for this theory to be applicable.

Porous Surface Heat Transfer - Boundary Layer Thickness Small Compared to Pore Dimensions

The heat transfer to a surface is given by

$$q = h\ A\ \Delta\ T = h\ A\ (T_r - T_w) \tag{14}$$

If both an impermeable surface and a porous surface are assumed to be subjected to the same free-stream conditions (altitude and velocity) it can be shown that

$$\frac{h_{suc}}{h_{imp}} = \sqrt{\frac{D\ P}{d\ \varphi}} \tag{15}$$

by assuming $Nu = 0.5\sqrt{Re}$.

The porosity P in the above expression arises because the pore entrance flow conditions differ from the post-shock conditions, that is, the expression takes into account the change in mass flow. It does not consider the effect of change in temperature on viscosity.

If both surfaces are held at the same temperature,

$$(\Delta T)_{suc} \approx (\Delta T)_{imp} \tag{16}$$

The reduction in area available for heat transfer due to porosity is given by

$$\frac{A_{suc}}{A_{imp}} = \frac{\pi d (s-d)}{s^2} = \pi (1-P) \tag{17}$$

Since the boundary layer is not continuous over the whole surface, the reduction in heat transfer area due to porosity must be considered in the calculation of the total heat transfer. Therefore,

$$\frac{q_{suc}}{q_{imp}} = \sqrt{\frac{D}{d}\frac{P}{\varphi}}\, \pi (1-P) \tag{18}$$

This expression is not applicable at very small porosities. It gives a ratio of zero instead of one at zero porosity. Since the ratio D/d is usually large this error is not significant except at the very small porosities. Equation (18) is only applicable up to the porosity at which the pores can accept the full free-stream (swallow the shock). Assuming $\gamma = 1.4$, this occurs at $P = 0.65$.

Equation (18) is strongly dependent on the square root of the ratio of the over-all body diameter to the filament diameter. For conventional parachute type drag devices this ratio can be extremely large. The heat transfer ratio given by Equation (18) increases with increasing porosity from zero to a maximum at $P = 0.33$ and then decreases.

Calculations of the heat transfer increase to a porous body were made using Equation (13) for an altitude of 150,000 feet, a wall temperature of 1500°F, free-stream velocities of 5,000 ft/sec and 10,000 ft/sec, a nozzle coefficient C_W of 0.10 and an over-all body dimension of 1000 inches. Under these flow conditions the entrance Reynolds number for a low to moderate porosity porous structure of 1.0 mil filaments is approximately critical ($0.5<Re<2$). Thus, the theory represented by Equation (13) is applicable for filament diameters of 1.0 mil or less and the above flow conditions, while the theory represented by Equation (18) is applicable for filament diameters greater than 1.0 mil.

The heat transfer increase obtained using the modified Hidalgo theory, Equation (13), for the flow conditions discussed above is insignificant. However, the increase obtained using Equation (18) is large, of the order of several hundred, even for small porosities. Thus, under some re-entry conditions a moderate porosity, possibly as high as 25%, might be tolerable.

METAL FABRICS

Fabric Research Laboratories, under U. S. Government Contract No. AF 33(616)-7222, demonstrated that fabrics with high temperature durability, low porosity, good flexibility and bending recovery can not be obtained with monofilament screens but can be obtained with fabrics woven from yarns stranded from fine metal filaments. The feasibility of stranding and plying into yarns metal filaments as fine as 0.5 mil diameter and subsequently weaving the yarns was shown, Figure 1. Fabric porosities as low as 0.2% light transmission were obtained. These fabrics have a flexibility and bending recovery comparable to that found in a conventional heavy textile.(3)

The yarn in these fabrics was bunched, stranded and plied on a small laboratory twister. The main difficulties in the yarn fabrication are the low tensile strength and yield strain of fine metal filaments. A 0.5 mil nickel alloy filament has a rupture load of approximately 13 grams and a yield strain of 0.5%. The difficulties were overcome by utilizing a set-up that avoided all small radii of curvature bends and bunching the single filaments together on a large cylinder before twisting. A conventional textile winder was modified for this purpose, Figure 2; such machines have a sensitive tension-control which prevents filament overloading. The bunched yarn was then mounted on a rotating creel, the yarn pulled down through a central hole, and wound on a spool, Figure 3. The yarn is twisted due to the rotation of the creel relative to the takeup spool. The amount of twist was regulated by the ratio of the creel speed to the takeup speed. The twisted singles yarns are then mounted on the rotating creel, pulled down through the central hole and wound on a spool as a plied yarn, Figure 4. The major shortcoming of such a machine design is the low production rate, 2-3 ft/min; the higher the twist the lower the production rate due to the limitation of the speed at which the creel can be rotated.

The yarns were woven into fabrics on a small hand loom. To facilitate weaving torque-free yarns were fabricated (the ply twist direction was opposite to the singles twist direction) and some of the yarns were coated with nylon.

The various factors that affect fabric performance were taken into consideration in designing the yarns and fabrics. In the course of bending a fabric, the filaments in the yarns are subjected to both deformations and displacements.(5) Bending strains are certainly imposed on the filaments and perhaps to some degree tensile and torsional strains, also. Therefore, fabric flexibility and bending recovery are functions of yarn and filament flexibility and bending recovery, both of which are enhanced by reducing filament diameter, as previously pointed out. However, these are not the only considerations. The fabric structure, i.e., yarn spacing and weave pattern, is also an important variable. Any factors which reduce the filament strain in a bent fabric improve the fabric flexibility and bending recovery.

The occurrence of yarn flattening during the weaving of a fabric gives rise to lower filament strains during fabric bending and thus a greater flexibility and bending recovery. The lower strain results from the greater radius of yarn curvature, due to yarns being bent over a flattened yarn. The degree of yarn flattening that takes place depends upon the amount of yarn twist. Low twist yarns flatten more easily than high twist yarns. The degree of flattening is also dependent

on the amount of beat-up and yarn tension during weaving, and the weave pattern.

A long float weave results in less yarn flattening than a plain weave since the normal pressures between yarns at cross-overs is less for a given yarn tension where there are more points of contact along the yarn length prior to the yarn reversing direction of curvature. However, an increase in the length of floats in a fabric increases the fabric flexibility and bending recovery. The filament bending strains caused by fabric bending decrease gradually in the straight region between yarn intersections, reaching zero two or three yarn diameters from the region of yarn intersections. Hence an increase in yarn length between yarn intersections creates the opportunity for bending strains to be dissipated and, therefore, results in improved bending recovery. The occurrence of yarn buckling during the bending of a fabric also improves fabric flexibility and bending recovery since buckling results in a lower filament strain than that which would occur if buckling did not take place. The opportunity for and extent of yarn buckling increases as the distance between yarns increases and as the length of straight yarn between reversals in yarn curvature increases.

Relative twist directions of yarns have an effect on fabric flexibility and bending recovery. The effect is due to the bedding tendency at yarn intersections of the bottom filaments of the raised yarn and the topmost filaments of the lower yarn. Such bedding (nesting) serves both to increase the surface of contact between the two yarn systems, warp and filling, and to lock the yarn intersections at their point of contact. Therefore, nesting restricts yarn movement and hence decreases fabric flexibility and bending recovery.

For parallel nesting of the contact filaments at yarn cross-overs the local helix angle must be approximately 45°. Although straight-yarn helix angles do not usually approach 45°, the local helix angle of the yarn at yarn cross-overs can approach the required 45° due to the geometry of a bent yarn, even for conventional straight-yarn twists. Yarn nesting can be prevented by using low twist yarns. The filaments at yarn cross-overs will then be approximately perpendicular.

It is desirable in most fabric applications to have the same flexibility and bending recovery in both the warp and filling directions. Assuming identical warp and filling yarns, this requires a square fabric. There must be the same number of warp yarns per inch as filling yarns and both sets of yarns must have the same amount of crimp.

As has already been pointed out, for re-entry applications fabric porosity is a critical consideration. All the re-entry schemes require a fabric porosity of less than 25%. Porosity is a function of both yarn and fabric structures. Yarn flattening during the weaving of a fabric results in low porosity. The lower the yarn twist the greater the amount of yarn flattening and thus the lower the fabric porosity. Long float weave patterns can also give a lower porosity fabric by enabling more yarns to be packed into a unit area of fabric. However, for the same number of picks and ends as in a plain weave fabric, a long float weave pattern fabric will give a higher porosity due to the possible oblique paths for air flow.

Fabric porosity can also be decreased by introducing a crimp unbalance, enabling more yarns to be packed into one direction than the other. In the extreme case one set of yarns can be held straight during weaving and all the crimp put

into the other set. This allows the crimped yarns to be packed in until they touch each other. A zero line-of-sight porosity will result, although the fabric is still porous due to oblique air passages.

As previously pointed out, crimp unbalance results in different fabric properties in the warp and filling directions, which is undesirable in most applications.

The tensile strength of a fabric is a function of the yarn tensile strength and fabric geometry. The tensile strength of continuous-filament yarns is a function of the yarn twist, yarn size and individual filament properties.[8] The singles yarn tensile strength decreases with increasing yarn twist. The relations predicting the strength translation of singles yarns to plied yarns[9] show initially an increase in translation of strength from singles yarns to plied yarns with increasing ply back twist, and then a decrease as the ply twist is further increased.

Yarn crimp in a fabric decreases the translation of yarn strength to fabric strength. Crimp imposes bending strains on the yarn and results in the yarn being at an angle to the plane of the fabric over much of its length. The yarn-to-fabric strength translation efficiency is decreased approximately by the cosine of this angle.

The occurrence of yarn flattening in a woven fabric results in a decrease in yarn crimp, and thus a decrease in yarn bending strains and the average angle of the yarn to the plane of the fabric. Therefore, a higher yarn-to-fabric strength translation results. Long float weave patterns also result in lower yarn bending strains and a lower average angle of the yarn to the plane of the fabric. Thus, yarn-to-fabric strength translation can also be increased by utilizing long float weave patterns.

Fabrics employed in re-entry drag and lift-drag devices must possess considerable tear strength. The tear strength of a fabric composed of yarns with a given tensile strength depends on the amount and type of distortion which occurs at or near the del section of the tear. Some of the possible effects of fabric factors on the del are the following[14]:

1. The more easily the cross-yarns pull out of the fabric, the longer are the del yarns and the longer is the del. Smooth, strong yarns which pull out of the fabric rather than break make for a long del. Also, the less grip the fabric matrix has on the individual yarns, the better are the chances for forming a long del structure.

2. Any crimp which is removed from the cross-yarns near the tearing area acts to lengthen the del. There is also some crimp interchange which occurs in the untorn fabric ahead of the del and which subsequently results in jamming this portion of the fabric.

3. The elongation of the del resulting from the approach to jamming of the fabric depends upon how far the original undistorted fabric was from the jammed state in the direction of tear. If the fabric was already jammed in the direction of tear, no further elongation of the del could result from the jamming action of the tear. Thus, the lower the cover factor in the direction of tear,

the greater the del elongation that can be derived from the crimp interchange in the fabric ahead of the del.

4. The trellis-type distortion in which both sets of yarns, warp and filling, tend to parallel the del yarns seems greater when the cover factor and crimp in both directions are lower. For a given cover factor in the direction of tear, however, the effect of the trellis action is greater when the cover factor in the perpendicular direction is lower. The trellis action is very much dependent upon weave differences and especially upon the presence of long floats.

The above forms of distortion which result in a longer and less deep del bring the del yarns closer together for a better load distribution and thus a higher tear strength. Distortions which result in the fabric ahead of the del being distorted so that both sets of yarns tend to be parallel with the del yarns and bunch together also give a higher tear strength.

The yarn elongation influences the del shape. Elongation of the del yarns increases the del length and elongation of the yarns parallel to the direction of tear increases the depth of the del.

It has been found experimentally(14) that both continuous filament yarn fabric tear strength and fabric tear strength normalized to yarn tensile strength decrease with increasing yarn twist.

As a tear progresses through a fabric, the cyclic loading of the fabric mechanically conditions the yarns ahead of the del. Therefore, the amount of non-recoverable yarn deformation is important. It lengthens the yarns in the del and thus increases the tear strength.

In view of the above relationships between fabric performance and yarn and fabric geometry, a low twist yarn and long float weave were chosen. This resulted in the required low fabric porosity, good bending flexibility, bending recovery, tear strength and tensile strength translation.

At the present time, under a subcontract to U. S. Government Contract AF 33(616)-7854-S-1, Fabric Research Laboratories is involved in a program that has as its goal the stranding, plying and weaving of fine metal filaments on standard or semi-standard commercial equipment. Metal filaments of 1.0, 0.7 and 0.5 mil diameter are to be used. An 80-20 nickel chromium alloy wire has been selected for this work because it can be purchased off-the-shelf at a comparatively low price. It has room-temperature mechanical properties very similar to the special high temperature alloys under consideration for re-entry decelerators. Therefore, fabrication experience gained with it should be directly applicable to the various special alloy wires. Recent attempts to twist fine wire on conventional textile ring-type "down twisters" has met with considerable success. Spindle speeds as high as 7300 rpm and feed speeds as high as 500 ft/min have been obtained. Attempts will be made in the near future to weave this yarn on standard textile looms.

Due to the high poundage cost of fine metal filaments and the current state of the art in the wire stranding and weaving industry, other possible structural designs resulting in a high temperature durable fabric with the required mechanical characteristics are being investigated. Designs utilizing the materials in

either filamentous or nonfilamentous form are possible. These designs might incorporate mechanical operators such as flex-points or hinge-points. A flex-point, by arbitrary definition, is a discrete, localized, flexible geometric configuration. An example is a straight filament with pigtail loops distributed along its length. In contrast, a hinge-point is a localized configuration that exhibits zero resistance to rotation. An example is a well-oiled door hinge.

A knitted textile fabric is a structural design that exhibits both of the above mechanical operators. The yarn interlooped with itself has not only the flex-point flexibility of the loop but also the hinge-point rotational freedom between the loops. Although most designs of this type have one or more shortcomings, such as a high porosity, one class of designs looked particularly promising. These were the types of meshes used in conveyor belting and jewelry (Milanese mesh), Figure 5. They are successively connected helical springs, either joined with a hinge pin or by twisting and inserting one spring into the next. These designs result in a structure with essentially infinite flexibility and zero bending recovery in one direction due to the hinges and a relatively high rigidity in the other direction. By weaving ribbon widths of these meshes it is possible to obtain a flexible fabric, Figure 6. Low porosity meshes are available.

Thin, rolled metal sheet is available at a relatively low cost. If a method of slitting sheet into narrow widths can be devised, it may be possible to avoid the problems and expense of fine filament drawing.

A 40 mesh plain weave fabric was woven on a handloom from a low twist plied yarn composed of ribbons, Figure 7(a), (4 mil by 0.35 mil), and its properties were compared to those of a fabric woven from a yarn composed of circular filaments of the same material and cross-sectional area. Approximately a twofold decrease in rigidity was observed due to the orientation of the ribbon filaments in the woven fabric, Figure 7(b).

Another possible approach to a high temperature durable textile type of fabric is based on the metamorphic principle[2]. Instead of attempting to overcome the destructive re-entry environment by using a thermally durable material the metamorphic principle treats the re-entry environment as the medium for a desired chemical process. In the "A" state (the pre-deployment state) the ideal metamorphic textile should be readily fabricated, folded, packed and eventually deployed. Once deployed, the aerodynamic heating would transform the textile into the "B" state. In the "B" state the system need only maintain its integrity in order to provide drag for a short length of time.

An application of this principle is a fabric woven from yarns of flameproofed organic yarns and 0.5 mil metal filaments. It is similar to a conventional textile at room temperature. At high temperatures the organic yarn foams and forms a viscous char, resulting in a low porosity flexible fabric with the metal filaments supplying the required strength.

The fabrication of fine metal filaments and the weaving of them into fabrics are only the first two steps toward the utilization of such structures in re-entry decelerators and other space applications. The fabrics must be evaluated in an environment simulating that of their contemplated application. The various

types of evaluation that are necessary are strip tensile, tear, creep, rigidity, bending recovery and flex life at elevated temperatures. The translation of filament properties to yarn properties, and yarn properties to fabric properties at elevated temperatures should also be measured. The effect of various filament and yarn coatings on the above properties should be noted. Coatings which give improved filament abrasion resistance, oxidation resistance, and freedom of individual filament motion during fabric bending should be considered. The effect of high temperature fabric coatings on fabric properties should also be determined, particularly the effect of fabric porosity (weave tightness) on coated fabric permeability in high temperature, high velocity air.

The fabric must also be tailored to the required configuration, and the mechanical characteristics of the resulting structure must be known. The various methods of joining panels of fabric should be investigated. Sewing by conventional or semi-conventional procedures would probably be the most desirable method of seaming. Coating the sewing yarn with a material such as nylon or Teflon might facilitate the sewing by improving the yarn abrasion resistance.

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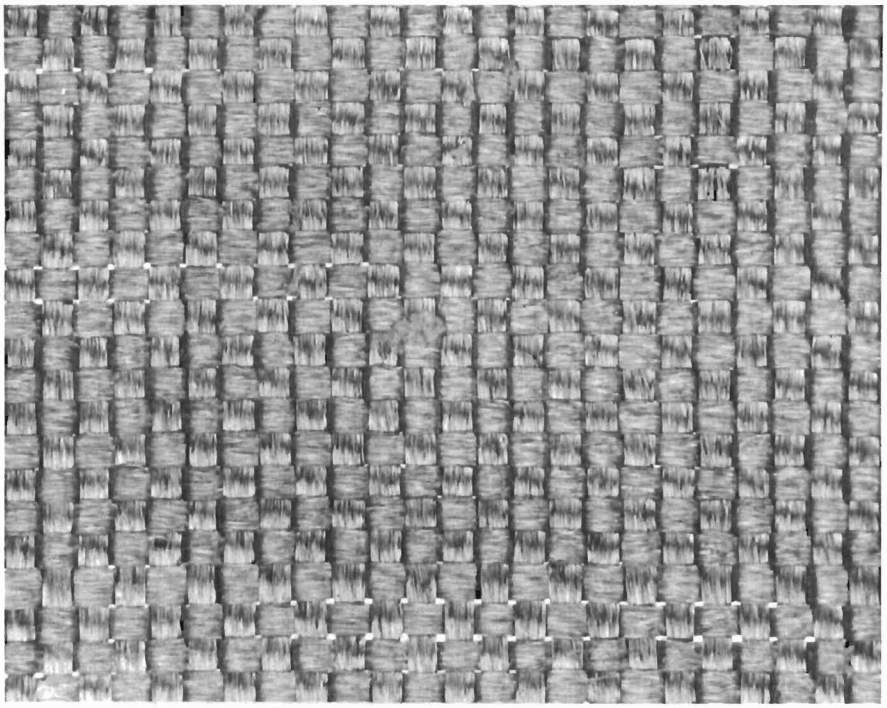


FIGURE 1. ONE HUNDRED FILAMENT SINGLES YARN, PLAIN WEAVE.

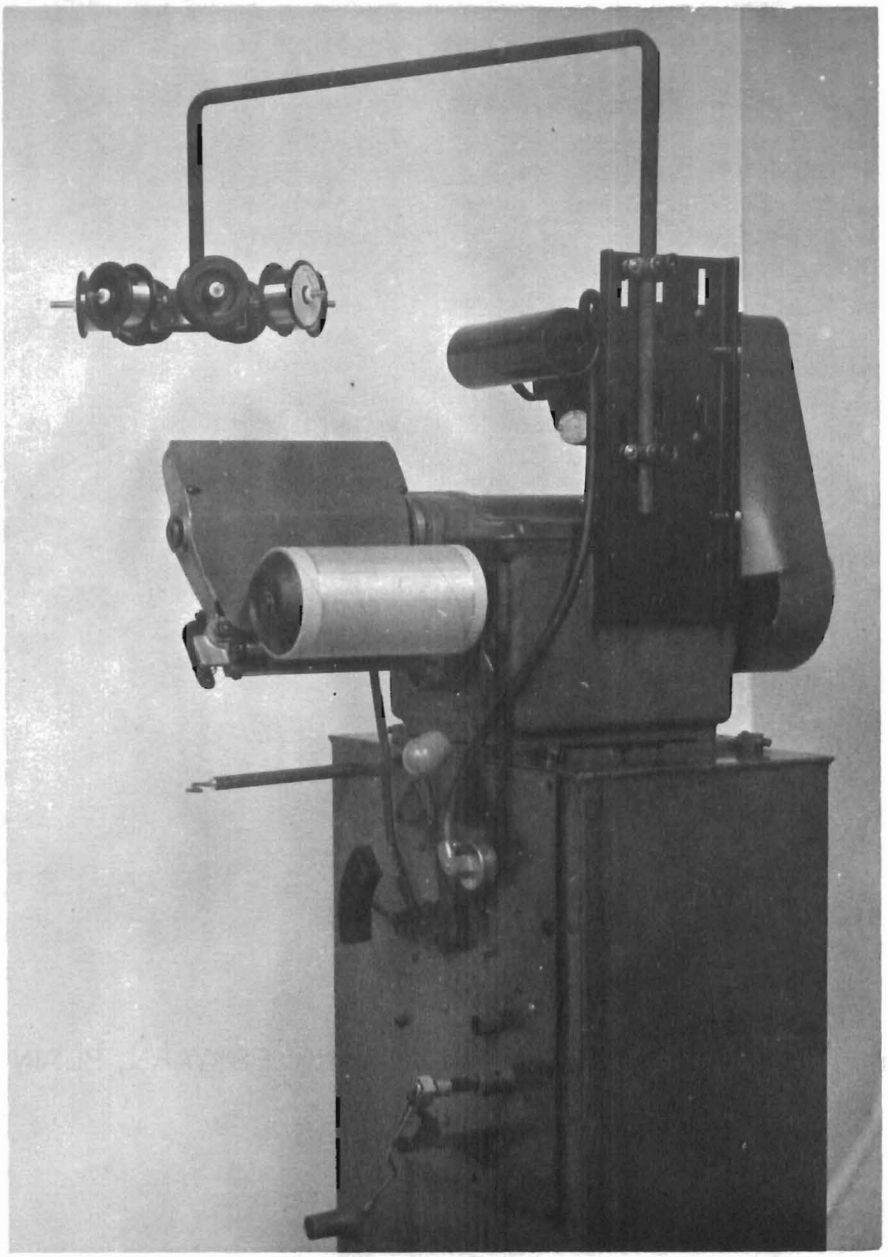


FIGURE 2. 0.5 MIL WIRE BUNCHER.

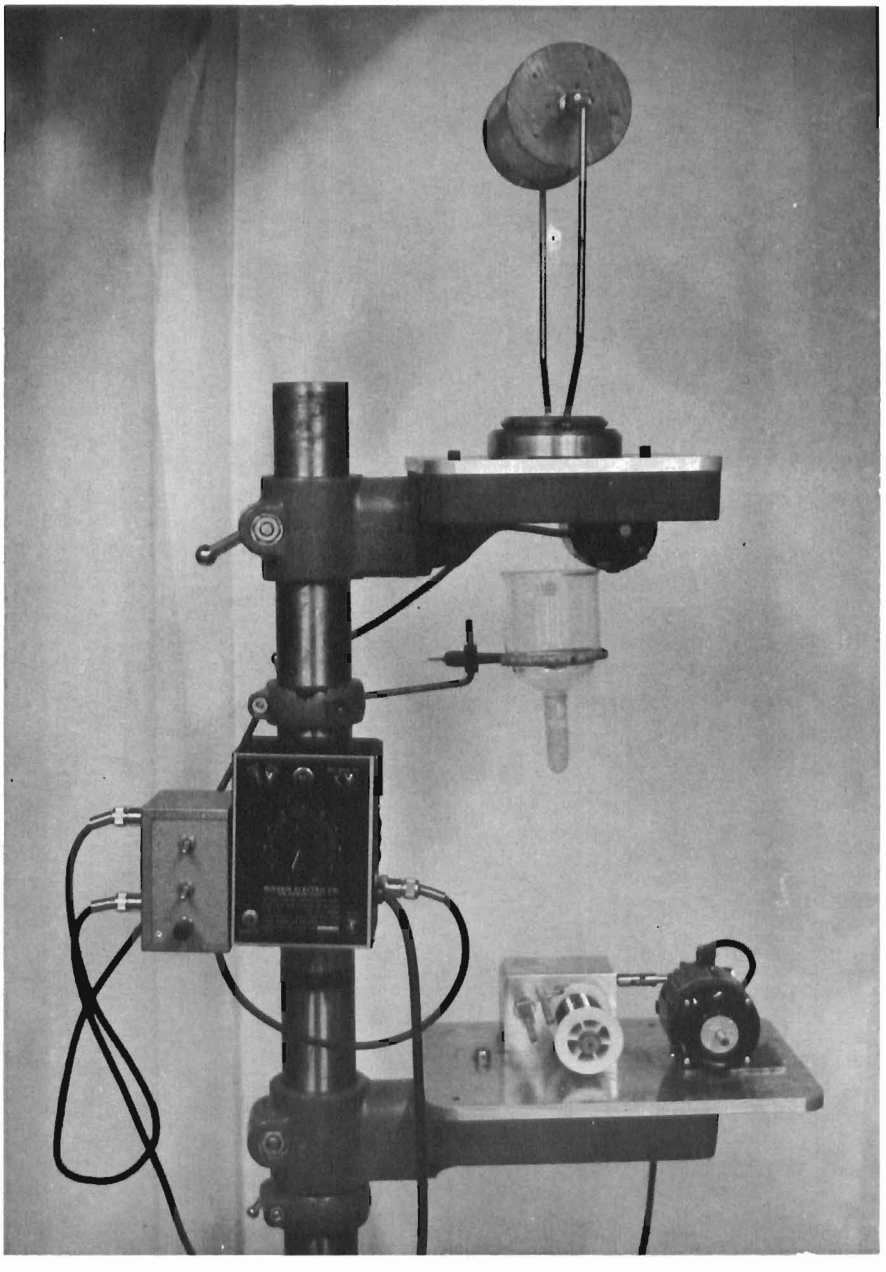


FIGURE 3. SINGLES YARN TWISTER.

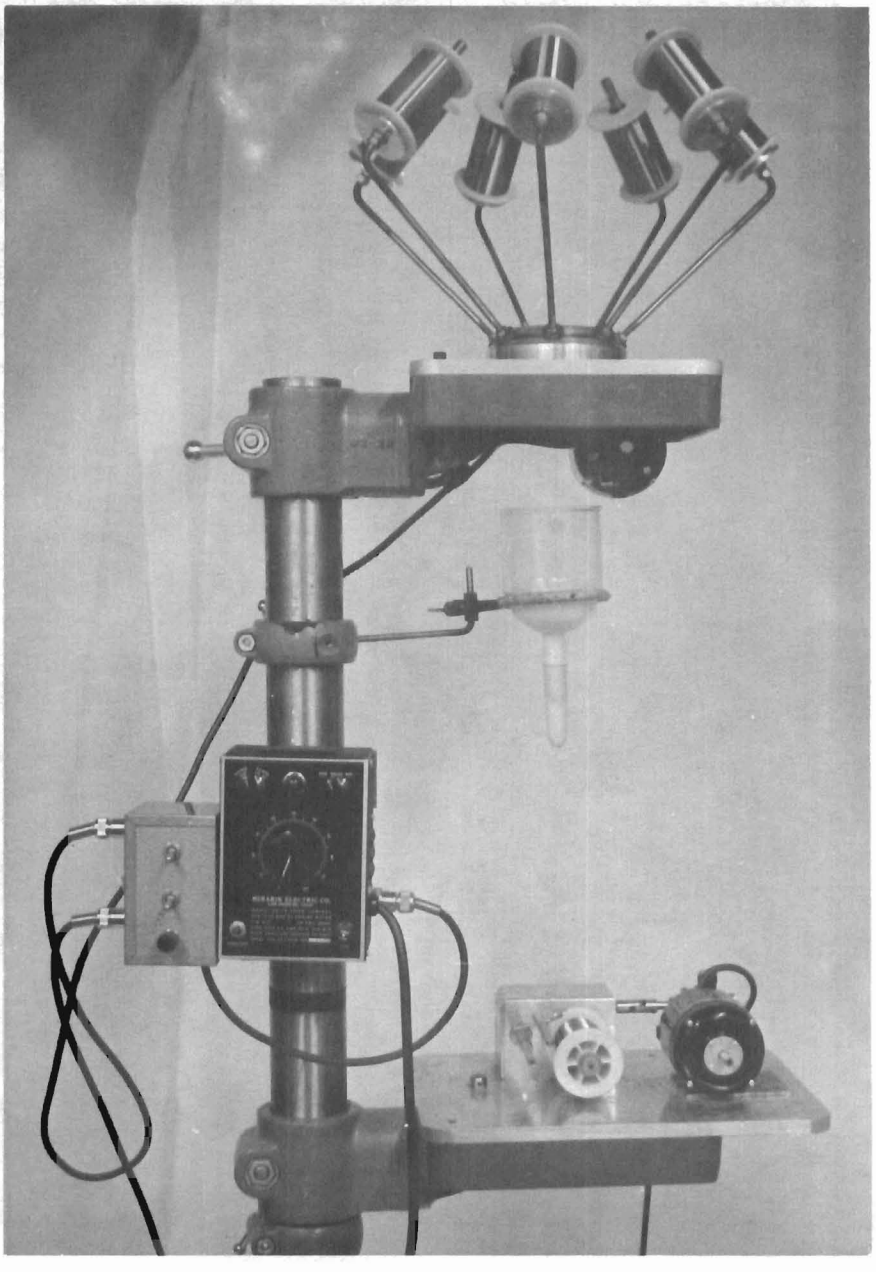


FIGURE 4. PLIED YARN TWISTER.

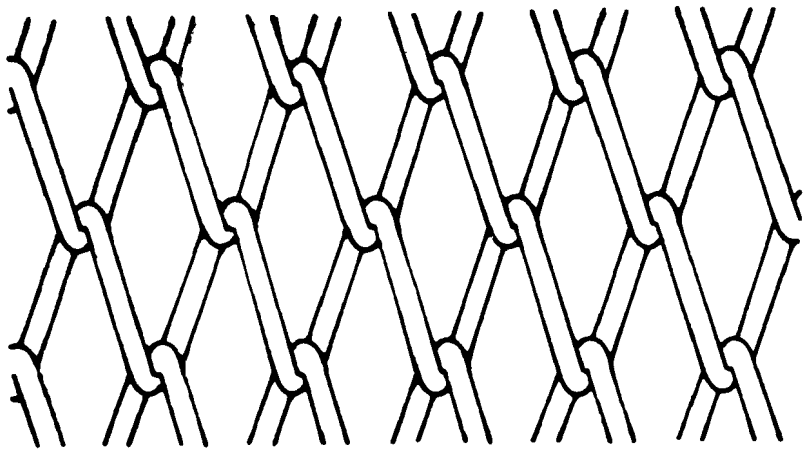


FIGURE 5. SECTIONAL BELTING - MILANESE MESH.

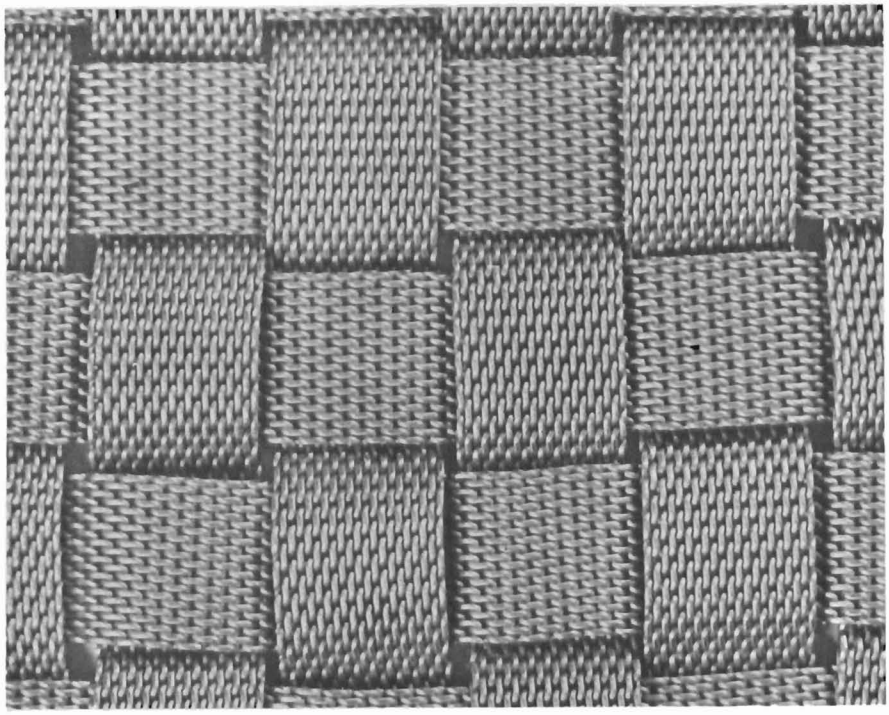
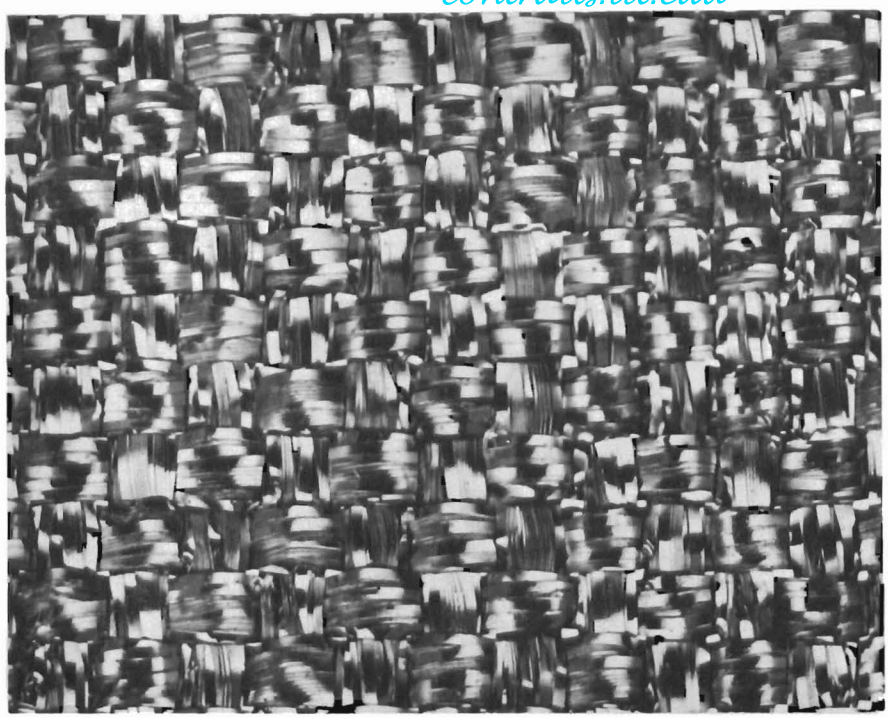
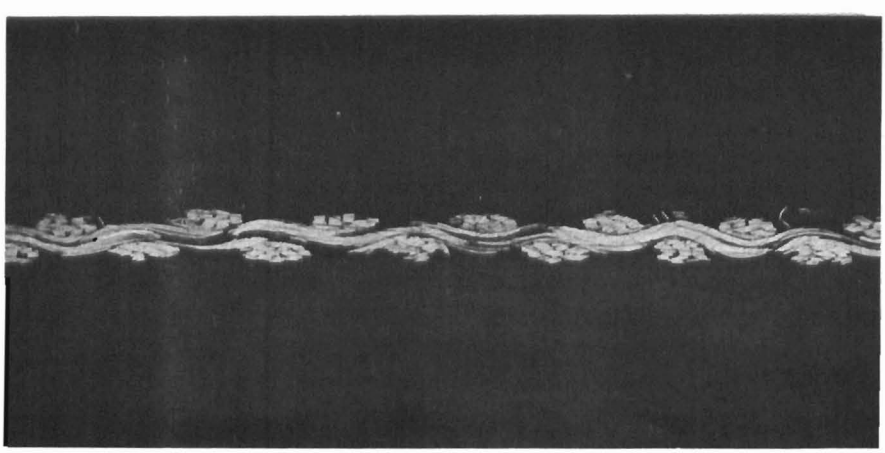


FIGURE 6. FABRIC WOVEN FROM MILANESE MESH RIBBONS.



a



b

FIGURE 7. MULTIFILAMENT RIBBON YARN, PLAIN WEAVE.