NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 4299

EFFECTS OF FABRICATION-TYPE ROUGHNESS ON TURBULENT

SKIN FRICTION AT SUPERSONIC SPEEDS

By K. R. Czarnecki, John R. Sevier, Jr.,
and Melvin M. Carmel

Langley Aeronautical Laboratory
Langley Field, Va.

NACA

Washington

July 1958

B

NATIONAL ADVISORY COMMITTEE FOR AERONAI

TECHNICAL NOTE 4299

EFFECTS OF FABRICATION-TYPE ROUGHNESS ON TURBULENT

SKIN FRICTION AT SUPERSONIC SPEEDS

By K. R. Czarnecki, John R. Sevier, Jr.,
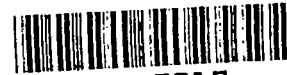and Melvin M. Carmel

SUMMARY

An investigation has been made of the effects of fabrication-type surface roughness on turbulent skin-friction drag at supersonic speeds. Insofar as the present data are concerned, it was found that fabrication of the thin-skin constructions (sandwich or honeycomb) could be done sufficiently well in practice so as to cause no increase in drag over the smooth body; however, the juncture-type roughnesses (gaps, steps, etc.) produced significant increases in drag as compared with the smooth body. The results indicate that the effects of both Reynolds number and Mach number can be correlated on the basis of changes in flow characteristics within the inner parts of the boundary layer. Consequently, increasing the unit Reynolds number has a detrimental effect and increasing Mach number has a powerful alleviating effect on drag due to surface roughness.

INTRODUCTION

As the designs of supersonic aircraft become more refined the proportion of the airplane drag assignable to skin friction generally increases. This fact makes it imperative, from the standpoint of obtaining optimum performance in speed and range, that the airplane skin friction be maintained at the lowest practicable value by keeping the airplane surfaces aerodynamically smooth. In actual practice the aerodynamically smooth surface is difficult to achieve and a certain amount of surface roughness in the form of waviness, steps, grooves, and similar protuberances must be accepted. This paper will review briefly some results from recent tests made to evaluate the magnitude and other drag characteristics of a few of these types of fabrication roughnesses in a turbulent boundary layer at supersonic speeds.

SYMBOLS

C_f skin-friction drag coefficient based on wetted surface area of basic smooth body and free-stream flow conditions

$C_{D,r}$ roughness drag coefficient based on total frontal area of roughness and free-stream flow conditions

k critical or allowable roughness height

$k_{M=1.61}$ critical or allowable roughness height at $M = 1.61$

M Mach number

R_{FT} free-stream unit Reynolds number

$R_{FT,CR}$ free-stream unit Reynolds number at which drag due to roughness first appears

δ_L laminar sublayer thickness

$\left(\delta_L\right)_{M=1.61}$ laminar sublayer thickness at $M = 1.61$

BASIC PROBLEM

The basic problem is illustrated by the sketch in figure 1. This sketch shows a three-quarter front view of a supersonic airplane configuration and some of the external details that create the problem. First, because of high surface temperature requirements, the airplane will be built of sandwich construction and these sandwich panels probably will cover most of the airplane surface. If the sandwich panels contain a honeycomb core, the external surface may have a "waffle" like appearance after exposure to heat as illustrated for the panel on the wing. If the panel is constructed of a stringer core, the seam welding of the external skin may leave lines of dents and protuberances resembling "hemstitching" as indicated for the panel on the fuselage. Further, the joining of the panels one to another and the provision of access doors, as exemplified by the thin lines in the airplane sketch, will generally result in some local surface imperfections. These imperfections can be in the form of steps, grooves, waves, creases, or combinations thereof. These types of surface roughness, however, will not saturate the surface but will occur only at fairly large intervals.

Whereas the sandwich-panel-type roughness distribution is measured in square feet, the juncture-type roughness is measured in lineal feet.

MODELS AND TESTS

In order to determine the effects of fabrication-type roughness on skin-friction drag at supersonic speeds the investigation had to be carried out on a simple model wherein the various components of total drag could be readily measured and/or separated; thus, the incremental drag due to roughness is isolated. Consequently, the investigation was carried out on the basic ogive-cylinder body illustrated in figure 2. This basic body had a length of 50 inches and a diameter of about 4.1 inches, which gave the body a fineness ratio of 12.2. The ogival nose was 3 calibers in length and faired tangentially into the constant-diameter cylindrical afterbody.

For simplicity in construction, the fabrication roughnesses were built into the cylindrical portion of the model only. In order to obtain measureable increments in drag due to roughness in these tests, the drag was determined for a number of the steps, grooves, or waves set apart at intervals judged to be sufficiently large to eliminate the effects of mutual interference. These intervals range from 1 inch for the grooves to two inches for stepped models.

Sixteen bodies representing different types or heights of fabrication-type roughness were investigated, exclusive of the smooth body. Some details of the juncture-type roughnesses are shown in figure 2. Included are 0.050-inch-square grooves and two heights each of forward- and rearward-facing steps, of protruding waves and transverse creases, and of combinations of steps and grooves. Three of the models had waffle-like surfaces representative of sandwich-construction panels with honeycomb cores, and two had surfaces representative of sandwich-construction panels with the external skin seam-welded to stringers along lines resembling hemstitching. Since it is difficult to describe the waffle or hemstitching type of roughnesses, no sketches are shown for these configurations. It should be mentioned, however, that the smooth waffle model had a rather gently wavy surface with waves approximately 0.002 inch in height, whereas the coarse waffle models had rather sharp ridges approximately 0.005 to 0.006 inch in height.

All of the models were tested at Mach numbers of 1.61 and 2.01 in the Langley 4- by 4-foot supersonic pressure tunnel and seven representative models were tested in the Langley Unitary Plan wind tunnel at $M = 2.87$. The range of free-stream unit Reynolds numbers varied from about 0.5×10^6 to 9×10^6. For all tests, transition was fixed near

the nose of the model by means of narrow strips of carborundum or sand
grains. Skin friction was determined by measuring the total drag on
the models by means of an internal strain-gage balance and subtracting
measured values of forebody and base pressure drags. All tests were
limited to zero angle of attack.

BACKGROUND INFORMATION

Before the results of the present investigation are discussed, it
appears appropriate to mention some of the physical concepts that are
involved. To begin with, a large number of investigations of surface
roughness have been made at subsonic speeds. (See ref. 1.) These tests
indicate that when the roughness did not protrude beyond the laminar
sublayer there was little if any drag due to roughness. If the rough-
ness protruded beyond this height, it created an additional form drag
above and beyond the skin-friction drag of the basic smooth surface.
For protrusions well beyond the laminar sublayer, the drags of rough-
nesses of similar shape could be readily correlated with the use of a
drag coefficient based on the height of the roughness and the average
dynamic pressure existing within the boundary layer over the height
of the roughness. Lastly, since changes in sublayer thickness are
indicative to a first order of the changes in local conditions in the
inner portion of the boundary layer and this thickness changes but
little with increase in model length at constant free-stream unit Reynolds
number, the free-stream unit Reynolds number obviously is the controlling
parameter.

It may be expected that the basic concepts just discussed for low
speeds will also apply at supersonic speeds. Thus, it was possible in
the present investigation to test full-scale roughness at full-scale
unit Reynolds number. For example, an airplane flying at $M = 3$ at
about 70,000 feet altitude would be operating at a Reynolds number per
foot of about 1.5×10^6. This Reynolds number lies in the lower part
of the test range.

RESULTS AND DISCUSSION

Smooth Bodies

Some skin-friction results for the reference smooth body and for
some typical models having the type of roughness insufficiently large
to cause any measurable penalty in drag are shown in figure 3 for the

lowest test Mach number of 1.61. The ordinate in this figure is the
effective skin-friction coefficient based on the smooth body wetted
surface area and the abscissa is the free-stream Reynolds number per
foot. As may be seen, there is little or no difference in drag for the
smooth body or the bodies with hemstitching or smooth waffle type of
roughness. This result does not necessarily mean that the dents or
protuberances on the models with roughness do not produce drag, but
that the number and size of the surface irregularities may be so small
and the smooth part of the surface relatively so large that the drag
produced by the roughness is well within the accuracy of measurement.
The main conclusion to be derived from figure 3 is that, for the well
distributed type of roughness associated with the construction of sand-
wich panels which may cover a large portion of the airplane, it appears
readily feasible to maintain the surface sufficiently smooth with nor-
mal fabrication procedures to escape any measurable drag due to roughness.

The straight line in the figure is an average "smooth" body curve
drawn through the composite data which will be used for reference in
figures 4 and 5.

Configurations With Roughness

Some typical basic test results for configurations with roughness
of the type sufficiently large to cause a measurable penalty in drag
are presented in figures 4 and 5 for M = 1.61 and 2.87. The ordinate
and abscissa are the same as in figure 3 and the average smooth body
curve is the reference previously described. Note that the coarse
waffle surfaces show a sizable increment in drag and are therefore rep-
resentative of the types of sandwich-panel surfaces that must be avoided
in fabrication or after exposure to heat.

The results of the investigation indicate, as illustrated by the
typical plots in these figures, two items of significance. First, the
smaller is the increment in drag due to roughness, defined as the differ-
ence in effective drag coefficient between the curves for the models with
roughness and that for the smooth bodies, the more closely the curves
for the models with roughness parallel the smooth body curve. This
result suggests the possibility of correlating the effects of changes
in drag increment with Reynolds number on the basis of some parameter
involving the unit Reynolds number. Second, the data in general do not
indicate the existence of a critical Reynolds number below which the
drag of the bodies with roughness merge with the smooth body drag curve
as was illustrated supersonically for distributed surface roughness in
references 2 and 3. The explanation is that the roughnesses protrude
through the laminar sublayer, usually by a substantial margin, even at
the lowest test Reynolds number.

Critical Roughness

As an item of interest at this point, it may be pointed out that, as the Mach number increases, the temperature of the boundary layer near the surface also increases rapidly and the density decreases while viscosity increases. The laminar sublayer thickness, therefore, increases rapidly with M and it may be expected that the critical or allowable roughness height, below which no drag due to roughness appears, will also increase. This statement is shown to be true in figure 6. The allowable roughness is defined as indicated by the sketch on the right of the figures as the maximum roughness which will not cause an increase in skin-friction drag below some arbitrary critical Reynolds number. For larger values of roughness, the skin-friction curve for the model with roughness will diverge from the smooth body curve at lower values of R_{FT}

and create a drag increment at the reference Reynolds number such as is evident above the critical Reynolds number. In the plot on the left of figure 6 is presented the ratio of critical or allowable roughness height at the test Mach number to allowable roughness height at M = 1.61 as a function of M at constant Reynolds number for distributed sand-grain type of roughness. The experimental points are plotted as circular symbols while the theoretical curve, which assumes that the first appearance of the drag due to roughness occurs at a constant value of the ratio of roughness height to laminar sublayer thickness, is shown as a dashed line.

The results of figure 6 indicate excellent agreement between theory and experiment. The accuracy of the experimental data is probably on the order of ±10 or ±15 percent so that the nearly perfect agreement may be somewhat fortuitous. Still, the data do show that the basic concept is probably correct and that increasing the Mach number has a powerful alleviating effect on the critical or allowable roughness height.

Reynolds Number Correlation

In the form presented thus far the results for the juncture-type roughnesses are not in a form suitable for application to model configurations other than the ogive-cylinder tested. In figures 7 and 8, therefore, some of the results obtained at M = 1.61 and 2.87 have been reduced to a more useful form wherein the increment in drag coefficient due to roughness is based on free-stream flow conditions and the total frontal area of the roughnesses investigated. At the same time this

drag increment has been divided by $\sqrt[5]{R_{FT}}$. The minus 1/5th power of the Reynolds number per foot corresponds to the slope of the skin-friction curve of the smooth bodies. The test points in these figures

represent average values of drag increment picked from data such as shown
in figures 4 and 5 at the various Reynolds numbers indicated.

The results indicate that the effects of Reynolds number can be pre-
dicted quite well except possibly at the lowest Reynolds numbers. In
this range, however, the accuracy of measurement is quite low due to low
tunnel dynamic pressure and the problem of fixing transition. Also, only
a few of the many configurations investigated show this disagreement at
low Reynolds numbers per foot and all have been included here. It should
be noted, however, that the correlation must eventually break down at low
Reynolds numbers if a critical Reynolds number is to exist. A similar
Reynolds number correlation is obtained for the distributed type of
roughnesses except that the drag generally cannot be expressed in terms
of roughness dimensions because of the difficulty of measuring the rough-
ness height or density of distribution.

For subsonic speeds Hoerner (ref. 1) has demonstrated that the drag
of the juncture-type roughnesses increases approximately as $\sqrt[18]{R_{FT}}$
because of the combined effects of decreasing boundary-layer thickness
and the consequent projection of the roughness into a higher dynamic pres-
sure region within the boundary layer. In these tests the increase is
only as $\sqrt[5]{R_{FT}}$. The reason for this faster increase is not known at
present, inasmuch as there is no change in this factor in the Mach num-
ber range from 1.61 to 2.87. The final answer awaits completion of the
breakdown of the roughness drag into its components of wave and vortex
drag. The correlation of the results for the various roughness heights
also awaits completion of this analysis.

In using the data of figures 7 and 8, the procedure requires that
the type and size of roughness on an airplane be identified. The drag
coefficient parameter based on roughness frontal area can then be
estimated from these data for the proper Mach number. This parameter
is multiplied by the flight $\sqrt[5]{R_{FT}}$ and the drag coefficient converted
from roughness frontal area to wing area on the basis of the number of
lineal feet of roughness existing on the airplane and the height of the
roughness. Thus the smaller the number and heights of juncture-type
roughness on an airplane the smaller is the increment in drag due to
roughness in terms of airplane coefficients.

Mach Number Effects

The effects of Mach number on drag due to roughness are illustrated
in figure 9. In this figure, the ordinate is the drag parameter

$\dfrac{C_{D,r}}{\sqrt[5]{R_{FT}}}$ as was used in figures 7 and 8 and the abscissa is the test Mach number. Results are shown for only a few cases but are representative of configurations not shown. The results show that, as the Mach number is increased, the drag coefficient decreases. The rate of decrease appears to be roughly proportional to the magnitude of the coefficient involved.

Inasmuch as changes in drag due to roughness with Mach number can logically be expected to vary in direct proportion to the changes in the flow characteristics of the inner parts of the boundary layer and these changes can be described to a first order by the changes in laminar sublayer thickness, a correlation of the Mach number effects was made on the basis of the expected changes in sublayer thickness with Mach number. The results for a few typical cases are shown in figure 10. In this figure the ordinate is the roughness drag parameter multiplied by the ratio of the thickness of the laminar sublayer at the test Mach number to that at $M = 1.61$ $\dfrac{\delta_L}{\left(\delta_L\right)_{M=1.61}}$. The correlation exhibits a considerable amount of scatter, but the corrections for Mach number effects appear to be correct.

<div align="center">CONCLUDING REMARKS</div>

The results of this investigation of the effects of fabrication-type surface roughness on turbulent skin-friction drag at supersonic speeds indicate that the effects of both Reynolds number and Mach number can be correlated on the basis of changes in flow characteristics within the inner parts of the boundary layer. Consequently, increasing the unit Reynolds number has a detrimental effect and increasing Mach number has a powerful alleviating effect on drag due to surface roughness. The correlation of the effects of changes in roughness height or shape requires a more comprehensive analysis than was attempted in this paper. Further investigation must be made of the effects of roughness sweep and possibly mutual interference effects.

Langley Aeronautical Laboratory,
    National Advisory Committee for Aeronautics,
        Langley Field, Va., March 20, 1958.

REFERENCES

1. Hoerner, Sighard F.: Aerodynamic Drag. Publ. by the author (148 Busteed, Midland Park, N. J.), 1951.

2. Czarnecki, K. R., Robinson, Ross B., and Hilton, John H., Jr.: Investigation of Distributed Surface Roughness on a Body of Revolution at a Mach Number of 1.61. NACA TN 3230, 1954.

3. Sevier, John R., Jr., and Czarnecki, K. R.: Investigation of Effects of Distributed Surface Roughness on a Turbulent Boundary Layer Over a Body of Revolution at a Mach Number of 2.01. NACA TN 4183, 1958.
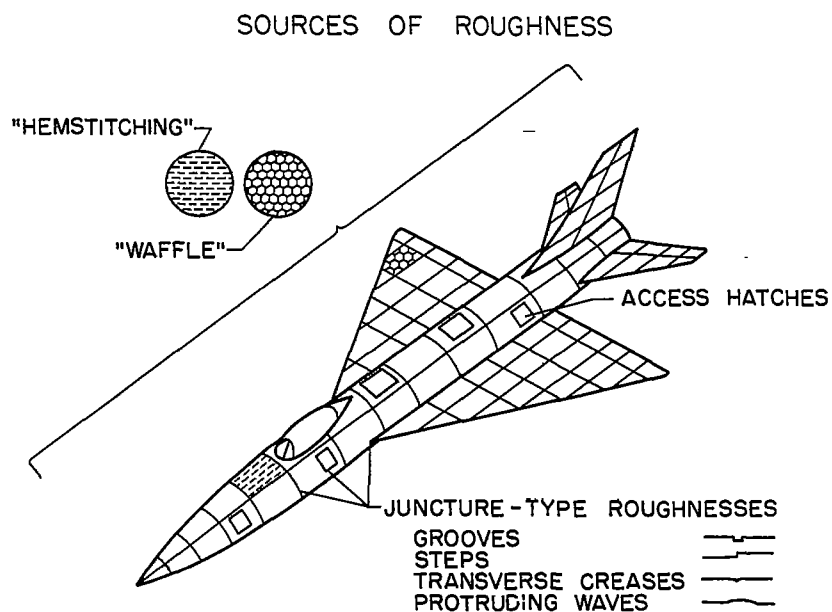
SOURCES OF ROUGHNESS

"HEMSTITCHING"

"WAFFLE"

ACCESS HATCHES

JUNCTURE-TYPE ROUGHNESSES
GROOVES
STEPS
TRANSVERSE CREASES
PROTRUDING WAVES

Figure 1

BASIC MODEL AND DETAILS OF JUNCTURE-TYPE ROUGHNESSES
BASIC MODEL; ALL DIMENSIONS IN INCHES

4.1

12.3
50

TRANSVERSE GROOVES   FORWARD STEPS   REARWARD STEPS
.010 OR .020   .010 OR .020
.050   .050   2   2

GROOVES AND STEPS   TRANSVERSE CREASES   PROTRUDING WAVES
.010 OR .020
.050   2   .020   .017 OR .050   1.5   .024 OR .050   1.5

Figure 2

SKIN-FRICTION DRAG COEFFICIENT OF "SMOOTH" BODIES
M = 1.61

o   SMOOTH BODY
□   SMOOTH "WAFFLE"
△   TRANSVERSE "HEMSTITCHING"

AVERAGE "SMOOTH" BODY

R_{FT}

Figure 3

EFFECTS OF ROUGHNESS ON SKIN FRICTION
M = 1.61

AVERAGE "SMOOTH" BODY

o   0.050 PROTRUDING WAVES
□   .050 TRANSVERSE CREASES
◇   .020 FORWARD STEPS
△   .020 REARWARD STEPS
▽   .050 TRANSVERSE GROOVES
◿   COARSE REGULAR "WAFFLE"

R_{FT}

Figure 4(a)

EFFECTS OF ROUGHNESS ON SKIN FRICTION

M=1.61

O   0.024 PROTRUDING WAVES
□   .017 TRANSVERSE CREASES
◁   .020 GROOVES AND STEPS
◻   .010 GROOVES AND STEPS

Figure 4(b)

EFFECTS OF ROUGHNESS ON SKIN FRICTION

M = 2.87

□   0.050 TRANSVERSE CREASES
△   .020 REARWARD STEPS
▽   .050 TRANSVERSE GROOVES
◁   COARSE REGULAR "WAFFLE"

Figure 5(a)

EFFECTS OF ROUGHNESS ON SKIN FRICTION

M = 2.87

▫ 0.017 TRANSVERSE CREASES
◿ .020 GROOVES AND STEPS
▫ .010 GROOVES AND STEPS

c_f

.010
.007
.005
.004
.003
.002
.001

AVERAGE "SMOOTH" BODY

.5 .7 1.0 2 3 4 5 7 10×10^6

R_{FT}

Figure 5(b)

EFFECT OF MACH NUMBER ON CRITICAL ROUGHNESS

○ EXPERIMENT
— — THEORY
(NACA TN 4183)

$\dfrac{k}{k_{M=1.61}}$

6
5
4
3
2
1

1 2 3 4 5

M

$R_{FT,CR}$

WITH ROUGHNESS

c_f

SMOOTH BODY

R_{FT}
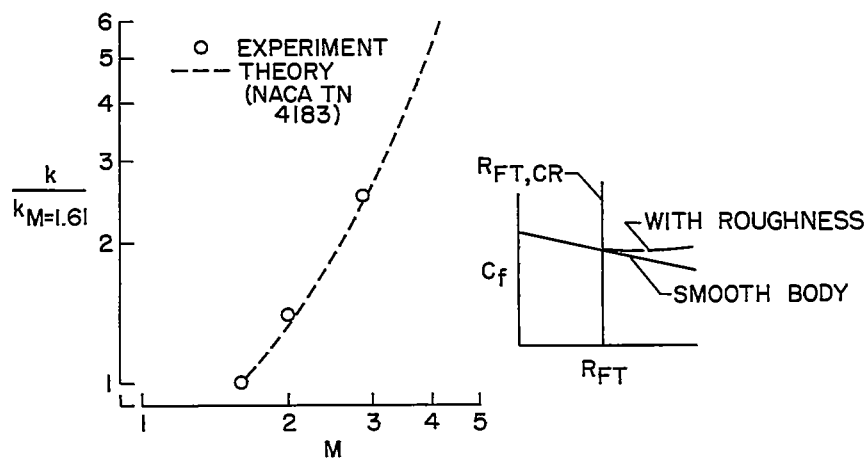
Figure 6

REYNOLDS NUMBER CORRELATION

M = 1.61

○ 0.050 PROTRUDING WAVES
◻ .024 PROTRUDING WAVES
◇ .020 REARWARD STEPS
△ .050 TRANSVERSE GROOVES
▽ .050 TRANSVERSE CREASES
◿ .010 REARWARD STEPS
◸ .020 GROOVES AND STEPS
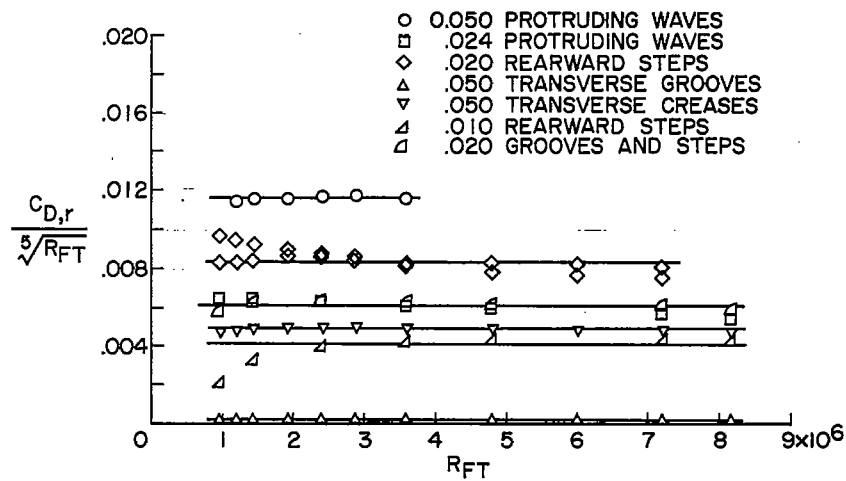
Figure 7

REYNOLDS NUMBER CORRELATION

M = 2.87

◇ 0.020 REARWARD STEPS
△ .050 TRANSVERSE GROOVES
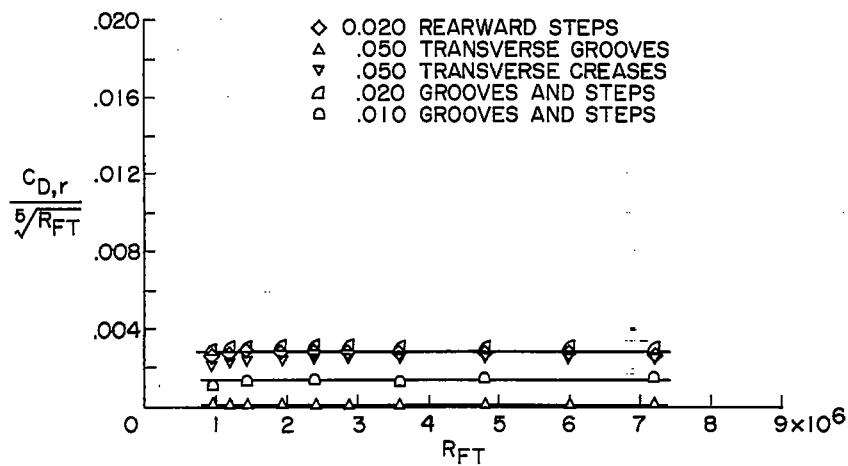▽ .050 TRANSVERSE CREASES
◿ .020 GROOVES AND STEPS
◻ .010 GROOVES AND STEPS
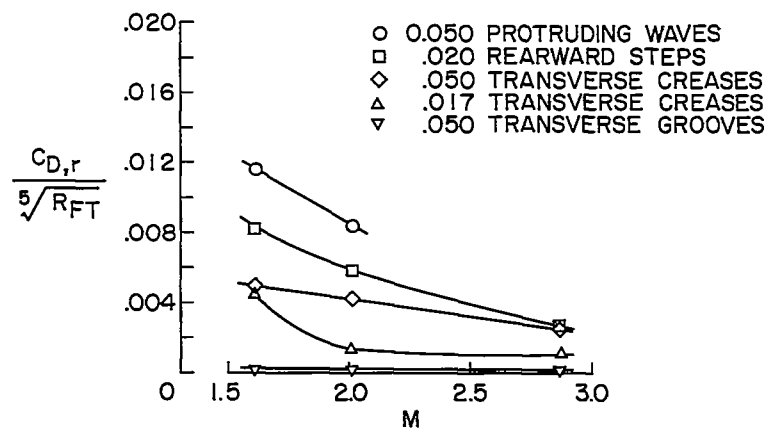
Figure 8

EFFECT OF MACH NUMBER ON ROUGHNESS-DRAG PARAMETER

Figure 9

MACH NUMBER CORRELATION

Figure 10