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CALCULATIONS OF BRAIDING PARAMETERS

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PHILIP C. WHEELER

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BENÉT LABORATORIES
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Braiding is a process in which fibrous strands of m:terial are interlocked and precisely placed onto a mandrel. Resin may be applied to the fibers prior to placement onto the mandrel through a resin applicator.

Certain parameters are needed in the braiding process for the operator to fabricate an item displaying specific properties. Some of these parameters are braider speed, mandrel traverse rate, and volume flow rate of the resin and

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20. ABSTRACT (CONT'D)

the fiber onto a mandrel.

Descriptions and calculations of these parameters are covered in this report.

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INTRODUCTION

The New England Butt* 144 carrier braiding machine is designed to braid (knit) fibrous material into cylindrical, but not necessarily symmetric, shapes over a mandrel form. The braiding machine is capable of applying 144 continuous strands of material simultaneously onto a mandrel as well as 72 longitudinal strands to give lateral strength to the component. As the 144 strands of fiber are being applied to the mandrel, each fiber is coated with a specific amount of resin from a resin applicator. The resin applicator is an added piece of hardware to the braiding machine and was fabricated by U.S. Composites Corporation.** Coating of the fibers with wet resin occurs just prior to the fibers being applied to the mandrel. For more information on braiding, see Reference 1, and for more information on the resin applicator, see Reference 2.

During the braiding operation, the braiding machine remains stationary while a mandrel form is traversed horizontally in and out of the center of the braider's braid ring to apply layers of composite material to the mandrel's surface.

This report addresses some of the braiding parameters such as braider speed, mandrel traverse rate, fiber flow rates, and resin flow rates onto a mandrel during the braiding process.

CALCULATION OF BRAIDER SPEEDS

Listed in Table I are dashpot settings for the New England Butt 144 carrier braiding machine versus the revolutions of carriers around the braider carrier ring.

*New England Butt Company, 1211 High Street, Central Falls, RI 02863.
**U.S. Composites Corporation, Rensselaer Technology Park, 105 Jordan Road, Troy, NY 12180.

TABLE I. BRAIDER DASHPOT SETTINGS VERSUS BRAIDER SPEED

Braider Dashpot Setting	Time Per Two Revolutions (Seconds)	Minutes Per Revolution	Revolutions Per Minute
30	161.9	1.35	0.74
40	112.3	0.94	1.06
50	82.9	0.69	1.45
60	66.2	0.55	1.82
70	55.7	0.46	2.17

There are 144 carriers on the front face of the braider as shown in Figure 1. If 72 carriers travel clockwise while 72 travel counterclockwise, there will be 72 crossovers of yarn around the circumference of a mandrel.

Braiding speeds are typically referred to as picks per minute in the textile industry. A pick is the overlap of two yarns. One pick per minute refers to one overlap of yarn onto a mandrel in one minute. There will be 72 picks around the circumference of a mandrel or 72 picks per revolution of the braider carriers around the carrier ring.

A normal operating speed for the braider is 125 picks per minute. Dashpot settings for the braider can be calculated as follows:

$$(72 \text{ picks/rev})\ (\text{R.P.M.}) = 125 \text{ picks/min}$$

$$\text{R.P.M.} = 1.736$$

where R.P.M. = rotational speed of the braider in revolutions per minute.

Using the graph in Figure 2 and following the R.P.M. of 1.736 over to the slope of the line, the dashpot setting is 58.

CALCULATION OF THE RESIN FLOW RATES FOR A FULLY COVERED MANDREL

Assume that the diameter of a mandrel to be braided over is 2 inches. We want the braid angle over the mandrel to be ± 45 degrees and we are braiding at a rate of 125 picks per minute. What will be the volume flow rate of Epon 828 resin and the catalyst methyl tetrahydrophthalic anhydride (MTHPA) and accelerator Benzyldimethylamine (BDMA) mixture through the resin applicator in order to achieve a fiber-volume fraction of 60 percent? Assume the mandrel is covered 100 percent by fiber. The fiber type is S2-CG-150-1/3-6 fiber glass.

From Figure 3 the following equations can be derived:

$$V = \frac{\pi D\ (R.P.M.)}{\tan \alpha} \qquad (1)$$

$$L = \frac{\pi D}{\sin \alpha} \qquad (2)$$

where

- V = mandrel feed rate through the braider
- α = angle of wrap of material onto the mandrel
- L = length of material wrapped onto the mandrel (length of material from point A to point B in Figure 3)
- D = diameter of mandrel

A braid speed of 125 picks per minute corresponds to a dashpot setting of 58. This also corresponds to a rotational speed of the carriers around the braider carrier ring of 1.736 revolutions per minute.

From Eq. (1),

$$V = \frac{2\pi(1.736\ R.P.M.)\ in.}{\tan 45°} = 10.92 \text{ inches per minute}$$

This is the traverse speed of the mandrel through the braider required to give a braid angle of ± 45 degrees.

From Eq. (2),

$$L = \frac{2\pi \text{ in.}}{\sin 45°} = 8.885 \text{ in.}$$

This is the length of material wrapped around the mandrel. Since this is the length of one yarn, we must multiply by 144 to get the total length, L_T, of yarn:

$$L_T = 144 \times 8.885 \text{ in.} = 1{,}279.44 \text{ in.}$$

The supplier gives a length per unit pound for S2-CG-150-1/3-6 fiber glass yarn as 5,000 yards per pound which converts to 180,000 inches per pound. The C refers to continuous fiber, G refers to 0.00036-inch nominal fiber diameter, and 150 refers to 15,000 yards per inch for each individual strand. The 1/3 refers to one end being composed of three strands plied together with each strand containing 150 basic strands twisted together. The 6 at the end of this number refers to the number of ends the yarn is made from.

The 180,000 inches per pound represents the length of fiber required to give one pound of fiber. But this only applies for one end of fiber for each bundle of fiber. In this example there are six ends per bundle, therefore, the length per unit weight must be divided by six to obtain the total length of fiber per pound, L_W:

$$L_W = \frac{180{,}000 \text{ in./lb/end}}{6 \text{ ends}} = 30{,}000 \text{ in./lb}$$

Dividing the total length of yarn, L_T, by the length per pound, L_W, of fiber gives a total weight of yarn applied to the mandrel, WT_{total}:

$$WT_{total} = \frac{1{,}279.44 \text{ in.}}{30{,}000 \text{ in./lb}} = 0.04265 \text{ lb}$$

This value represents the total weight of fiber glass material braided onto the mandrel over the longitudinal length, l, in Figure 3. The longitudinal length, l, and weight per unit of longitudinal length, W_L, are calculated below:

$$l = \frac{\pi D}{\tan \alpha} = \frac{2\pi \text{ in.}}{\tan 45°} = 6.283 \text{ in.} \tag{3}$$

$$W_L = \frac{WT_{total}}{l} = \frac{0.04265 \text{ lb}}{6.283 \text{ in.}} = 0.006788 \text{ lb/in.} \tag{4}$$

To calculate the volumetric flow rates of the resin and the catalyst required to give a fiber-volume fraction of 60 percent, we must first calculate the weight of the fiber being applied to the mandrel per minute during the operation of the braider. The calculated rate, R, is shown below:

$$R = W_L \times V \tag{5}$$

$$R = (0.006788 \text{ lb/in.})\ (10.92 \text{ in./min}) = 0.074125 \text{ lb/min}$$

This weight flow rate can be converted into volumetric flow rate as follows:

$$Vol = R\left[\frac{1}{\text{Density of glass}}\right] \tag{6}$$

$$Vol = (0.074125 \text{ lb/min})\ \frac{1 \text{ in.}^3}{0.090 \text{ lb}} = 0.8236 \text{ in.}^3\text{/min}$$

Convert cubic inches to milliliters by multiplying by the conversion factor 16.4 ml/in.^{3}:

$$Vol = (0.8236 \text{ in.}^3\text{/min})\ (16.4 \text{ ml/in.}^3) = 13.50 \text{ ml/min}$$

This is the volumetric flow rate of fiber onto the mandrel. From this volumetric flow rate, both the resin and hardener flow rates can be calculated. This is done as follows:

V_T = total volumetric flow rate of resin, catalyst, and fiber

$$Vol = V_T \times 60 \text{ percent} = 13.50 \text{ ml/min}$$

$$V_T = 22.5 \text{ ml/min}$$

The volumetric flow rate of the resin/catalyst mixture can be calculated as follows:

V_m = volumetric flow rate of resin/catalyst mixture

$$V_m = V_T \times 40 \text{ percent} = 22.5 \text{ ml/min} \times 40 \text{ percent}$$

$$V_m = 9.0 \text{ ml/min}$$

To calculate the flow rates of the resin and the catalyst separately, the percentages of each must be known. To do this, the specific gravity of each component must be known. Listed below are values of the specific gravity of Epon 828, MTHPA, and BDMA:

Epon 828:	1,162 kg/m^3
MTHPA:	1,210 kg/m^3
BDMA:	900 kg/m^3

The mixing ratios for each of the components are 100 parts-by-weight of Epon 828, 80 parts-by-weight of MTHPA, and 1 part-by-weight of BDMA. The total weight is (100 + 80 + 1) = 181 grams of resin mixture. The weight percent (Wt%) of each is as follows:

Wt% Epon 828 = 100/181 = 55.25 percent

Wt% MTHPA = 80/181 = 44.2 percent

Wt% BDMA = 1/181 = 0.55 percent

Out of a total mass of 100 grams there will be 55.25 grams of Epon 828, 44.2 grams of MTHPA, and 0.55 gram of BDMA. Since the density of Epon 828 is 1.162 gm/ml and the mass of resin is 55.25 grams, then it follows through the following equation:

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}} \quad (7)$$

that the volume of resin is 47.547 ml. Similarly, the volumes of MTHPA and BDMA can be found. The results are listed below:

Epon 828:	47.546 ml
MTHPA:	36.528 ml
BDMA:	0.6138 ml

Knowing that the total volume is (47.546 + 36.528 + 0.6138) = 84.6878 ml, we can calculate the volume percent (Vol %) of each by the following equation:

$$\text{Vol\% of component} = \frac{\text{Volume of component}}{\text{Total volume}} \quad (8)$$

The volume percentages are listed below:

Vol% of Epon 828 = 47.546/84.6878 = 56.14 percent Epon 828

Vol% of MTHPA = 36.528/84.6878 = 43.13 percent MTHPA

Vol% of BDMA = 0.6138/84.6878 = 0.724 percent BDMA

The volumetric flow rate of resin is calculated below:

V_r = Volume flow rate of resin

$V_r = V_m \times 56.14$ percent

$V_r = 9.0$ ml/min $\times$ 56.14 percent

$V_r = 5.0$ ml/min

The volumetric flow rate of the catalyst plus the accelerator is calculated below:

V_c = Volume flow rate of catalyst plus accelerator

$V_c = V_m \times$ (100 percent - 56.14 percent) $= V_m \times 43.86$ percent

$V_c = 9.0$ ml/min $\times$ 43.86 percent

$V_c = 3.95$ ml/min

These volumetric flow rates are only good if the mandrel is fully covered by fiber. To determine the percent of coverage, consider Figure 4.

In this figure four strands of yarn will make a total of eight crossovers or eight picks. Six strands will make eighteen picks. The general equation which gives the number of picks obtained from a given number of yarns is given below:

$$N_p = N_y^2/2 \tag{9}$$

$$A_p = (B.W.)^2/\sin 2\alpha \tag{10}$$

$$A_y = N_y \times B.W. \times L \tag{11}$$

$$A_{TP} = N_p \times A_p \tag{12}$$

where

N_p = number of picks

N_y = number of yarns

A_p = area covered by one pick

A_y = area covered by yarn

A_{TP} = total area of picks

B.W. = bandwidth of yarn

The bandwidth for the six-ended fiber glass yarn used in this problem was determined by U.S. Composites as 0.06 inch (ref 2). For the example illustrated above, the area of coverage, A, is calculated:

$$A = A_y - A_{TP} = (N_y \times B.W. \times L) - (N_y^2/2 \times (B.W.)^2/\sin 2\alpha) \tag{13}$$

$$A = (144 \times 0.06 \times 8.885) - [(144)^2/2 \times (0.06)^2/\sin 2(45)] = 39.44 \text{ in.}^2$$

Since the total area covering the braided cylinder, A_c, is

$$A_c = \pi \times D \times l \tag{14}$$

$$A_c = 3.14 \times 2 \times 6.28 = 39.44 \text{ in.}^2$$

the percent coverage is 39.44/39.44 = 100 percent.

CALCULATION OF THE RESIN FLOW RATES FOR A PARTIALLY COVERED MANDREL

For each diameter mandrel, there will be only one braid angle at which the fibers will be able to produce 100 percent coverage of the mandrel. In the above example, a 2-inch diameter mandrel with a braid angle of 45 degrees produced a laminate which covered 100 percent of the mandrel.

At times it is desirable to produce a laminate using a braid angle which will not produce a fully covered mandrel. In these cases there will be regions over the mandrel void of fibers. Additional resin must be added to the fibers to cover the fibers and also to fill in these voids between the fibers. The following example calculates the flow rate of mixed resin onto the fibers. Also calculated is the overall fiber-volume fraction of the laminate. The braid angle and material will remain the same as in the first example and the mandrel diameter is 4 inches instead of 2 inches.

U.S. Composites (ref 2) determines the ply thickness and fiber bandwidth by taking into consideration the bundle fiber-volume fraction (the percentage of fiber in the bundle, typically 0.75) and the aspect ratio of the fiber bundle (the cross-sectional shape of the fiber bundle). It can either be circular with the aspect ratio equal to one, or elliptical with the aspect ratio greater than one.

The approximation of both bandwidth and ply thickness is not determined in this report. However, a ply thickness of 0.0205 inch, as calculated by the U.S. Composites "Braid" program, is used.

To calculate the amount of resin needed to completely saturate the fibers and also give complete coverage of the mandrel, we must first determine the fiber-volume fraction, V_f, of the laminate.

The fiber-volume fraction is calculated using the following equation and knowing the laminate thickness, t:

$$V_f = \frac{\text{Volume of fiber}}{\text{Volume of composite cylinder}} = \frac{V_{fiber}}{V_{fiber} + V_{resin}} \tag{15}$$

$$V_{cyl} = V_{fiber} + V_{resin} = \pi \times D \times 1 \times t \tag{16}$$

$$V_{cyl} = 3.1415 \times 4 \times 1.0 \times 0.0205 = 0.2576 \text{ in.}^3$$

$$V_{fiber} = (1.6457 \text{ in.}^3/\text{min}) \times 1.0 \text{ in.}/21.82 \text{ in.}/\text{min} = 0.0754 \text{ in.}^3$$

$$V_f = \frac{0.0754}{0.2576} = 29.20 \text{ percent}$$

The amount of resin required to give 29.20 percent fiber-volume fraction is found as follows:

$$V_{cyl} = V_{fiber} + V_{resin} = 0.0754 \text{ in.}^3 + V_{resin} = 0.2576 \text{ in.}^3$$

$$V_{resin} = 0.2576 \text{ in.}^3 - 0.0754 \text{ in.}^3 = 0.1822 \text{ in.}^3$$

$$V_{resin} = 0.1822 \text{ in.}^3 \times 16.4 \text{ ml/in.}^3 = 2.98 \text{ ml}$$

This value is the amount of mixed resin needed to saturate the fibers and cover the mandrel over a one-inch length. With a feed rate of 21.82 in./min, the flow rate of resin onto the mandrel is

$$V_{resin} = 2.9857 \text{ ml/in.} \times 21.82 \text{ in./min} = 65.0 \text{ ml/min}$$

This is the flow rate of mixed resin through the resin applicator required to give the laminate an overall fiber-volume fraction of 29.20 percent.

To calculate the volume flow rates of the resin and the catalyst, we need to know the mixing ratios of each. This was calculated in the previous section as 56.14 percent for Epon 828 resin and 43.86 percent for the MTHPA/BDMA mixture. The results are listed below:

$$V_r = 65 \text{ ml/min} \times 0.5614 = 36.49 \text{ ml/min}$$

$$V_c = 65 \text{ ml/min} \times 0.4386 = 28.51 \text{ ml/min}$$

REFERENCES

1. Philip C. Wheeler, "Braided Composite Bore Evacuator Chambers for the 120-mm M256 Cannon," ARCCB-TR, Benet Laboratories, Watervliet, NY, to be published.

2. August H. Kruesi and Gregory H. Hasko, "Computer Controlled Resin Impregnation for Composite Braiding," MTL Contractor Report MTL TR 87-23, U.S. Composites Corporation, Troy, NY, April 1987.

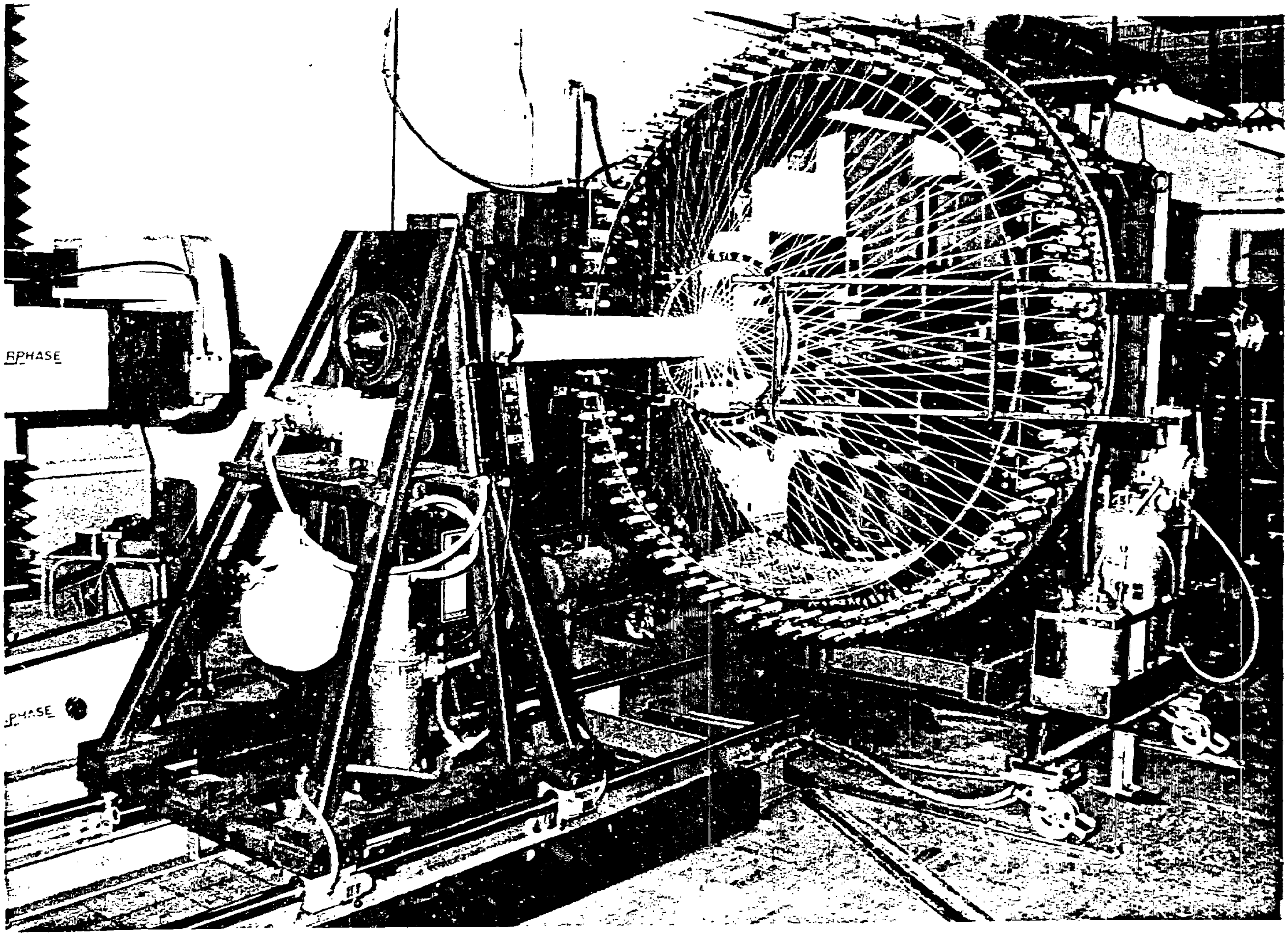

Figure 1. 144 carrier braiding machine.

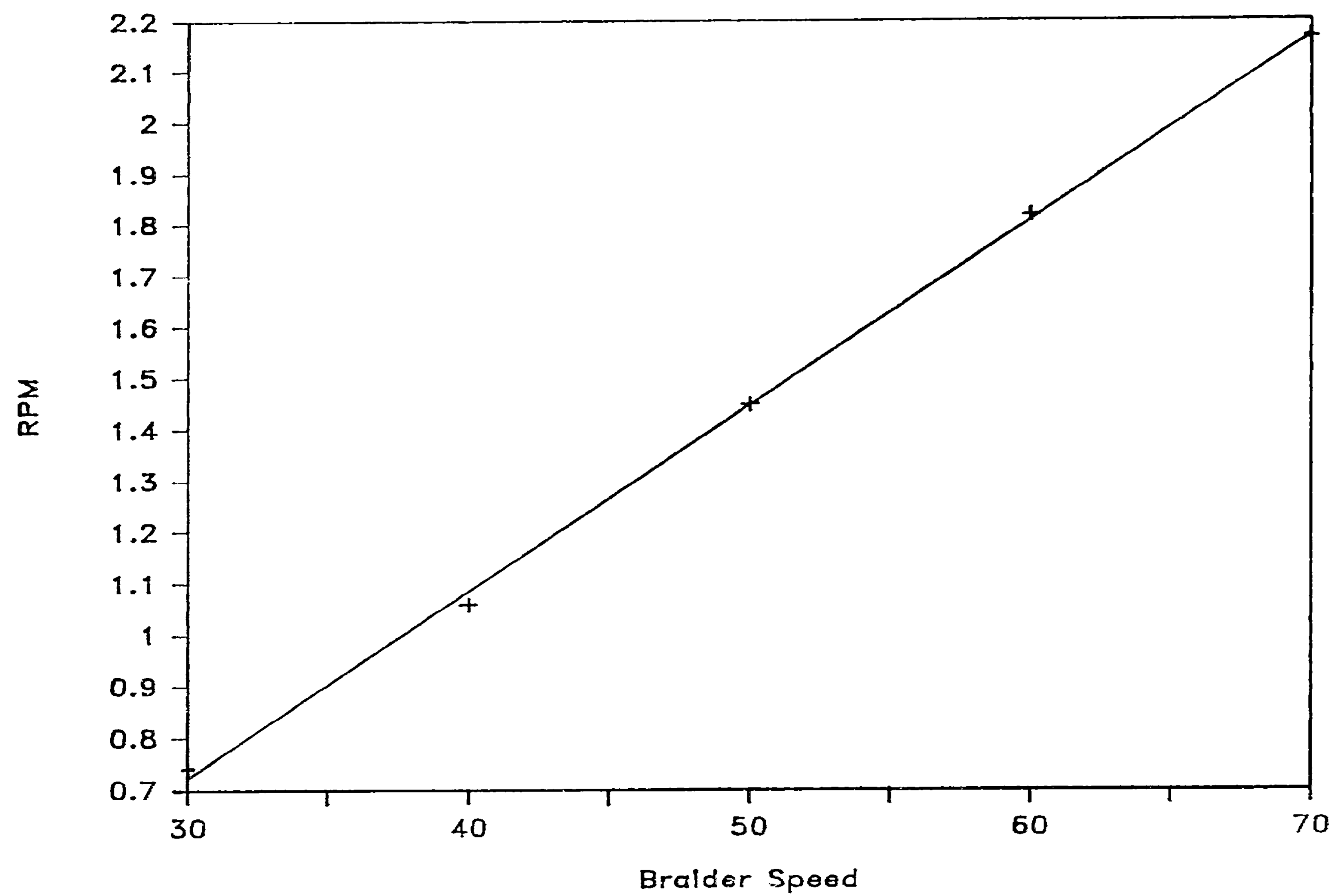

Figure 2. Graph of revolutions per minute versus braider dashpot setting.

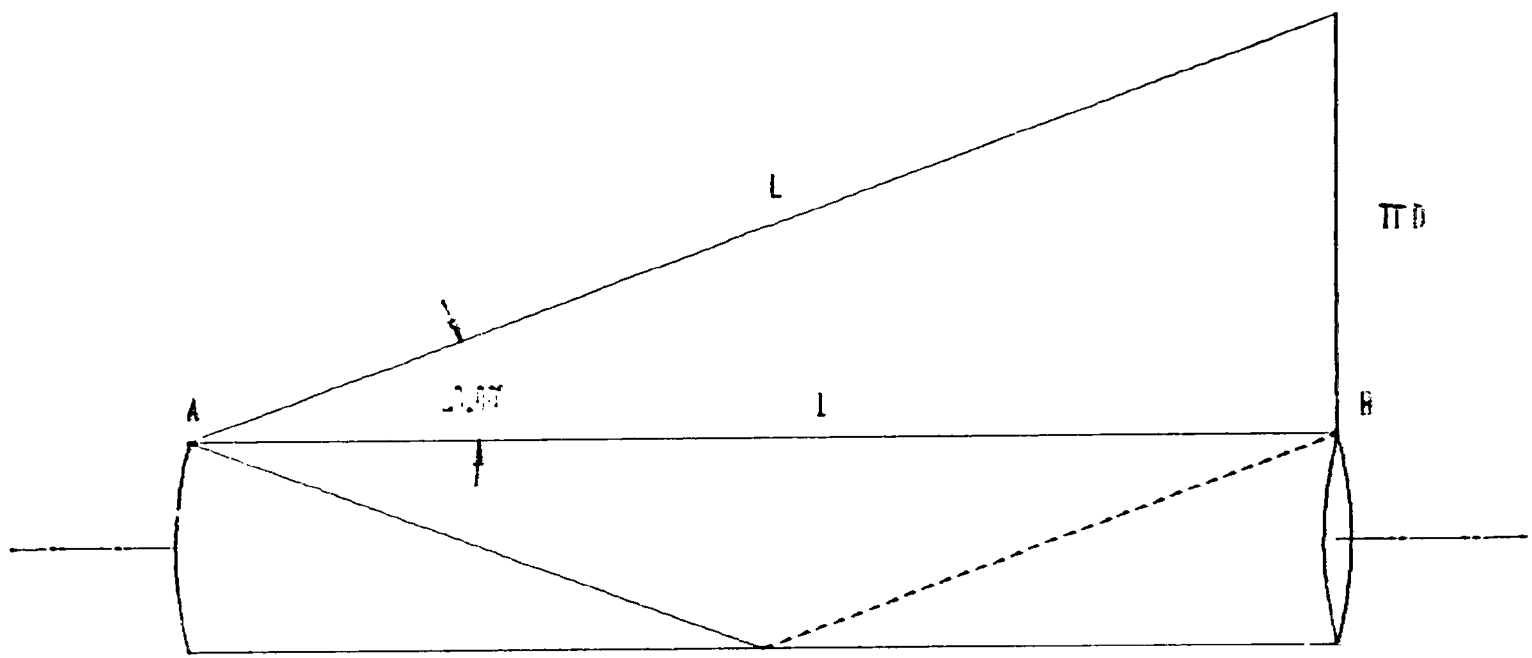

Figure 3. Illustration of single fiber wrapped around mandrel.

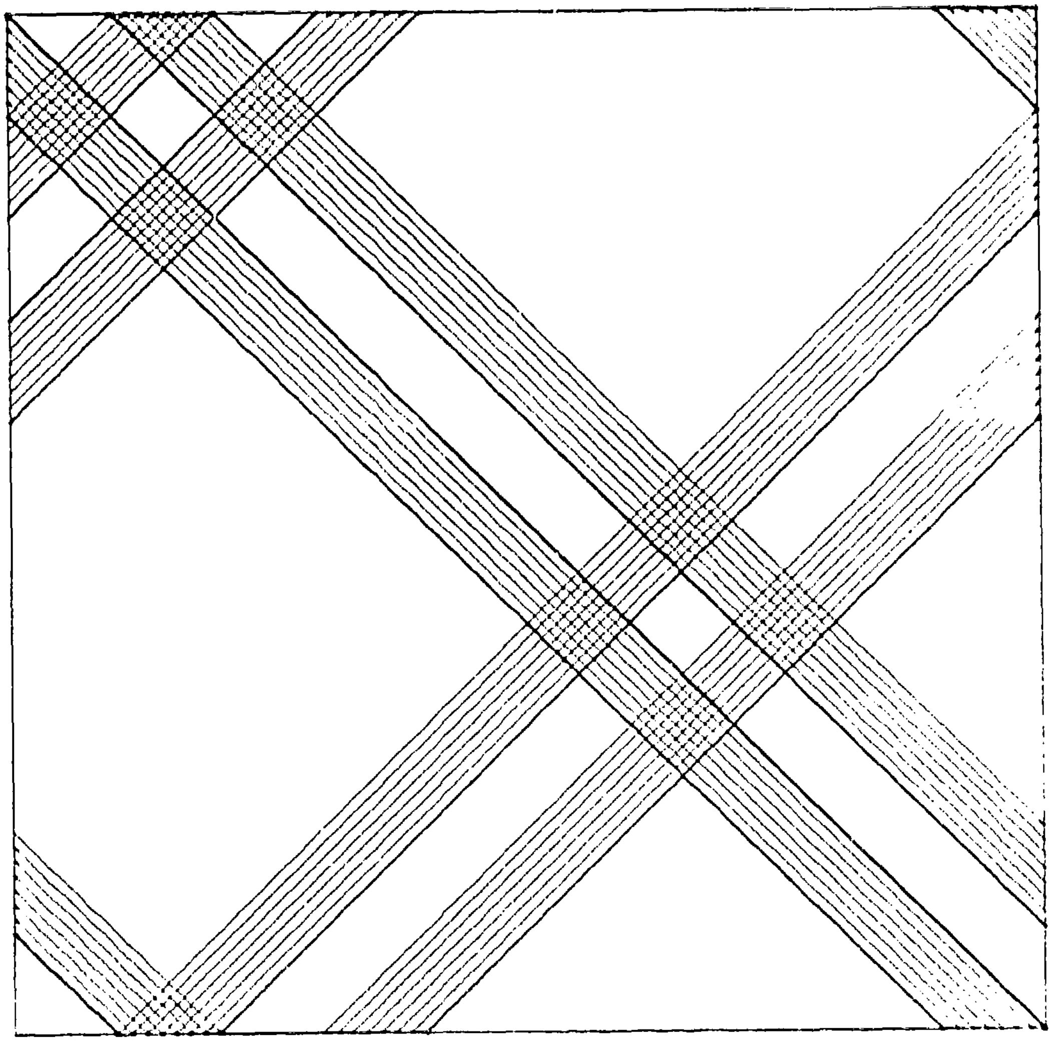

Figure 4. Illustration of braid weave produced by four strands of yarn.

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