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CURRENT PAPERS

An Investigation at Transonic Speeds of the Performance of various distributed roughness Bands used to cause Boundary-Layer Transition near the Leading Edge of a Cropped Delta Half-Wing.

by

E. W. E. Rogers and I. M. Hall

with an Appendix
A Roughness Band Technique and Materials
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Aerodynamics Division

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May, 1959

Summary

Distributed roughness bands of No.320 and No.500 carborundum were found to be effective in causing boundary-layer transition if they extended over the first 5% and 10% respectively of the local chord. Use of larger grain sizes, or increases in the band width for a given grain size resulted in a drag penalty. With very large particle sizes (about 0.010 in.), this drag penalty could be reduced by reducing the spacing between the particles. The drag penalty was constant over the test Mach number range (0.80 to 1.15) and decreased slowly with incidence. The wing lift and pitching moment were only slightly modified by the presence of any of the roughness bands tested, but this result would not of course necessarily apply to wings of other planforms or section shapes. The test Reynolds number was about 2.7 million.

In the Appendix, the structure of the roughness bands is discussed, as well as the details of the materials used and the techniques used to apply the band.

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An investigation at transonic speeds of the performance of various distributed roughness bands used to cause boundary-layer transition near the leading edge of a cropped delta half-wing

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with an Appendix

A roughness band technique and materials

C.J. Berry and J.F.G. Townsend

1. Introduction

In recent years increasing use has been made of distributed roughness bands to provoke boundary-layer transition near the leading edge of wings and aerofoils. The merits of such a procedure have been argued elsewhere[1,2,3]; once the practice is accepted it is important to determine the deleterious effects which may result from the use of an unsatisfactory roughness band. Ideally, the band should do no more than provoke transition within its chordwise extent and the resulting flow should then correspond to that which would occur with a similar natural transition position. The artificially stimulated layer therefore must not be thickened in an unnatural manner, nor should the band itself contribute to the aerodynamic forces acting on the model. How closely this ideal state is approached in practical wind-tunnel tests is arguable at present.

The transition band most frequently used at present consists of discrete grains of a material such as carborundum partially embedded in a thin base of adhesive material, the latter bonding to the model surface. Aluminium paint or a proprietary lacquer is often used for this purpose. The minimum grain size required to provoke transition has been investigated by many authors (e.g. References 4, 5, 6), and simplified methods have been provided[7,8] to determine the requisite grain size for any particular experiment. However much of the experimental data obtained at high speeds are for simple models like cones[14] and flat plates and there is a need for more information on the performance of roughness bands on swept wings and aerofoils. In particular not enough is known about the effects on the aerodynamic characteristics of the model due to using larger grain sizes than are necessary just to cause transition.

Further, there is little published information about the physical characteristics of roughness bands employed at present; for example the particle spacing achieved and the particle size in relation to the base thickness. The actual techniques used in forming transition bands too are of considerable interest to the tunnel operator since a poorly-formed roughness band of the correct particle size may well be ineffectual.

The present note attempts to improve, in some measure, the present position. Results of tests made at the NPL on a cropped delta half-wing with several different distributed roughness bands are presented and discussed. The tests were devised mainly to provide information on the variation of zero-lift drag with roughness-band state at transonic speeds, but some lift and pitching-moment measurements at incidence were also made. In the Appendix, the structure of the present roughness bands is discussed, together with the practical problems that arise in constructing and using such bands.

2. Experimental Details

The model used in the present tests was a half-wing of cropped delta planform (Figure 1) having a leading edge sweepback of 53.5°, and a 6% thick RAE 102 section along the stream. This was mounted on one of the solid side-walls of the NPL 18 in. × 14 in. wind tunnel; the top and bottom walls are slotted. The model drag, lift and pitching moment were measured by means of a four-component strain-gauge balance.

The stream Mach number (M_0) was varied between 0.80 and 1.15 at wing incidences of 0°, 4°, 5° and 6°; this corresponds to a Reynolds number range (based on the mean aerodynamic chord) of $2.5.10^6$ to $2.8.10^6$. In addition, balance measurements were made for incidences up to 11°, at stream Mach numbers of 0.80 and 1.10.

Six grades of carborundum particles were used to form the transition bands. It is not easy however to relate the carborundum grade number accurately to the particle size, since wide variations may occur in the material obtained commercially. This matter is discussed further in Section 1.1 of the Appendix. The following list gives representative sizes in inches; the control sieve opening may regarded as an approximate measure of the mean particle size, but because of the irregular shape of the carborundum grains it is possible for larger (i.e. longer) particles to exist in a given grade.

The carborundum used in the present tests was not sieved further but used in the form supplied by the manufacturers.

Carborundum Grade No.	Control sieve opening	Probable size of largest particle present
60	0.0099	0.017
150	0.0041	0.006
240	0.0026	0.0035
320	0.0019	0.0025
400	0.0014	Not known accurately
500	0.0011	" " "

Measurements of wing drag at zero incidence were also made with two grades of Ballotini, which are small spherical glass beads. These were sieved between limiting sieves before use, but it seems that beads outside the theoretical range were present in the bands, due probably to insufficient sieving time.

Limiting Sieve Nos	Theoretical Limiting sphere diameters (in.)
140 - 200	0.0041 to 0.0030
240 - 300	0.0026 to 0.0021

The techniques used to form the various bands, together with information on the possible particle distribution are discussed in the Appendix.

Carborundum bands extending over both the first 5% and 10% of the local chord were tested for each grade number. However in the case of the No. 60 carborundum, only zero-incidence drag measurements were made when the band width was 5% chord.

The complete range of balance measurements were also obtained for the clean wing, transition being allowed to occur naturally and its position measured (see below).

The tests were carried out in January and February, 1959.

3. Boundary-layer Transition Position

3.1. Clean Wing

The natural transition position on both surfaces was determined by using hexachlorethane as a sublimation indicator[10]. The test range of wing incidence (0° to 11°) was covered at stream Mach numbers of 0.80 and 1.10, and typical mean transition positions at 0.45 and 0.70 semispan are plotted in Figure 2. At zero incidence and M_0 = 0.80, boundary-layer transition occurred just after 0.6 of the local chord along most of the span (Figure 3(a)), except close to the root where there is contamination from the turbulent wall boundary layer. When incidence is applied, the upper-surface transition position moves rapidly forward and reaches the leading-edge region along the whole semispan by $\alpha = 4°$. On the lower surface, the transition position remains constant (or even moves rearward slightly) at $\alpha = 1°$, but at larger incidences, a forward movement occurs, which decreases markedly above $\alpha = 4°$. The results obtained at M_0 = 1.10 are similar.

The chordwise pressure distributions on the wing surface at these two spanwise stations were known from earlier tests, and the position of minimum pressure at 0.7 semispan is plotted in Figure 2(a). A leading-edge suction peak rapidly develops on the upper surface with increasing incidence and this presumably influences strongly the boundary-layer transition. On the lower surface, the minimum pressure position moves rearward with increasing incidence and the pressure gradients in this region are small. This trend is in contrast to that for the observed transition position, and hence transition is felt to be mainly influenced on the lower surface by the boundary-layer instability effects which arise from the swept leading edge, and which promote transition through the presence of small instability vortices lying in the general direction of the local flow. These vortices show up faintly as fine striations in the residual hexachlorethane, and the transition 'front' has a characteristic ragged appearance (Figure 3(b)). The instability vortices and the forward movement of transition with incidence on both surfaces have been observed before.[2,11].

3.2. Effect of Roughness Bands

The effectiveness of the various roughness bands in promoting boundary-layer transition was checked by using a similar sublimation method at Mach numbers of 0.80 and 1.10. Part of each band near the middle of the semispan was removed in these tests however, in order to provide some laminar flow on the wing. In this way the interpretation of the hexachlorethane pattern is made more certain. At zero incidence, boundary-layer transition occurred at the roughness band for all states and materials at both test Mach numbers, the only exceptions being the No. 400 and No. 500 grades of carborundum of 5% chord extent, when small regions of laminar flow were present behind the band at the lower incidences. Figure 3(c) shows the sublimation pattern for the 500/5% band at $\alpha = 0°$ and M_0 = 0.80. The flow was completely turbulent when the band width was increased to 10% local chord. By comparison the laminar flow patches were reduced in size for the 400/5% band, and appeared only near the wing tip, but the band was still considered to be unsatisfactory.† Increasing the test Mach number had little effect on the sublimation pattern in both these cases.

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†The condition of no laminar flow to the rear of the band may well be too severe in many cases, but from the practical point of view it is a convenient one to adopt.

For all other band states, transition took place at the band for moderate incidences (as in Figure 3(d)). In some cases at incidences above 8°, the sublimation patterns suggested that the transition front near the tip was further rearward on the lower surface. The effect was not consistent however and may well be due to the difficulty of interpreting the rather unsatisfactory hexachlorethane patterns which are produced in these conditions.

In summary then, it was concluded that to provoke boundary-layer transition in a satisfactory manner on the present wing at the test conditions, the minimum grade of carborundum required for a 10% chord band was No. 500, and for a 5% band, No. 320.

Methods of estimating the minimum grain size necessary to produce immediate transition are given in References 7 and 8. The variation of the critical roughness height with chordwise position was calculated by the method of Braslow and Knox[7] and results for positions at 0.15 and 0.9 semispan of the cropped delta planform are shown in igure 4. In this method, the critical height is sel ed so that a roughness Reynolds number (R_k) based on this height and the velocity and kinematic viscosity at the top of the particle reaches a certain value, (600 in the present case). For comparison, similar results using the free-stream velocity and kinematic viscosity have been included on Figure 4. The changes in critical gram height caused by this simplifying assumption are very small. In addition, the predicted spanwise variation in roughness height is not large.

Near the wing leading edge the estimated critical grain height is comparable with the thickness of the boundary layer and it is no longer permissible to assume that R_k is unaffected by the flow conditions. The estimates therefore cease to be valid. The chordwise position at which the critical grain height is equal to 0.9 of the boundary-layer thickness is shown on each of the curves in Figure 4.

The smallest particle sizes which were found experimentally to cause transition in the present tests are also shown in Fig.4. (The relation between the mean particle size and the control sieve size is discussed in the Appendix). The carborundum particle size, (No.320 grade) which just produced transition when applied between the leading edge and 5% chord, was in fair agreement with the predicted grain size for the 5% chordwise position but the particle size required when a 10% band was used was much smaller than that predicted for a position at 10% chord. The decrease in critical grain size with increasing chordwise extent of the roughness band found experimentally in the present tests seems to be more in accordance with wind-tunnel experience than the opposite trend predicted by Reference 7. However the concept of a critical and constant roughness Reynolds number inherent in Braslow and Knox' method is based largely on tests in which the grains were widely spaced and the predictions obtained may correspond more to the critical sizes for single roughness grains.

4. Balance Results

In order to facilitate comparison, some of the balance results for C_D, C_L and C_M are listed in Tables I, II and III respectively.

4.1. Drag at $\alpha = 0°$

The measured values of the drag coefficient at zero incidence (C_{D_0}) are listed for the carborundum bands in Table I(a), and are also plotted in Figures 5(a) and (6). The presence of a roughness band naturally increases the value of C_{D_0} obtained when natural transition was allowed to take place, but there is still an appreciable variation in C_{D_0} as the type of roughness band is altered. For a given band width, the highest value of C_{D_0} occurs with a No. 150 band, and the lowest with a No. 500 band, the change in drag coefficient between these two states being about 0.0015 over the complete Mach number range. With one exception the wing drag increases with grain size; the exception is that

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the No. 60 band is associated with a lower drag than the No. 150 band despite the nearly three-fold increase in particle size. The No. 60 size particles, however, were more scattered than the No. 150, but were equally effective in causing transition.

It is concluded therefore that for the 10% chord bands, the excess drag coefficient above that for the No. 500 grain size is associated with the use of oversize particles in the band. This drag penalty is sometimes called 'roughness drag'. The variation of the drag coefficient increase from the transition-free state with mean particle size is shown in Figure 6 for both band widths at $M_o = 0.80$, before shock waves occur in the flow. The minimum increment in C_{D_o} due to a satisfactory distribution of roughness is 0.0029; this occurs with the 320/5% band and hence drag increases above this value may also be attributed to 'roughness'. For bands of the same type (Nos. 500 to 150) there is a progressive increase in roughness drag with grain size, and also an increment due to extending the band width from 5% to 10% chord. Both these effects seem to be independent of stream Mach number. (See for example Tables I(a) and (b)).

The increases in drag coefficient which results from the use of either a 320/5% band or a 500/10% band at $M_o = 0.80$ (0.0029 and 0.0031 respectively) are in close agreement with an estimate which assumes that the transition changes from 0.64 to 0.05 of the local chord when a roughness band is present. The theoretical two-dimensional results given in Reference 12 were used in this estimate, allowance being made for the spanwise variation in local Reynolds number, the root boundary-layer contamination, and the effect of wing sweep. It was further assumed that the calculated drag change is unaffected by compressibility[13].

Figure 6 also illustrates the advantage of increasing the particle spacing in the band with the grain size since the roughness drag associated with the large but comparatively widely spaced No. 60 particles is comparatively small. The closer particle distribution in the other roughness bands was intended to be similar to one another.

The drag coefficient change with stream Mach number from the value measured at $M_o = 0.80$ ($\delta\ C_{D_o}$) is almost independent of particle size and band width, as shown in Figure 7 and Table I(c). This suggests that the roughness band state is not influencing the wing wave drag to any significant extent. It is also interesting to note that the values of $\delta\ C_{D_o}$ for the transition-free condition agree well with those where transition was fixed by a roughness band (see Table I(c) also). It is likely therefore that the shock waves which develop at zero incidence on the present wing are insufficiently strong to differ markedly in their interaction with laminar or turbulent boundary layers, and this is consistent with the oil flow patterns for this Mach number range which were obtained during some earlier experiments. The onset of wave drag is rarely affected by the presence of a roughness band because of the comparatively weak shockwaves which are present further back on the model. On some wings, however, marked differences in C_{D_o} may occur at higher stream Mach numbers between the transition-fixed and -free cases, due to disparate shock-wave and boundary-layer interactions.

Figure 2 shows that the mean transition position on the wing at zero incidence moves from about 0.64 chord at $M_o = 0.80$ to 0.85 chord at $M_o = 1.10$; this should correspond to a drag coefficient decrease of about 0.0007 compared with the transition-fixed results. The fact that this change is not apparent may be due largely to small changes in the flow to the rear of the shockwave for the two types of boundary layer, which counter-balance the reduction in surface-friction drag.

The results obtained using Ballotini instead of carborundum are similar in that the zero-lift drag increases with particle size and also with the chordwise extent of the band (see Table IA and Figure 6). There is however a considerable difference between the results with 150 carborundum and with 140-200 Ballotini, the roughness drag being much smaller in the latter case, perhaps due to the absence of any excessively large particles. The results obtained with the 240 carborundum and the 240-300 Ballotini are almost identical.

4.2. Effect of Wing incidence at $M_0 = 0.80$ and 1.10

The wing drag, lift and pitching-moment coefficients at these two Mach numbers are listed against incidence for the various model states in Tables I, II and III and typical results are plotted in Figures 8(a) to 8(c). The roughness bands chosen for these figures were that which gave the highest zero-incidence drag (and hence it is assumed, the largest roughness drag) and that which was least effective in causing transition at the band position. In the latter case the regions of laminar flow are quite small, however.

The lift and pitching-moment coefficients (Figures 8(a) and (b)) show little change with model state, except at the highest incidences where the small differences are probably associated with slight changes in the position of a well-developed part-span vortex. The vortex grows and moves inboard quite slowly at $M_0 = 0.80$, but at the higher Mach number, separation, which starts at the tip at $\alpha = 9°$, has occurred along most of the leading edge by about 10° incidence; in this case the development of the vortex may be different if a roughness band is absent.

The corresponding drag results are shown in Figure 8(c). As might be expected the drag coefficient differences between the roughened leading edge tests and the transition-free state decrease with incidence due to a reduction of the amount of laminar flow in the latter case. The roughness drag, which can be regarded approximately as the difference between the two sets of symbols in this Figure is little changed by increasing incidence.

4.3. Effect of stress Mach number at constant incidence

In addition to the results described in section 4.2. the wing drag lift and pitching moment were also obtained at incidences of 4°, 5° and 6° for stream Mach numbers between 0.80 and 1.15. On the 5° incidence results have been listed (Tables I(f), II(c) and III(c)), but typical results at all three incidences are plotted in Figure 9. As before, the values obtained with a free transition position are compared with those for the bands giving the largest and smallest zero-incidence drags (150/10% and 500/5%).

The variation in wing lift and pitching moment is comparatively small for all model states and this suggests that the overall flow changes about the model are not influenced greatly by the boundary-layer state. Oil patterns show that with roughness bands present, shock-induced boundary layer separation is less significant on this planform than on others having a swept trailing edge, (and hence considerable wing area behind the rear shock) or a greater span (and a significant extent of strong outboard shock). Thus different results might well be obtained or wings having planforms or sections different from those considered in the present text, since changes in wing forces could arise from the influence of the various types of roughness band on local boundary-layer thickening and separation. The small variations shown in Figures 9(a) and 9(b) and the zero-incidence drag results discussed earlier should not be regarded as typical of all wings.

Most of the lift results fall within a range of C_L of ± 0.005 and moreover there is no clear trend with roughness grain size or band width. The resolving power of the balance is about ± 0.001 in C_L at the loadings being considered, and the repeatability for the same nominal flow conditions after removing and replacing the model was somewhat below $\pm 0.001_5$ in C_L. The measured differences might be without aerodynamic significance therefore, in some cases.

The corresponding drag results are plotted in Figure 9(c), and it seems that the difference in C_D between the transition-free case and when a 150/10% band is present is relatively unaffected by alterations in free-stream Mach number or incidence; a similar result is illustrated in Reference 3. A small reduction in the general drag level occurs however if a 320/10% band is substituted, but little further change takes place when this is replaced by a 500/5% band. The roughness drag of the 150/10% band may therefore be regarded approximately as the difference between the broken line and the isolated symbols, and this amounts to about 0.002_5 over most of the test range. This is rather greater than the value obtained at zero incidence and shown, for example, in Figure 6.

5. Concluding Remarks

The present tests on a cropped delta half-wing have shown that transition as indicated by a sublimation technique, is fixed satisfactorily by either a roughness band formed from No. 320 carborundum extending over the first 5% of

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the local chord, or by a No. 500 carborundum band covering 10% of the chord. It is encouraging to note that the grain size for the narrower band is in reasonable agreement with that predicted theoretically, and that the observed increase in drag is consistent with the required transition movement. A drag penalty is associated with both an increase in grain size from these values or from increasing the band width unnecessarily. The former effect can be reduced consideranly for very large grain sizes by increasing the spacing between the carborundum grains.

The wing lift and pitching moment are largely unaffected by changes in the roughness band state but it may be significant that the wing chosen for this test has aerodynamic characteristics which differ little between the transition fixed and free states, and a flow in which shock-induced boundary-layer separation occurs in only a limited range of conditions. This may well be a favourable case in which to study simple roughness band effects, since the matter is not complicated by other effects such as the influence of overfixing on rear separation or boundary-layer drift. It would be interesting to know however how far the present results can be generalised. The major effect of the roughness band in the present tests is to increase the zero-incidence drag in the transition-free state by a constant amount over the Mach number range of the test, the actual magnitude of the drag increase depending on the type and extent of the band. This effect persists at incidence, though for a given model state, the drag increment due to the roughness band decreases somewhat due to the forward transition movement on both surfaces when transition is allowed to occur naturally.

Though the variation in wing drag for the different types of roughness is not large, care must be taken in choosing a suitable grain size and spacing if accurate results are required.

There was no appreciable gain in using Ballotini glass beads instead of carborundum when the grain size was small, but the drag penalty at zero incidence for the larger grain size was reduced compared with carborundum, possibly due to the much more uniform particle size obtained with the beads and hence the absence of any excessively large grains.

It was found that the Ballotini tended to erode more rapidly than the corresponding grade of carborundum possibly because the regular particle shape causes less satisfactory adhesion to the base. The erosion can be prevented however, as mentioned in section A3 of the Appendix.

Except for the bands formed from No. 60 grade carborundum, it was considered that about 0.25 of the band area was actually covered by particles. In the case of the No. 60 material, this value was probably nearer 0.1. In view of the dependence of roughness drag on particle spacing shown by Figure 6 further work is required to determine how closely spacing should be controlled.

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APPENDIX

A transition-band technique and materials

by

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A.1. Transition-band materials

A.1.1. Carborundum (Silicon Carbide)

The process by which silicon carbide is manufactured depends upon chemical interaction between the main materials used - sand (silica) and petroleum coke (carbon) - which takes place at high temperatures. The carborundum leaves the furnace in large lumps which are crushed and then classified into sizes.

Grits Nos 8 to 220 are produced by bulk sieving through vibrating screens of various mesh sizes. Finer grits are sized by a wet grading process based on the rate of settling of the particles against a measured upward flow of water. These grades range from Nos 240 to 700. Neither method gives a very close grading. A small-scale laboratory test sieve analysis, for example, of nominal 120 mesh carborundum (predominant grain size 0.005 in.) showed that 53% of the material was in the range 120-150 mesh, while 95% ranged between 100-170 mesh (0.0035 in. - 0.006 in.). Closer grading can be obtained by hand sieving using sieves which comply (Table A1) with the British Standard 410 : 1943 or the American ASTM-E11-39≠ (Ref. 9). The very irregular shape of the carborundum grains (Figures A1 to A7) prevents a grading being obtained which is equal to the tolerances of the sieve. Commercially supplied and graded carborundum was used to form the roughness bands used in the present tests.

The grain sizes likely to be found in a particular grade of commercial carborundum are also discussed in two NACA papers[4,5].

TABLE A1. Nominal width of aperture of sieves

Mesh No.	60	72	85	100	120	150	170	200	240	320	350	400	500
Aperture width (0.001")	9.9	8.3	7.0	6.0	4.9	4.1	3.5	3.0	2.6	2.1	1.7	1.4	1.1
Reference	← British Standard →											American Standard	British Commercial use

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≠American practice seems to use a control sieve which is usually the next largest above the grit number. This complicates the comparison.

A.1.2. Other roughness materials

Because of their more regular shape some metal powders can be used to obtain a more closely graded particle size. Bronze and copper powders are spheres; molybdenum is cubical. The powders are supplied commercially in sizes from 60-600 mesh but in common with all other materials special sieving is required to obtain a close grading of particle size.

Another material which is available in the required range of sizes consists of solid glass beads called Ballotini. These are produced by a shot-tower technique and near-perfect spheres result though sometimes two spheres become attached. (Figures A8 and A9). Ballotini is marketed by the English Glass Co. Ltd. of Leicester.

A.1.3. Adhesives

A good adhesive is required to hold the grains to the highly-finished model surface. To obtain a uniform layer of the minimum thickness that is effective (about 0.0003 in.)/, the only satisfactory method of application is by spraying. A suitable adhesive is supplied by Cellons Ltd. of Kingston, Surrey as Adhesive 6SL096 which is mixed with catalyst 6SL10 in equal parts by volume. The mixture sets by chemical interaction instead of evaporation and is therefore unaffected by its passage through the spray gun. The adhesive base is best removed by means of acetone.

A.2. Method of applying the transition band

It has already been indicated that the adhesive is applied by spraying. A suitable spray gun is the Aerograph Air Brush. This gives a very close control of the spray and, if desired, makes the masking of the model unnecessary. The model surface should be cleaned with a solvent such as acetone or carbon tetrachloride.

The adhesive must be mixed immediately before use and the roughness grains should be applied at once. The best result will be obtained if the 'follow up' is so close that the spraying and the applying of grains is being carried out simultaneously an inch or so apart. A puffer type of powder dispenser, as used by hairdressers, which has a mesh fitted in the nozzle is ideal for applying the grains.

When masking is used, a ridge sometimes forms at its edges. This should be smoothed off. Normally twelve hours should be allowed for the setting of the adhesive although in some cases the model has been tested only three hours after the band was applied.

A.3. Band Structure and Performance

If the grain size has been chosen correctly and the chordwise extent of the band is adequate it will be unnecessary to 'saturate' the adhesive with grains. Indeed, such a band structure will probably ensure a large roughness drag, and may sometimes fail to produce a clean transition front due to filling up the spaces between the grains and thus reducing the effective roughness height. The actual coverage (which can be regarded as the fraction of the band area occupied by roughness grains) will depend on the operators experience and on the grain-size in use; it is not thought to be critical except for large grain sizes, though further work is required to substantiate this view.

/Satisfactory band performance depends not only on the correct choice of grain size, but also on having an adhesive base which is of small thickness compared with roughness height. A thick base in which particles of the correct size are buried may well be ineffective. A subsequent increase in particle size will then lead to undue roughness drag.

If too great a coverage is obtained there is a danger of a build-up of grains upon each other. In this case the bonding between the uppermost grains and the adhesive is light, and serious erosion (or removal of complete grains) takes place during the first test-run on the model, with a consequent change in model forces (mainly drag) with time. With carborundum bands formed in the standard fashion, erosion, if it occurs, is confined almost entirely to the first run and the subsequent deterioration of the band is very small. With some other materials erosion is more troublesome, but can be prevented by a very light application of adhesive after the grains have been applied.

Once erosion has become significant, or if the roughness band is damaged in any way, it is better to strip the band from the model and replace it completely rather than attempt to repair the unsatisfactory portions.

Sample roughness bands similar to those employed in the wind-tunnel tests reported above have been prepared on glass slides and photomicrographed (Figs. A1 to A9.). In some cases, which are indicated, the coverage is different from that used for the tunnel tests. The carborundum grains are shown in two magnifications, and the rapid diminuation of grain size with increasing grade number is clearly illustrated. The coverage of the various bands is indicated; this can only be an approximate value since only a small part of the band is analysed, but it seems that for the roughness bands at present in use it is between 0.15 and 0.35. The distribution of the roughness particles is reasonably even and agglomerations shown in the photographs would probably be reduced after the first test run, for reasons given above. The curly lines which exist between individual grains in some of the photographs are due to insufficient adhesive being used in the preparation of the microscope slide by 'dry' spraying so that boundaries of adhesive are formed due to surface tension effects. The effect is not typical of the bands applied to the model, which are similar to those shown for the specimen Ballotini photomicrographs (Figures A8 and 9). The adhesive base is even in these cases.

The actual carborundum grain sizes vary somewhat in any given picture due to the lack of adequate sieving and the irregular shape of the grains. There seems however to be predominantly more dust (very small particles) in the finer grades.

The use of the present type of roughness band at elevated temperatures will be limited by the softening point of the adhesive. This is about 200°C and so the band could be used safely at a stagnation temperature of 150°C.

TABLE I : DRAG RESULTS (CARBORUNDUM)

(a) Measured values of drag coefficient (C_{D_O}) at $\alpha = 0°$

Carborundum Grade No.	60		150		240		320		400		500		Transition Free:
Chordwise extent: / M_∞	5%	10%	5%	10%	5%	10%	5%	10%	5%	10%	5%	10%	
0.80	0.0096	0101	0102	0109	0094	0096	009[illegible]	0094	0089	0096	0087	0092	0061
0.85	0.0096	0102	0103	0110	0094	0097	0091	0095	0090	0097	0089	0093	0061
0.90	0.0099	0105	0106	0112	0096	0099	0093	0098	0093	0099	0091	0095	0064
0.92	0.0101	0107	0108	0114	0099	0102	0096	0100	0095	0101	0093	0098	0066
0.94	0.0103	0110	0110	0117	0101	0105	0098	0102	0098	0104	0096	0101	0072
0.96	0.0110	0117	0117	0122	0108	0111	0105	0109	0104	0110	0102	0107	0074
0.98	0.0123	0130	0130	0134	0120	0124	0117	0123	0117	0122	0115	0119	0086
1.00	0.0140	0147	0147	0150	0138	0141	0135	0138	0135	0140	0134	0137	0124
1.025	0.0166	0173	0172	0176	0163	0166	0160	0164	0161	0166	0158	0162	0131
1.05	0.0185	0192	0192	0193	0183	0185	0179	0183	0181	0185	0178	0181	0150
1.06	0.0195	0202	0201	0204	0192	0196	0191	0193	0190	0195	0188	0192	0163
1.08	0.0198	0205	0204	0212	0194	0199	0195	0196	0192	0199	0191	0195	0166
1.10	0.0193	0200	0199	0206	0190	0194	0189	0191	0187	0193	0186	0189	016[illegible]
1.15	0.0194	0201	0200	0207	0190	0196	0191	0192	0188	0194	0187	0191	0161

TABLE I : DRAG RESULTS (CARBORUNDUM) (continued)

(b) Drag increment due to increase in roughness band chord

$$\Delta C_{D_o} = (C_{D_o})_{10\%} - (C_{D_o})_{5\%}$$

Carborundum Grade No. / M_o	60	150	240	320	400	500
0.80	+0.0005	+0007	+0002	+0004	+0007	+0005
0.85	6	7	3	4	7	4
0.90	6	6	3	5	6	4
0.92	6	6	3	4	6	5
0.94	7	7	4	4	6	5
0.96	7	5	3	4	6	5
0.98	7	4	4	6	5	4
1.00	7	3	3	3	5	3
1.025	7	4	3	4	5	4
1.05	7	1	2	4	4	3
1.06	7	3	4	2	5	4
1.08	7	8	5	1	7	4
1.10	7	7	4	2	6	3
1.15	7	7	6	1	6	4

TABLE I : DRAG RESULTS (CARBORUNDUM) (continued)

(c) Drag increment from $M_o = 0.80$, $\delta C_{D_o} = (C_{D_o})_M - (C_{D_o})_{M = 0.8}$

Carborundum Grade No.	60		150		240		320		400		500		Transition Free:
Chordwise extent: / M_o	5%	10%	5%	10%	5%	10%	5%	10%	5%	10%	5%	10%	
0.80	0	0	0	0	0	0	0	0	0	0	0	0	0
0.85	+0	+0001	+0001	+0001	+0	+0001	+0001	+0001	+0001	+0001	+0002	+0001	+0
0.90	0.0003	0004	0004	0003	0002	0003	0003	0004	0004	0003	0004	0003	0003
0.92	0.0005	0006	0006	0005	0005	0006	0006	0006	0006	0005	0006	0006	0005
0.94	0.0007	0009	0008	0008	0007	0009	0008	0008	0009	0008	0009	0009	0011
0.96	0.0014	0016	0015	0013	0014	0015	0015	0015	0015	0014	0015	0015	0013
0.98	0.0027	0029	0028	0025	0026	0028	0027	0029	0028	0026	0028	0027	0025
1.00	0.0044	0046	0045	0041	0044	0045	0045	0044	0046	0044	0047	0045	0043
1.025	0.0070	0072	0070	0067	0069	0070	0070	0070	0072	0070	0071	0070	0070
1.05	0.0089	0091	0090	0084	0089	0089	0089	0089	0092	0089	0091	0089	0089
1.06	0.0099	0101	0099	0095	0098	0100	0101	0099	0101	0099	0101	0100	0102
1.08	0.0102	0104	0102	0103	0100	0103	0105	0102	0103	0103	0104	0103	0105
1.10	0.0097	0099	0097	0097	0096	0098	0099	0097	0098	0097	0099	0097	0099
1.15	0.0098	0100	0098	0098	0096	0100	0101	0098	0099	0098	0100	0099	0100

TABLE I : DRAG RESULTS (CARBORUNDUM) (continued)

(d) Measured values of drag coefficient (C_D) at $M_o = 0.80$

Carborundum Grade No.	60		150		240		320		400		500		Transition Free:
Chordwise extent: / α	5%	10%	5%	10%	5%	10%	5%	10%	5%	10%	5%	10%	
0°		0.0102	0101	0109	0092	0097	0091	0095	0088	0094	0087	0092	0061
2°		0.0109	0112	0119	0100	0104	0099	0106	0098	0104	0096	0101	0078
3°		0.0129	0132	0140	0117	0123	0117	0124	0116	0122	0116	0119	0102
4°		0.0164	0167	0173	0149	0152	0148	0154	0151	0152	0148	0153	0140
5°		0.0209	0220	0230	0201	0204	0200	0205	0202	0208	0199	0208	0197
6°		0.0281	0303	0312	0279	0282	0276	0282	0277	0283	0278	0285	0276
7°		0.0386	0402	0417	0382	0385	0384	0385	0385	0395	0374	0390	0379
8°		0.0502	0526	0540	0510	0510	0512	0510	0512	0517	0508	0514	0509
9°		0.0644	0668	0681	0647	0652	0653	0649	0655	0659	0649	0659	0650
10°		0.0817	0832	0839	0815	0811	0822	0815	0826	0830	0823	0834	0816
11°		0.0997	1003	1020	0998	0996	1002	0997	0997	1031	1007	1025	0990

TABLE I : DRAG RESULTS (CARBORUNDUM) (continued)

(e) Measured values of drag coefficient (C_D) at $M_0 = 1.10$

Carborundum Grade No.	60		150		240		320		400		500		Transition Free:
Chordwise extent: / α	5%	10%	5%	10%	5%	10%	5%	10%	5%	10%	5%	10%	
0°		0.0200	0198	0207	0190	0195	0190	0191	0188	0192	0186	0188	0163
2°		0.0223	0221	0228	0211	0214	0212	0213	0208	0214	0205	0211	0189
3°		0.0256	0256	0262	0245	0250	0245	0247	0242	0248	0241	0244	0230
4°		0.0311	0311	0319	0301	0302	0299	0301	0297	0302	0296	0297	0285
5°		0.0389	0392	0400	0378	0381	0376	0380	0376	0380	0372	0375	0369
6°		0.0488	0491	0499	0480	0479	0477	0480	0476	0480	0476	0478	0468
7°		0.0610	0619	0624	0600	0604	0598	0608	0599	0604	0599	0618	0596
8°		0.0761	0770	0774	0749	0753	0754	0748	0753	0753	0747	0753	0744
9°		0.0927	0928	0930	0916	0922	0918	0919	0922	0920	0916	0919	0919
10°		0.1107	1120	1121	1095	1091	1092	1089	1099	1094	1091	1095	1113
11°		0.1303	1322	1329	1298	1307	1310	1298	1309	1308	1308	1314	1317

TABLE I : DRAG RESULTS (CARBORUNDUM) (continued)

(f) Measured values of drag coefficient (C_D) at $\alpha = 5^\circ$

Carborundum Grade No.	60		150		240		320		400		500		Transition Free:
Chordwise extent: / M_o	5%	10%	5%	10%	5%	10%	5%	10%	5%	10%	5%	10%	
0.80		0.0211	0225	0226	0201	0205	0200	0205	0202	0208	0196	0206	0189
0.85		0.022C	0235	0236	0212	0215	0211	0215	0212	0217	0206	0216	0197
0.90		0.0236	0252	0250	0227	0231	0226	0229	0225	0232	0221	0231	0208
0.95		0.0265	0282	0280	0261	0263	0258	0264	0252	0265	0248	0267	0236
1.00		0.0328	0338	0328	0315	0317	0313	0319	0314	0317	0311	0321	0297
1.05		0.0379	0387	0381	0366	0368	0342	0381	0367	0370	0363	0371	0350
1.10		0.0390	0398	0396	0376	0380	0379	0386	0376	0382	0373	0381	0362
1.15		0.0382	0390	0389	0370	0374	0372	0376	0370	0375	0367	0375	0356

(g) Drag increment from $M_o = 0.80$, at $\alpha = 5^\circ$

Carborundum Grade No.	60		150		240		320		400		500		Transition Free:
Chordwise extent: / M_o	5%	10%	5%	10%	5%	10%	5%	10%	5%	10%	5%	10%	
0.80		0	0	0	0	0	0	0	0	0	0	0	0
0.85		0.0009	0010	0010	0011	0010	0011	0010	0010	0009	0010	0008	0008
0.90		0.0025	0027	0022	0026	0026	0026	0024	0023	0024	0025	0025	0019
0.95		0.0055	0047	0052	0060	0058	0058	0059	0050	0057	0052	0061	0047
1.00		0.0117	C113	0100	0114	0112	0113	0114	0112	0109	0115	0115	0108
1.05		0.0168	0162	0153	0165	0163	0142	0176	0165	0162	0167	0165	0161
1.10		0.0179	0173	0168	0175	0175	0179	0181	0174	0174	0177	0175	0173
1.15		0.0171	0165	0161	0169	0169	0172	0171	0168	0167	0171	0169	0167

TABLE IA Drag Results (Ballotini)

(a) Measured values of drag coefficient (C_{D_0}) at $\alpha = 0^\circ$

Ballotini Grade No.	140 - 200		240 - 300		Transiti-n Free:
Chordwise extent: / M_0	5%	10%	5%	10%	
0.80	0.0094	0101	0093	0099	0.0061
0.85	0.0095	0103	0094	0100	0.0061
0.90	0.0098	0105	0097	0102	0.0064
0.92	0.0101	0109	0099	0104	0.0066
0.94	0.0103	0109	0102	0106	0.0072
0.96	0.0109	0115	0109	0113	0.0074
0.98	0.0122	0127	0122	0126	0.0086
1.00	0.0139	0146	0140	0143	0.0104
1.025	0.0164	0170	0165	0169	0.0131
1.05	0.0185	0191	0185	0191	0.0150
1.06	0.0195	0201	0194	0199	0.0163
1.08	0.0199	0205	0195	0201	0.0166
1.10	0.0193	0199	0191	0195	0.0160
1.15	0.0194	0200	0192	0197	0.0161

TABLE IA Drag Results (Ballotini) (continued)

(c) Drag increment from M_o = 0.80

Ballotini Grade No.	140	- 200	240	- 300	Transition Free:
Chordwise extent: / M_o	5%	10%	5%	10%	
0.80	0	0	0	0	0
0.85	0.0001	0002	0001	0001	0001
0.90	0.0004	0004	0004	0003	0003
0.92	0.0007	0008	0006	0005	0005
0.94	0.0009	0008	0009	0007	0011
0.96	0.0015	0014	0016	0014	0013
0.98	0.0028	0026	0029	0027	0025
1.00	0.0045	0045	0047	0044	0043
1.025	0.0070	0069	0072	0070	0070
1.05	0.0091	0090	0092	0092	0089
1.06	0.0101	0100	0101	0100	0102
1.08	0.0105	0104	0102	0102	0105
1.10	0.0099	0098	0098	0096	0099
1.15	0.0100	0099	0099	0098	0100

TABLE II : LIFT RESULTS (CARBORUNDUM)

(a) Measured values of lift coefficient (C_L) at M_o = 0.80

Carborundum Grade No.	60		150		240		320		400		500		Transition Free:
Chordwise extent: / α	5%	10%	5%	10%	5%	10%	5%	10%	5%	10%	5%	10%	
0°		0.017	018	018	016	016	016	026	018	017	018	019	018
2°		108	108	108	103	103	105	106	110	106	108	110	107
3°		158	156	158	153	153	155	158	158	154	157	159	155
4°		205	205	205	200	198	201	203	205	201	204	207	201
5°		256	260	261	257	253	256	256	259	260	259	262	260
6°		311	315	316	311	308	311	310	313	312	313	314	311
7°		363	368	370	366	363	369	363	371	371	366	371	366
8°		422	421	421	420	414	421	414	424	421	424	428	422
9°		473	471	468	472	464	472	465	469	466	477	478	473
10°		529	519	513	516	513	518	511	530	521	520	526	526
11°		581	560	562	562	558	573	561	573	580	569	577	570

TABLE II : LIFT RESULTS (CARBORUNDUM) (continued)

(b) Measured values of lift coefficient C_L at $M_0 = 1.10$

Carborundum Grade No.	60		150		240		320		400		500		Transition Free:
Chordwise extent: / α	5%	10%	5%	10%	5%	10%	5%	10%	5%	10%	5%	10%	
0°		0.027	024	021	025	023	24	023	024	025	025	025	024
2°		129	129	128	128	127	129	129	129	129	127	129	133
3°		190	188	187	187	187	187	188	188	188	187	188	188
4°		245	244	245	243	243	243	243	245	246	245	245	242
5°		309	309	309	306	305	307	305	309	309	306	307	309
6°		370	369	369	372	367	370	369	371	370	369	372	369
7°		436	436	435	435	434	435	435	438	437	436	440	437
8°		507	506	505	504	504	507	503	511	508	506	512	506
9°		570	561	559	567	568	570	569	573	571	570	572	569
10°		627	626	621	620	614	620	618	623	620	620	622	634
11°		678	681	680	676	679	683	676	685	682	684	685	689

TABLE II : LIFT RESULTS (CARBORUNDUM) (continued)

(c) Measured values of lift coefficient (C_L) at $\alpha = 5^0$

Carborundum Grade No.	60		150		240		320		400		500		Transition Free:
Chordwise extent: / M_0	5%	10%	5%	10%	5%	10%	5%	10%	5%	10%	5%	10%	
0.80		0.258	265	259	256	255	257	259	260	260	255	263	0.257
0.85		0.263	270	265	262	261	263	264	265	264	261	268	0.261
0.90		0.270	279	267	268	268	270	270	270	270	266	274	0.264
0.95		0.274	283	273	275	273	277	279	275	276	271	281	0.270
1.00		0.288	295	280	285	283	287	292	288	285	285	293	0.282
1.05		0.309	314	301	305	304	307	310	310	307	307	313	0.304
1.10		0.309	305	301	306	305	311	315	311	309	307	313	0.304
1.15		0.297	303	291	295	295	299	299	298	297	295	303	0.294

(d) Increment of lift coefficient from $M_0 = 0.80$ at $\alpha = 5^0$

Carborundum Grade No.	60		150		240		320		400		500		Transition Free
Chordwise extent: / M_0	5%	10%	5%	10%	5%	10%	5%	10%	5%	10%	5%	10%	
0.80		0	0	0	0	0	0	0	0	0	0	0	0
0.85		0.005	005	007	006	005	006	005	005	004	006	005	0.004
0.90		0.012	016	008	012	013	013	011	010	010	011	011	0.007
0.95		0.016	018	014	019	018	020	020	015	016	016	018	0.013
1.00		0.030	030	021	029	028	030	033	028	025	030	030	0.025
1.05		0.051	049	042	049	049	050	060	050	047	052	050	0.047
1.10		0.051	040	042	050	050	053	056	051	049	052	050	0.047
1.15		0.039	038	032	039	040	042	040	038	037	040	040	0.037

TABLE III : PITCHING MOMENT RESULTS (CARBORUNDUM)

(measured about quarter mean aerodynamic chord)

(a) Measured values of pitching-moment coefficient (C_m) at M_o = 0.80

Carborundum Grade No.	60		150		240		320		400		500		Transition Free:
Chordwise extent: / α	5%	10%	5%	10%	5%	10%	5%	10%	5%	10%	5%	10%	
0°		+0.0001	0001	0001	+0005	+0005	+0002	0004	0	0002	0001	0002	+0003
2°		0113	0114	0111	0120	0102	0106	0105	0116	0114	0111	0117	0105
3°		0169	0166	0164	0159	0159	0160	0162	0172	0164	0165	0172	0161
4°		0221	0213	0214	0209	0207	0210	0206	0222	0213	0216	0226	0210
5°		0280	0280	0284	0280	0267	0270	0272	0292	0292	0284	0298	0286
6°		0351	0356	0356	0349	0344	0345	0344	0359	0360	0358	0363	0351
7°		0412	0416	0419	0418	0412	0419	0410	0436	0430	0414	0435	0416
8°		0487	0472	0469	0472	0461	0474	0462	0500	0481	0493	0493	0469
9°		0548	0520	0514	0546	0519	0522	0515	0532	0527	0539	0548	0516
10°		0598	0571	0558	0566	0557	0586	0567	0604	0604	0587	0611	0575
11°		0655	0613	0620	0647	0619	0652	0641	0639	0681	0657	0677	0617

All values negative unless otherwise marked

TABLE III : PITCHING MOMENT RESULTS (CARBORUNDUM) (continued)
(measured about quarter mean aerodynamic chord)

(b) Measured values of pitching moment coefficient (C_m) at M_0 = 1.10

Carborundum Grade No.	60		150		240		320		400		500		Transition Free:
Chordwise extent: / α	5%	10%	5%	10%	5%	10%	5%	10%	5%	10%	5%	10%	
0°		0.0060	0053	0049	0055	0053	0053	0058	0054	0057	0058	0058	0060
2°		0270	0268	0265	0266	0263	0264	0258	0274	0272	0266	0272	0281
3°		0408	0404	0398	0398	0398	0395	0432	0408	0408	0404	0407	0401
4°		0545	0540	0538	0534	0531	0537	0520	0545	0545	0544	0548	0537
5°		0690	0685	0685	0682	0670	0688	0718	0698	0691	0685	0691	0692
6°		0814	0812	0809	0824	0807	0820	0798	0826	0819	0820	0824	0818
7°		0979	0967	1052	0965	0963	0962	0960	0982	0973	0973	0983	0976
8°		1156	1137	1118	1137	1130	1139	1124	1163	1149	1146	1161	1145
9°		1280	1229	1209	1271	1269	1276	1274	1298	1286	1284	1293	1278
10°		1376	1357	1329	1344	1312	1342	1338	1356	1348	1342	1350	1409
11°		1456	1466	1456	1459	1462	1478	1435	1482	1471	1487	1483	1524

All values negative

TABLE III : PITCHING MOMENT RESULTS (CARBORUNDUM) (continued)
(measured about quarter mean aerodynamic chord)

(c) Measured values of pitching moment (C_m) at $\alpha = 5^\circ$

Carborundum Grade No.	60		150		240		320		400		500		Transition Free:
Chordwise extent: / M_o	5%	10%	5%	10%	5%	10%	5%	10%	5%	10%	5%	10%	
0.80		0.0280	0287	0283	0279	0272	0270	0270	0289	0289	0282	0295	0.0283
0.85		0.0297	0307	0303	0298	0293	0290	0290	0313	0307	0296	0313	0.0299
0.90		0.0326	0342	0325	0321	0320	0320	0314	0333	0332	0322	0335	0.0315
0.95		0.0366	0393	0376	0379	0375	0374	0381	0368	0389	0356	0398	0.0356
1.00		0.0475	0487	0444	0463	0453	0461	0478	0477	0466	0468	0485	0.0457
1.05		0.0646	0657	0617	0637	0625	0563	0695	0658	0643	0647	0658	0.0641
1.10		0.0686	0698	0658	0679	0674	0690	0718	0695	0688	0683	0700	0.0687
1.15		0.0668	0676	0656	0658	0655	0666	0694	0670	0665	0663	0681	0.0666

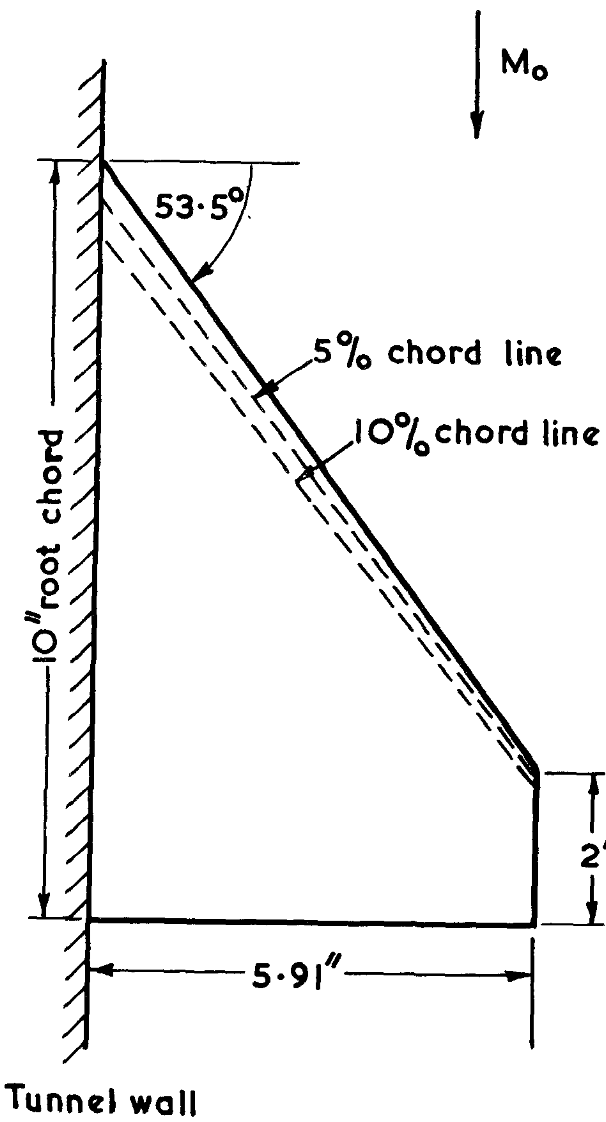
All values negative

(d) Increment of pitching moment from $M_o = 0.80$ at $\alpha = 5^\circ$

Carborundum Grade No.	60		150		240		320		400		500		Transition Free:
Chordwise extent: / M_o	5%	10%	5%	10%	5%	10%	5%	10%	5%	10%	5%	10%	
0.80		0	0	0	0	0	0	0	0	0	0	0	0
0.85		0.0017	0020	0020	0019	0019	0020	0020	0024	0018	0014	0018	0.0016
0.90		0.0046	0055	0042	0042	0048	0050	0044	0044	0043	0040	0040	0.0032
0.95		0.0086	0106	0094	0100	0103	0104	0111	0079	0100	0074	0103	0.0073
1.00		0.0195	0200	0161	0184	0181	0191	0208	0188	0177	0186	0190	0.0174
1.05		0.0366	0370	0334	0358	0353	0293	0425	0369	0354	0365	0363	0.0358
1.10		0.0406	0411	0375	0400	0402	0420	0448	0406	0399	0401	0405	0.0403
1.15		0.0388	0389	0373	0379	0383	0394	0424	0381	0376	0381	0386	0.0383

All values negative

FIG. 1.



Aspect ratio of full wing: 1·975

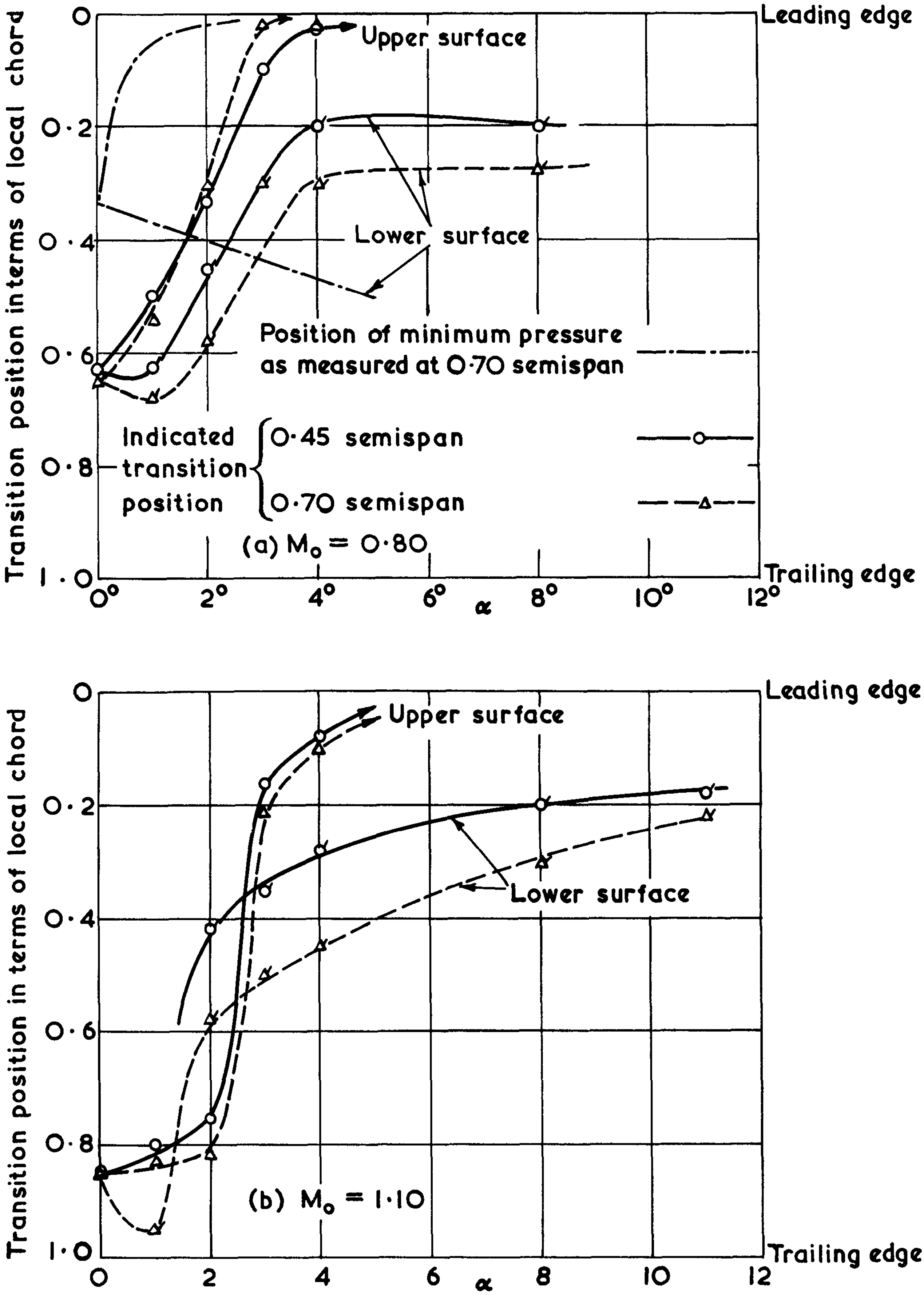
Taper ratio: 0·2

Streamwise section: 6% RAE 102

Mean aerodynamic chord: 6·89 in.

Wall-mounted cropped delta half-wing

FIG. 2.



Mean transition positions at zero incidence for two spanwise stations

FIG. 3 (a) & (b)

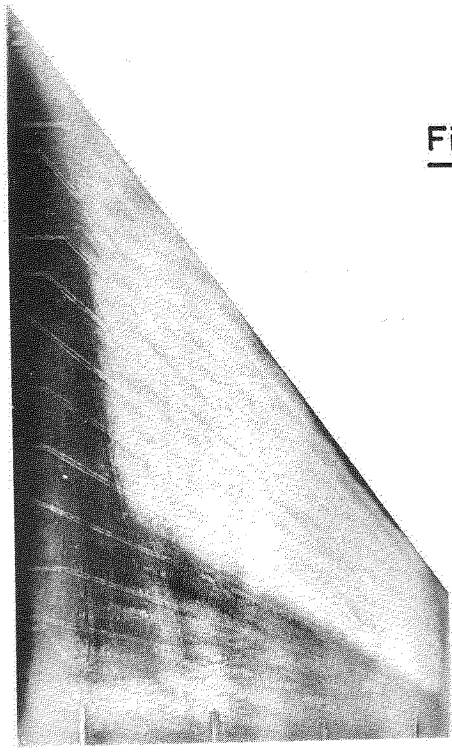


Fig. 3(a) Sublimation pattern at $\alpha = 0^\circ$, $M_0 = 0{\cdot}80$ (No roughness band)

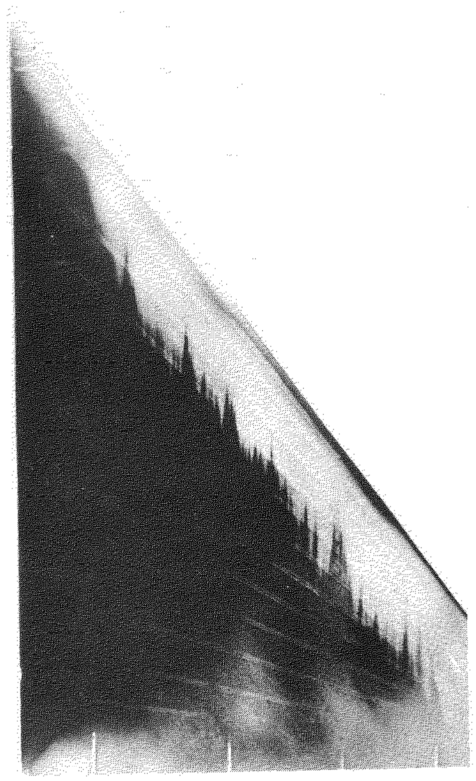


Fig. 3 (b) Sublimation pattern on lower surface at $\alpha = 4^\circ$, $M_0 = 1{\cdot}10$ showing traces of instability vortices and ragged front (No roughness band)

FIG. 3 (c) & (d)

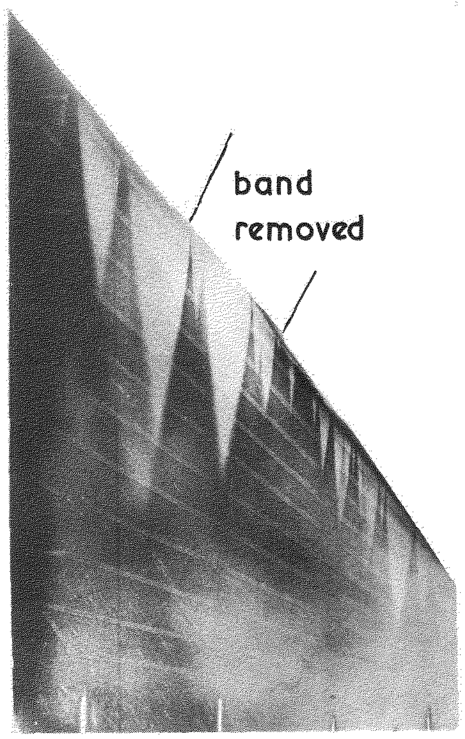


Fig. 3 (c) Failure of 500/5% band to promote transition satisfactorily at $\alpha = 0^\circ$, $M_o = 0{\cdot}80$.

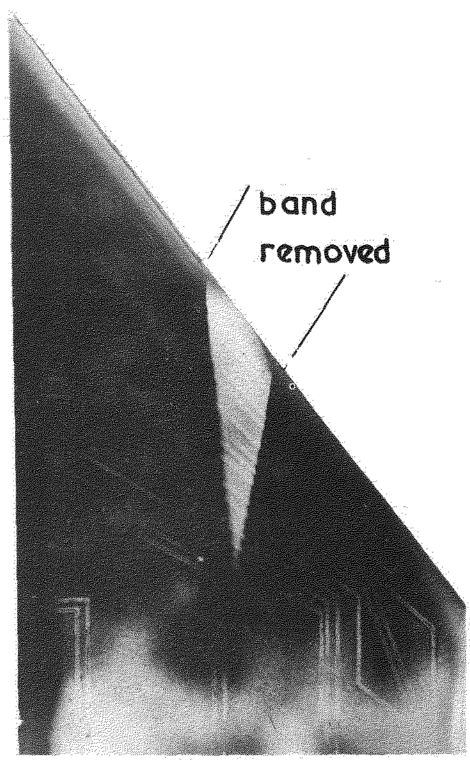


Fig. 3 (d) Satisfactory transition at $\alpha = 2^\circ$, $M_o = 1{\cdot}10$ with 240/5% band

FIG. 4.

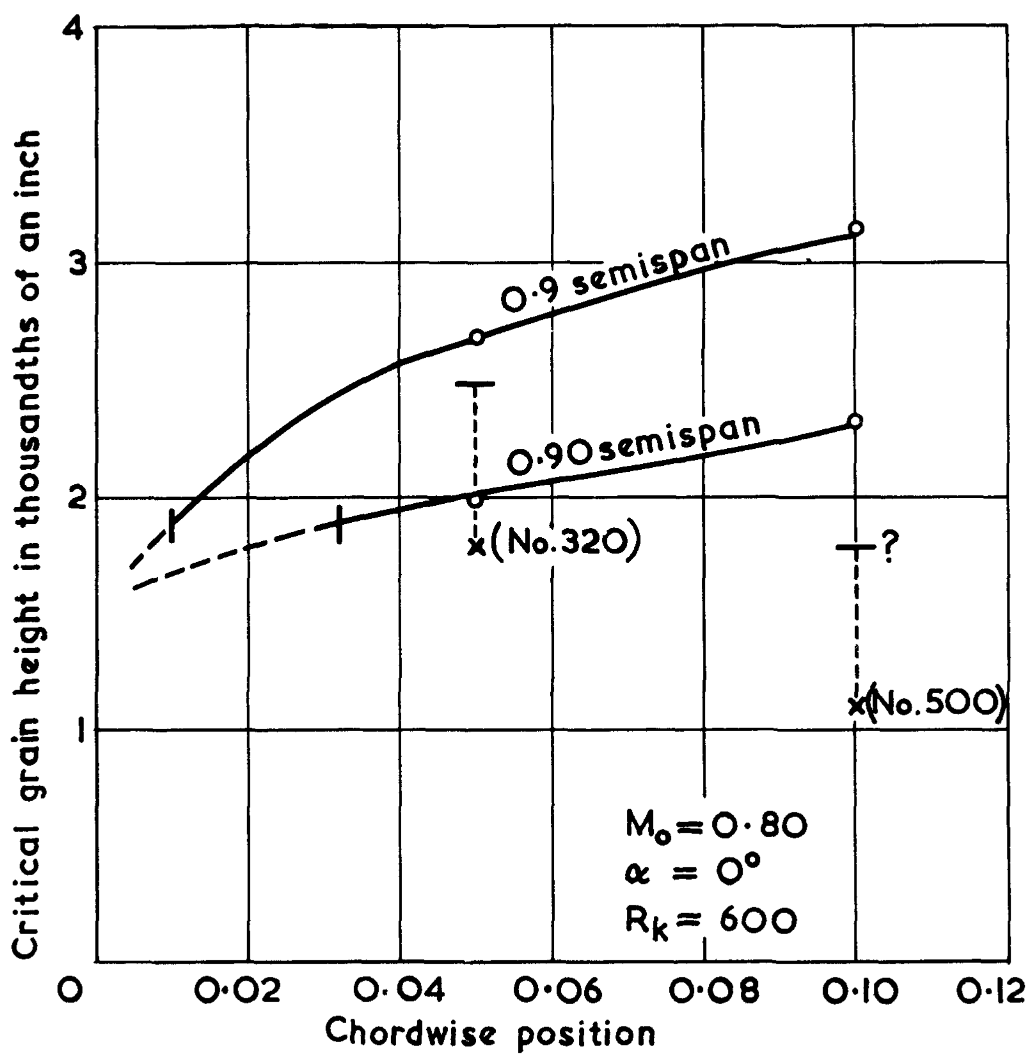
Probable maximum particle size in carborundum shown thus:-

Control sieve sizes for minimum satisfactory transition bands of 5% & 10% width

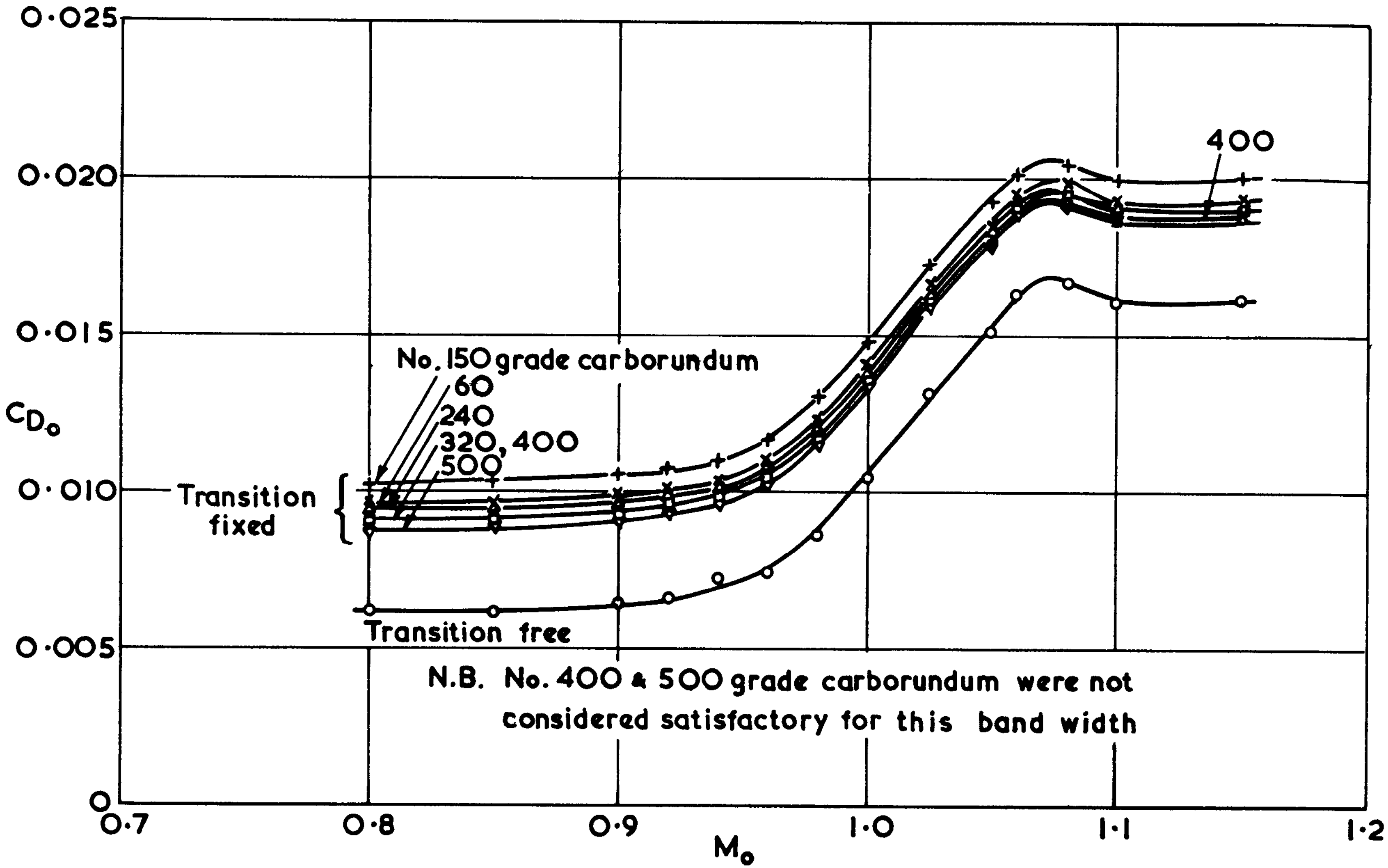
Calculated critical heights using local surface conditions (Ref 7)

Calculated critical heights, using free stream conditions (Ref 7)

Condition where roughness height is equal to 0·9 of boundary-layer thickness shown thus:-

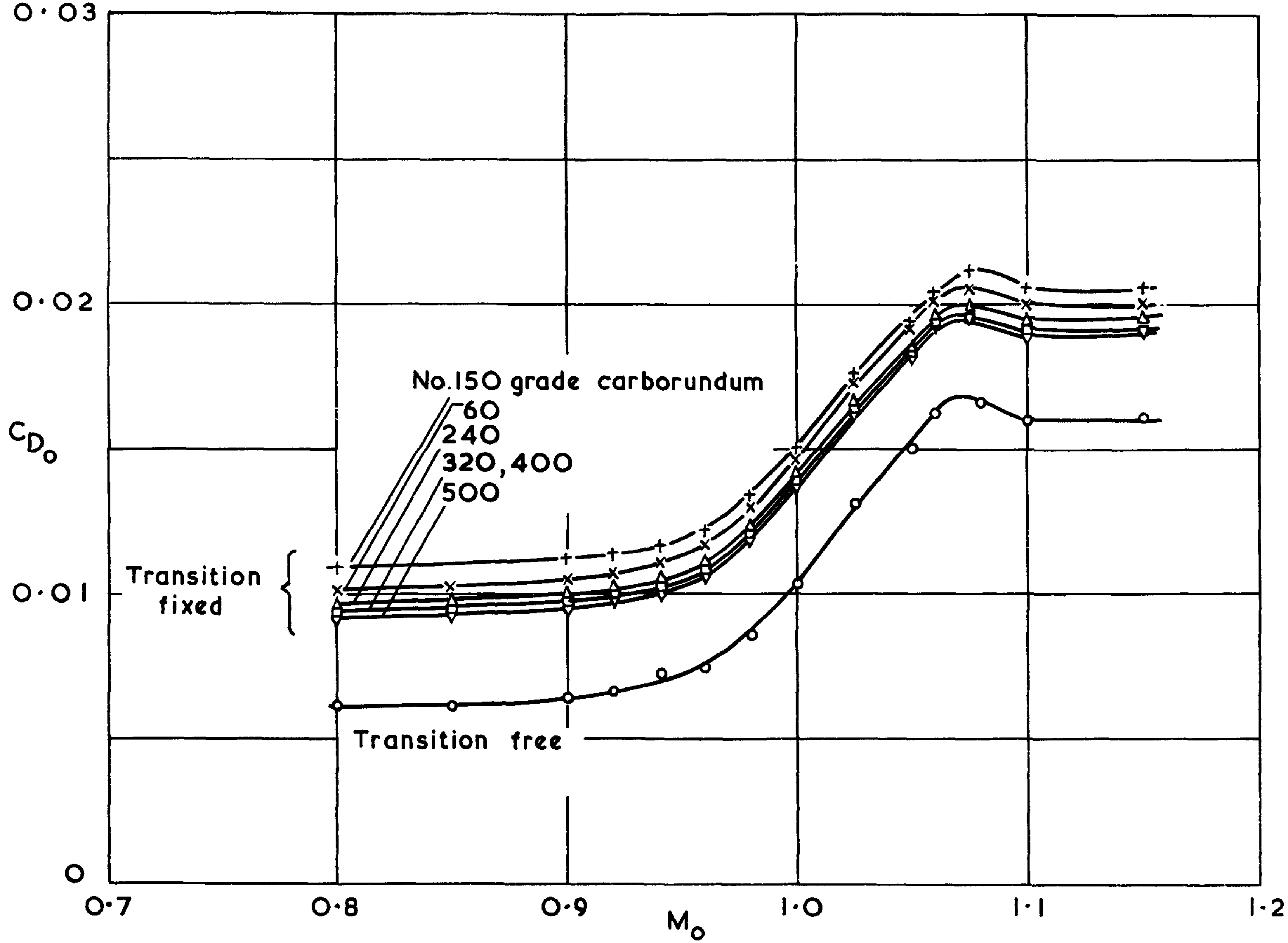


Comparison of theoretical grain heights needed to cause transition with experimental values for distributed roughness.



Effect of carborundum grain size on C_{D_0} (5% chord band)

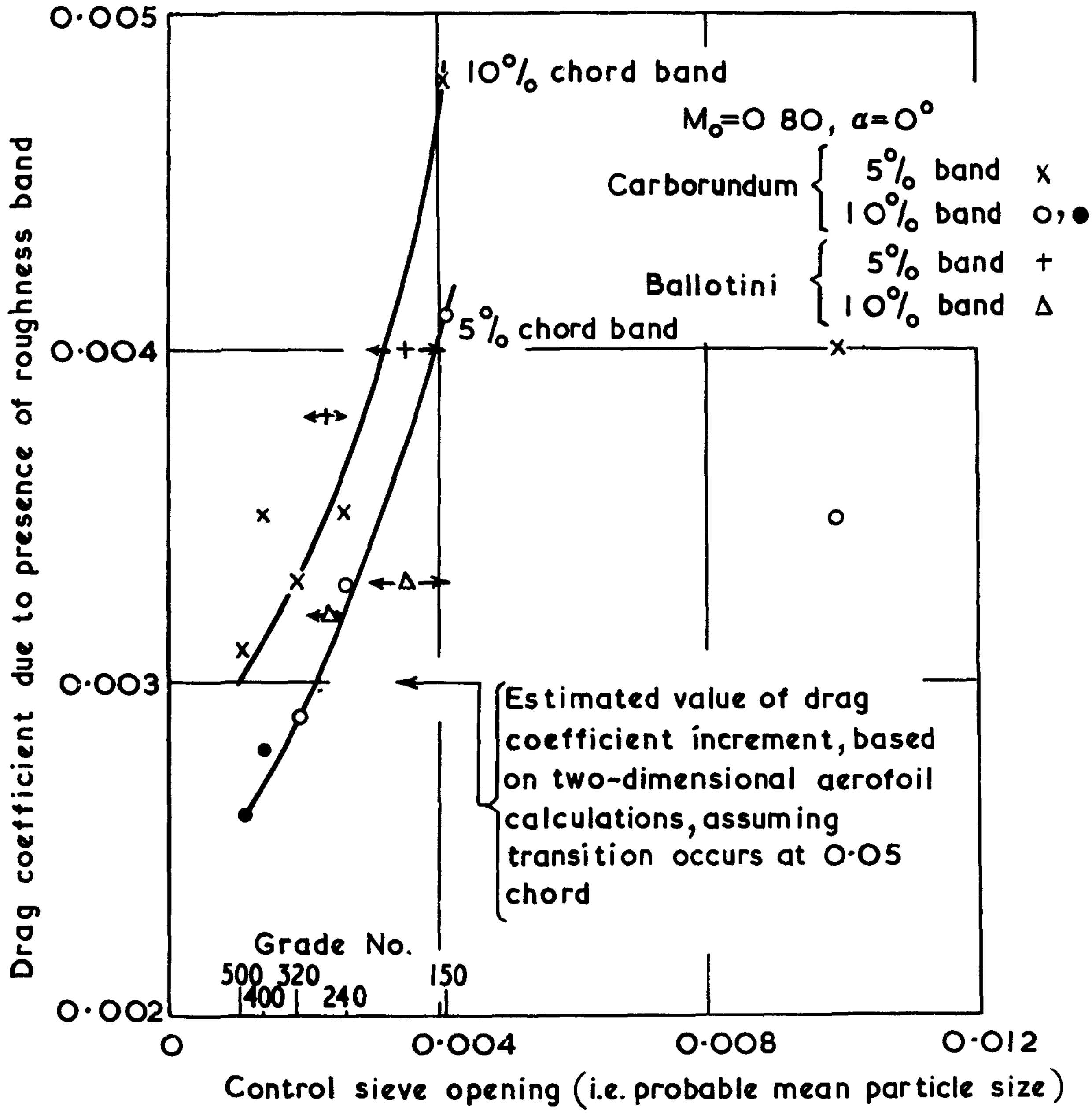
FIG. 5(a)



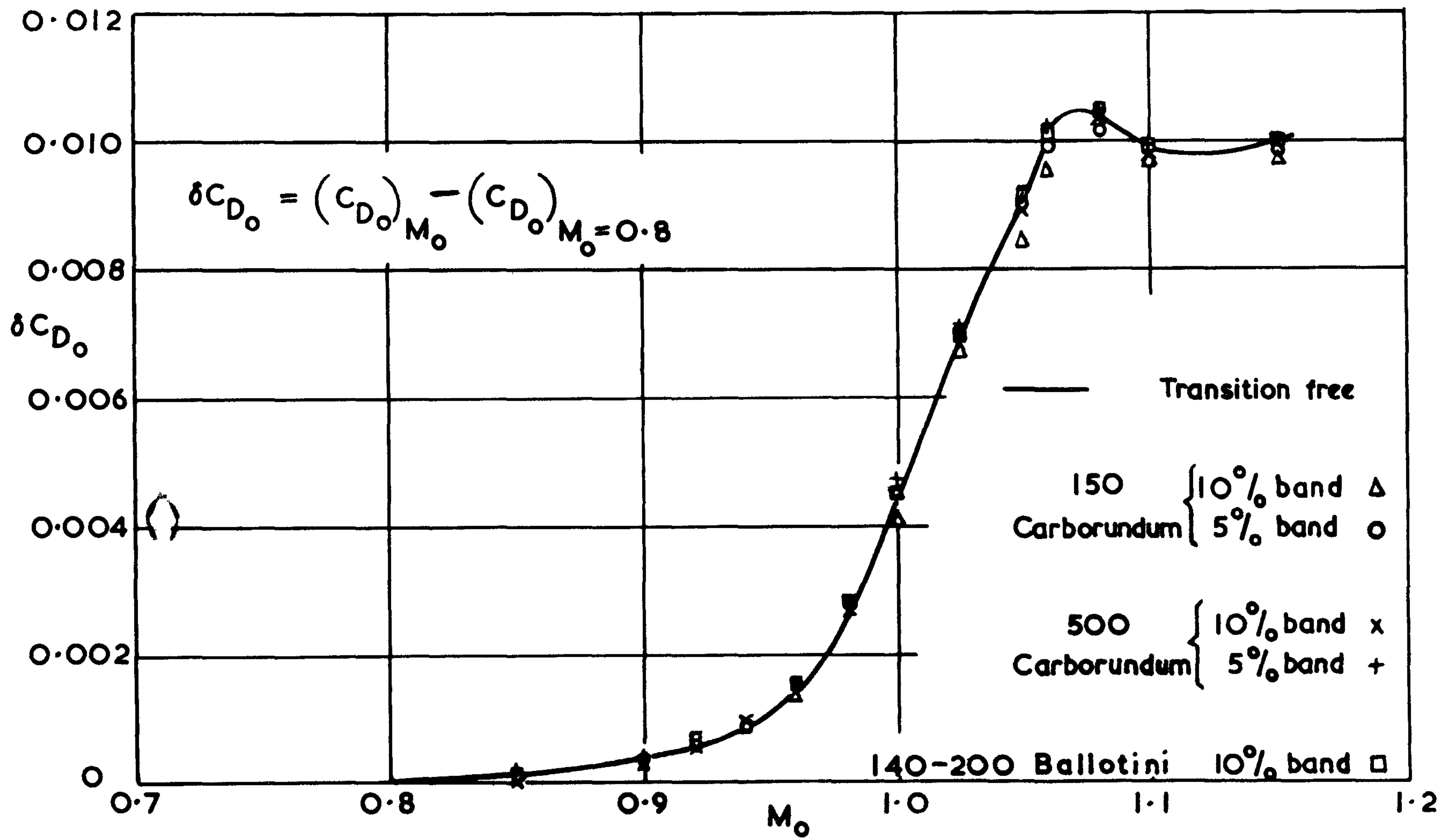
Effect of carborundum grain size on C_{D_0} (10% chord band)

FIG. 5(b)

FIG 6.



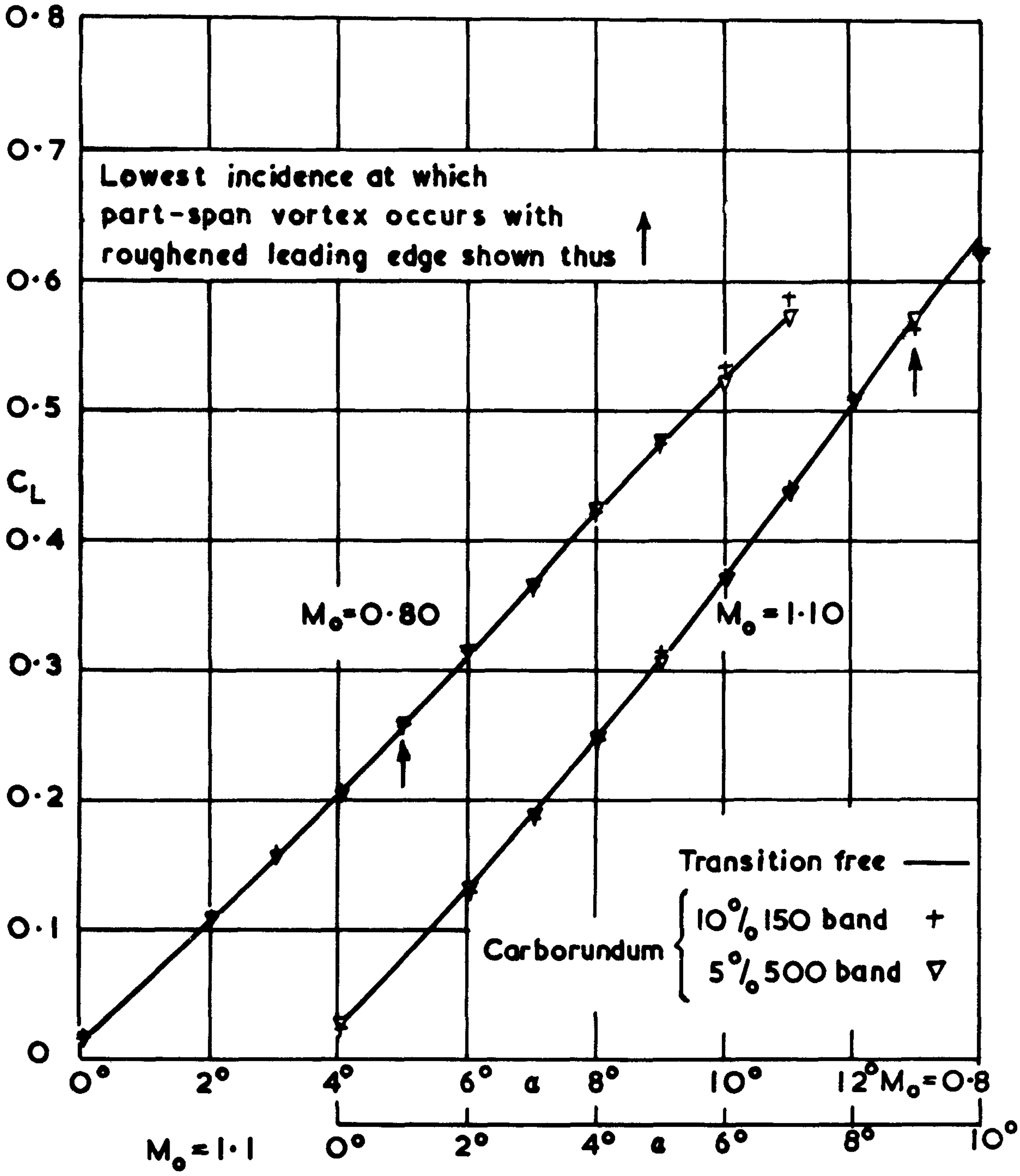
Increase in wing drag coefficient at zero incidence due to presence of roughness band. Filled symbols denote that transition did not take place at band along complete span.



Drag coefficient increment due to increase in stream Mach number.

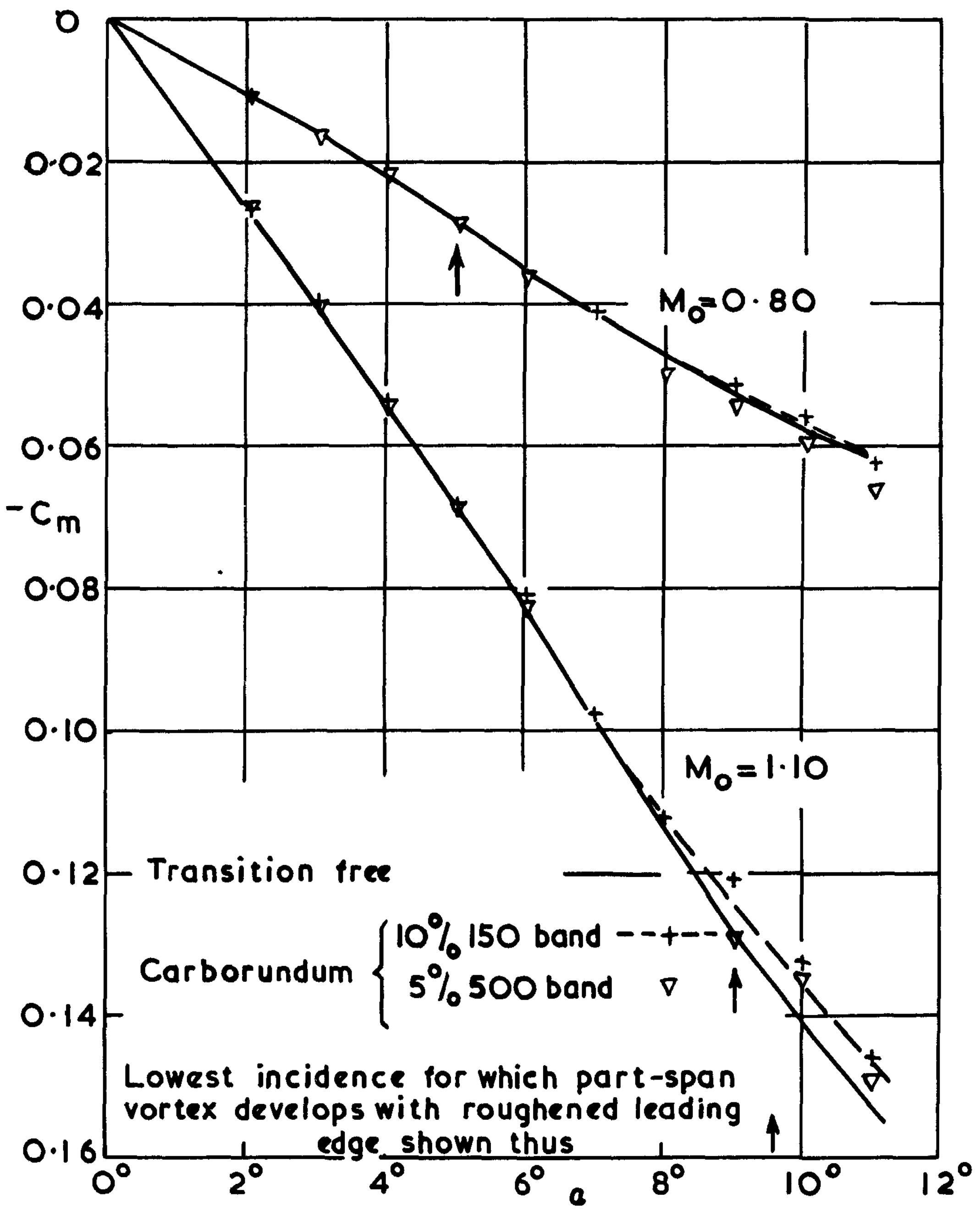
FIG. 7.

FIG. 8a.



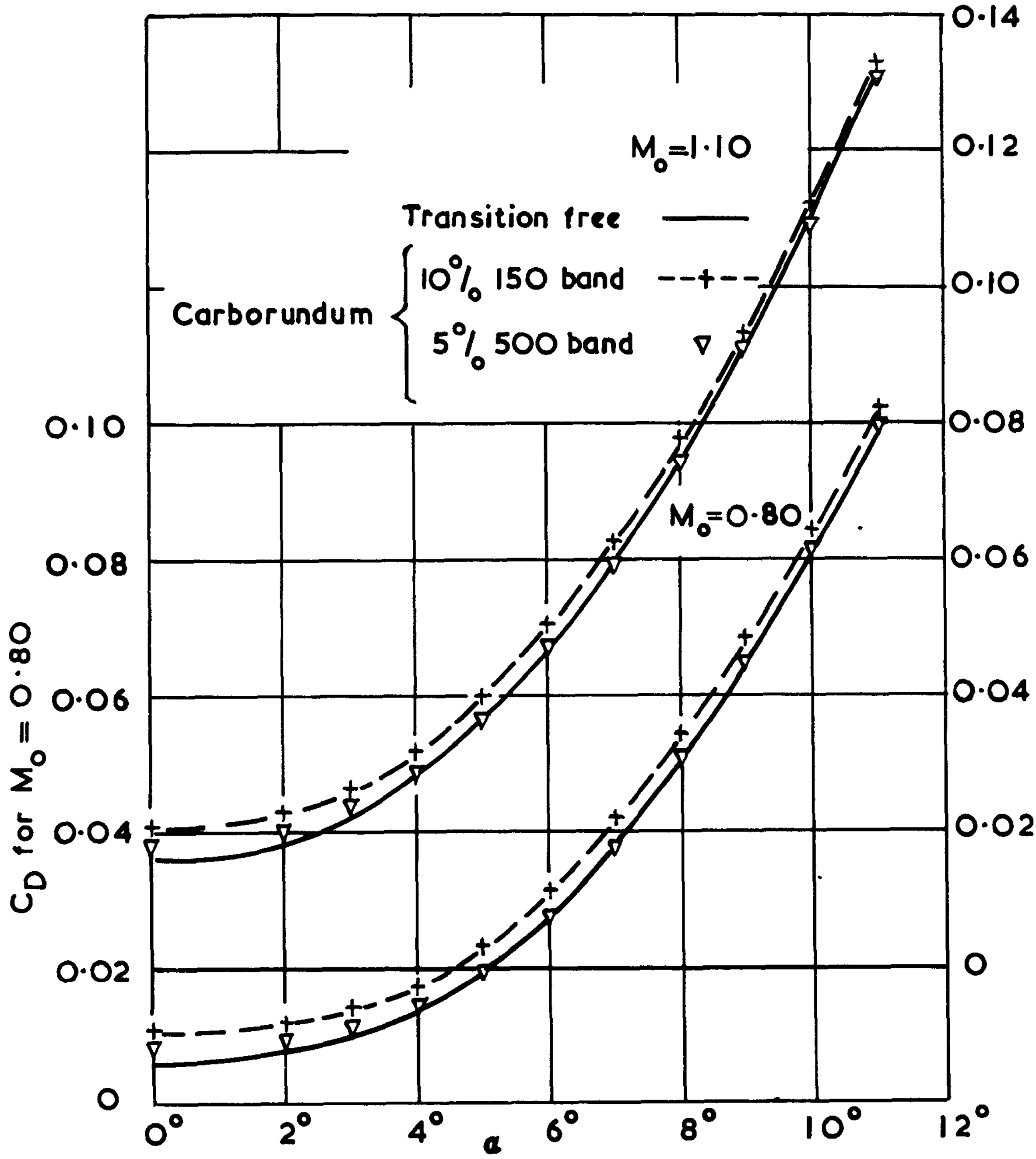
(a) Effect of roughness band state on lift curve

FIG. 8b.



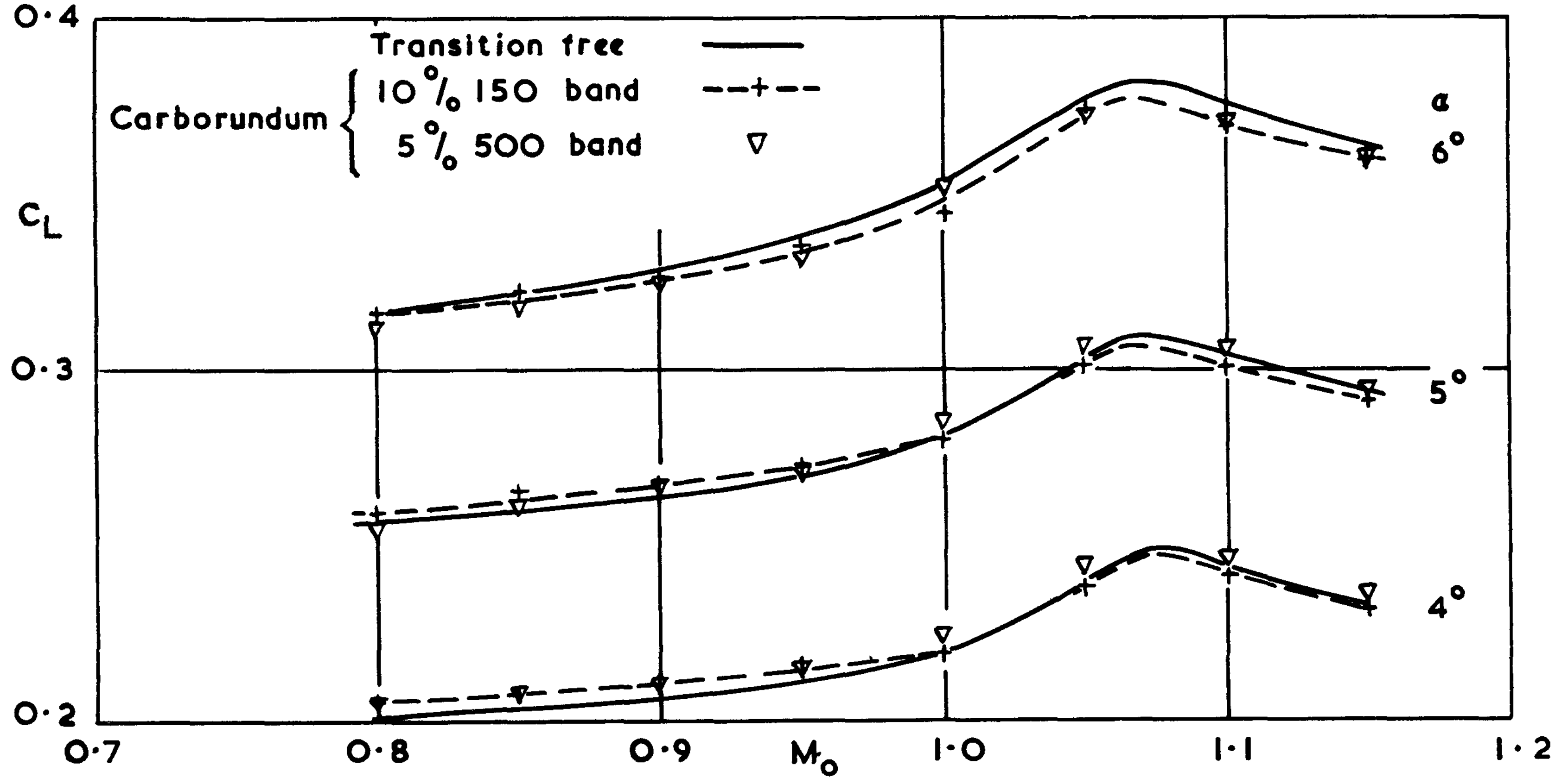
Effect of roughness band state on quarter-chord moment curve.

FIG. 8c.

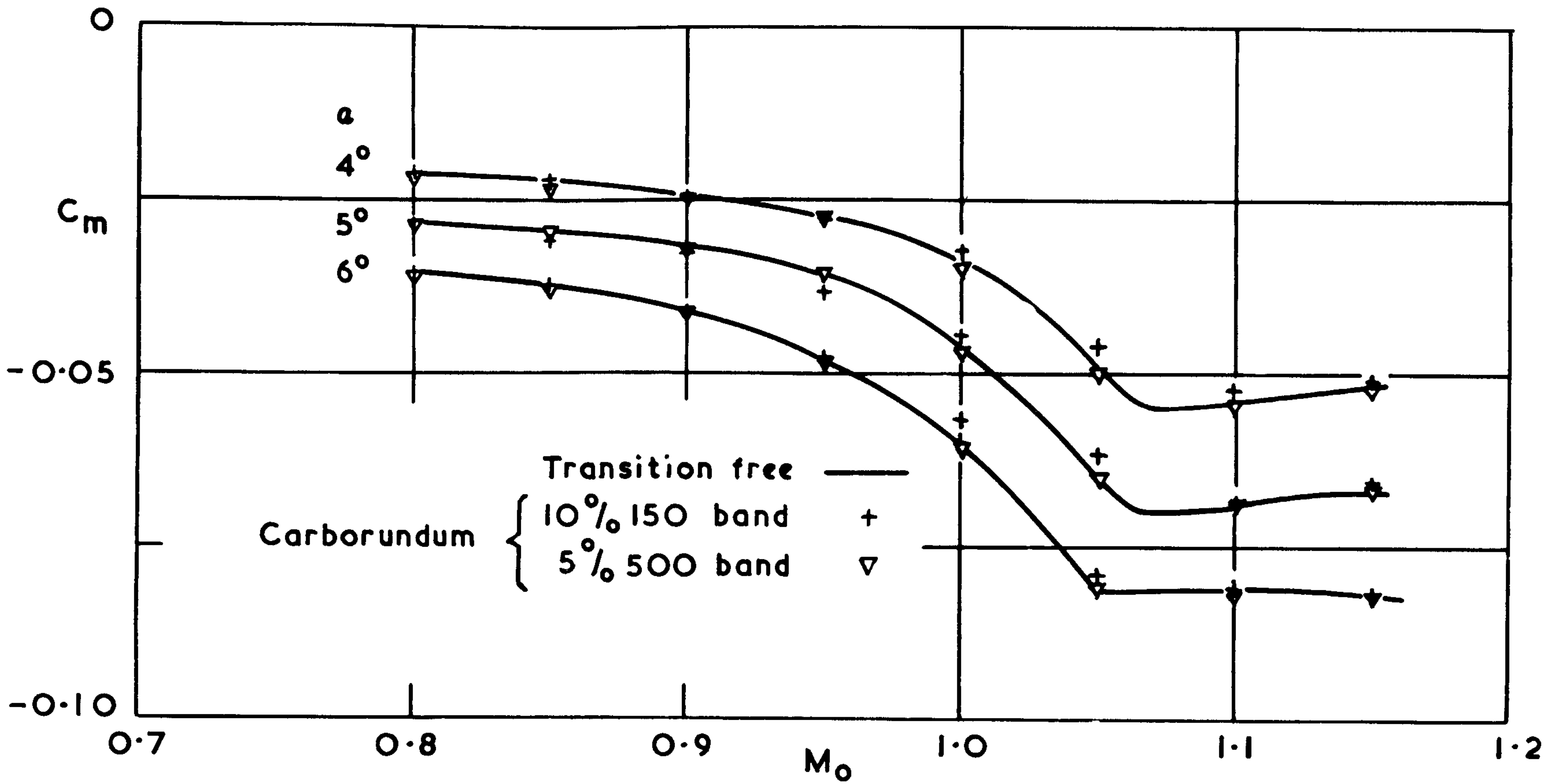


Effect of roughness band state on drag coefficient.

FIG.9a.



Effect of roughness-band state on lift variation with Mach number.



Effect of roughness-band state on pitching-moment variation with Mach number.

FIG. 9b.

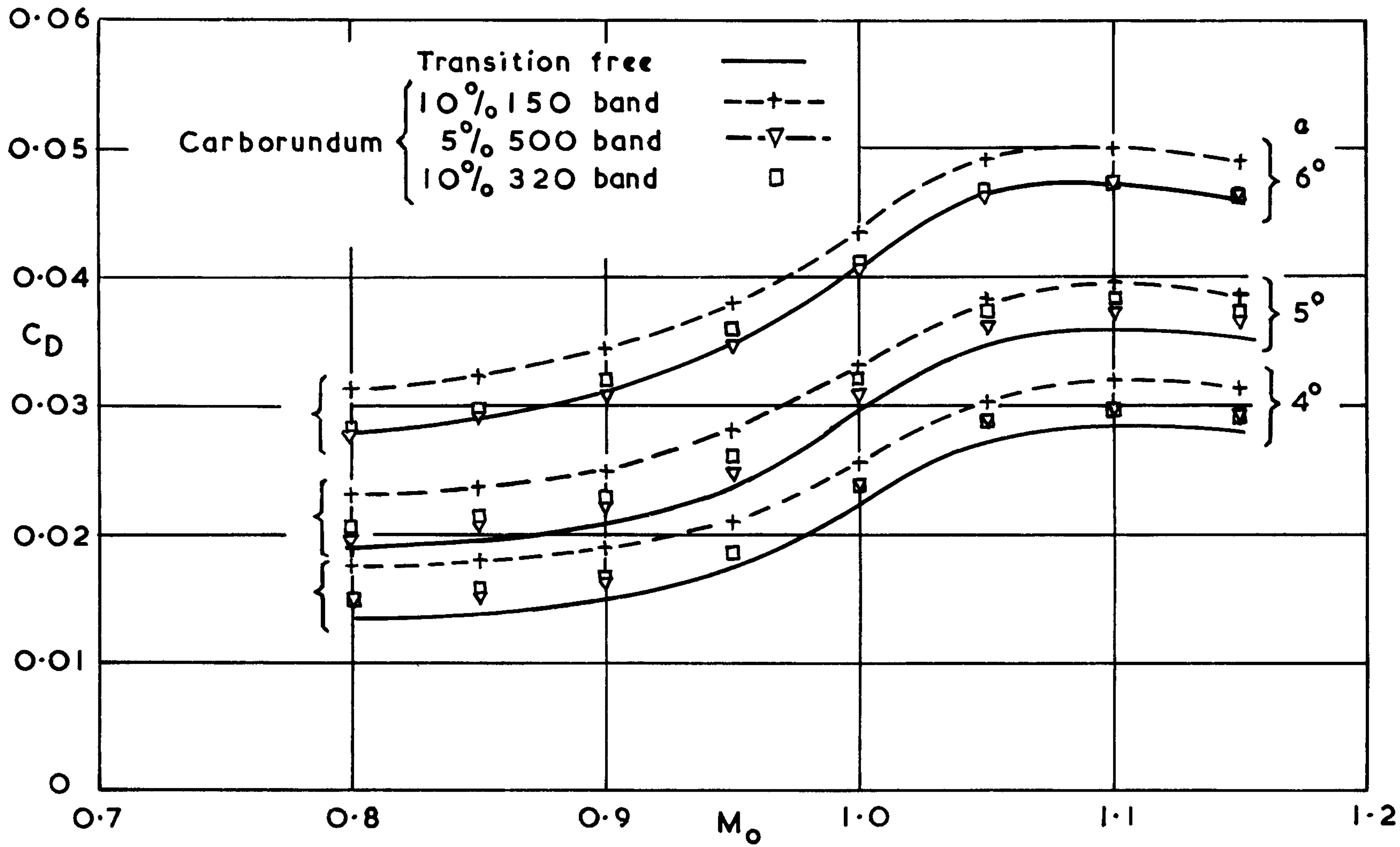


FIG. 9c.

Effect of roughness-band state on drag variation with Mach number.

FIG. A1, A2, A3.

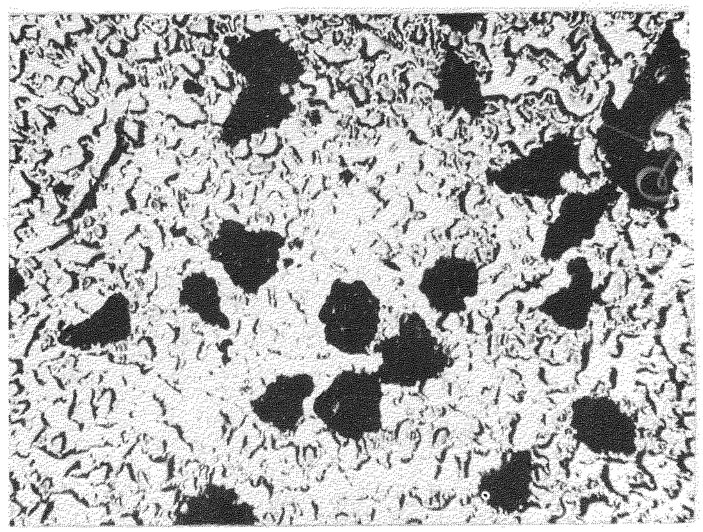


Fig A1: N° 60 Carborundum band
(coverage about 0·15)
N.B. Lower coverage was used in tests

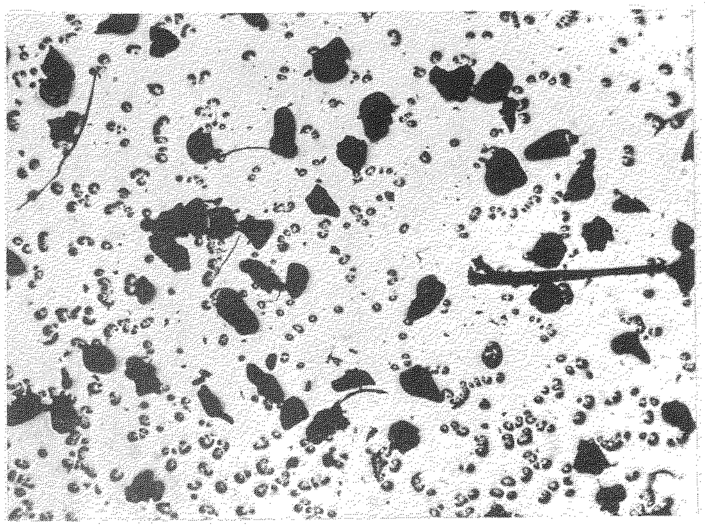


Fig A2: N°150 Carborundum band
(coverage about 0·15)
N.B. Higher coverage was used in tests

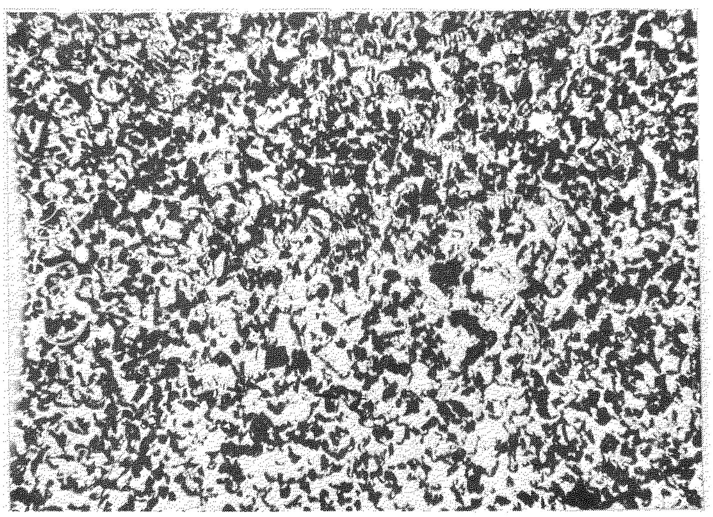


Fig A3: N°240 Carborundum band
(coverage about 0·35)

PHOTOMICROGRAPHS OF SPECIMEN ROUGHNESS BANDS (X 25)

FIGS. A4. & A5.

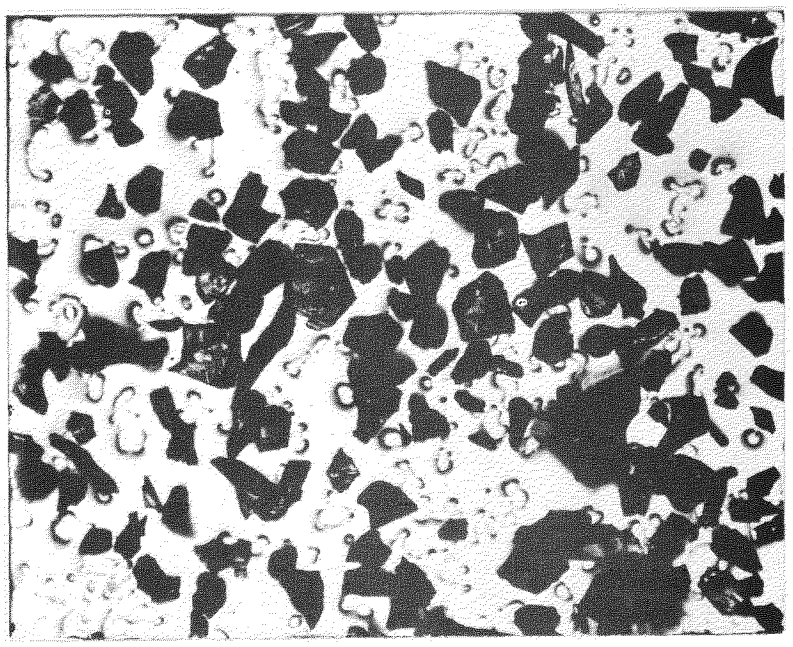


Fig. A.4. N° 240 Carborundum band (coverage about 0·35.)

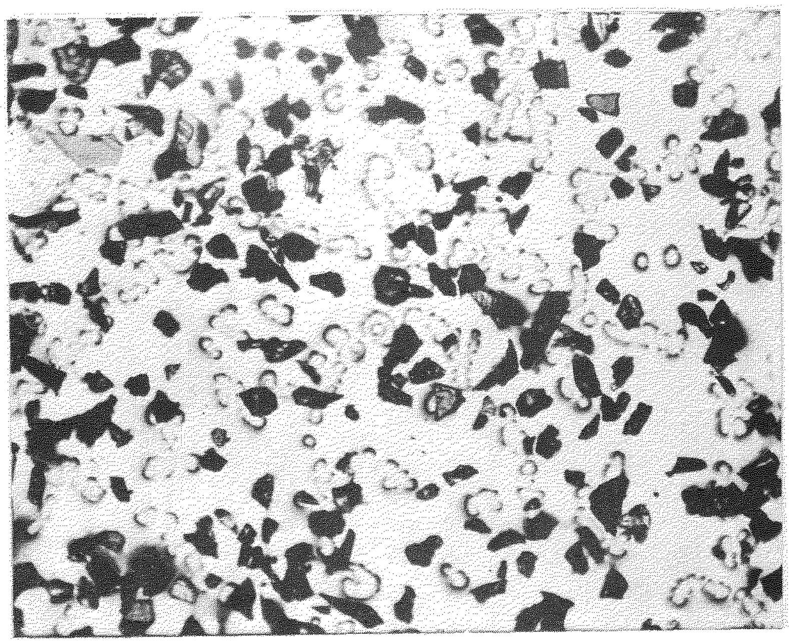


Fig. A.5. N° 320 Carborundum band (coverage about 0·15.)

PHOTOMICROGRAPHS OF SPECIMEN ROUGHNESS BANDS (x 100)

FIGS. A6. & A7.

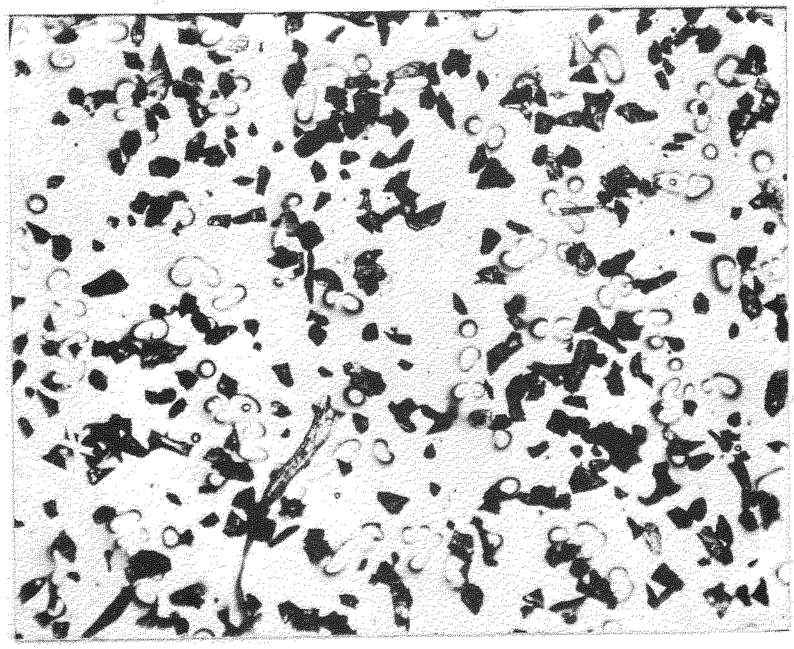


Fig. A.6. Nº 400 Carborundum band (coverage about 0·20.)

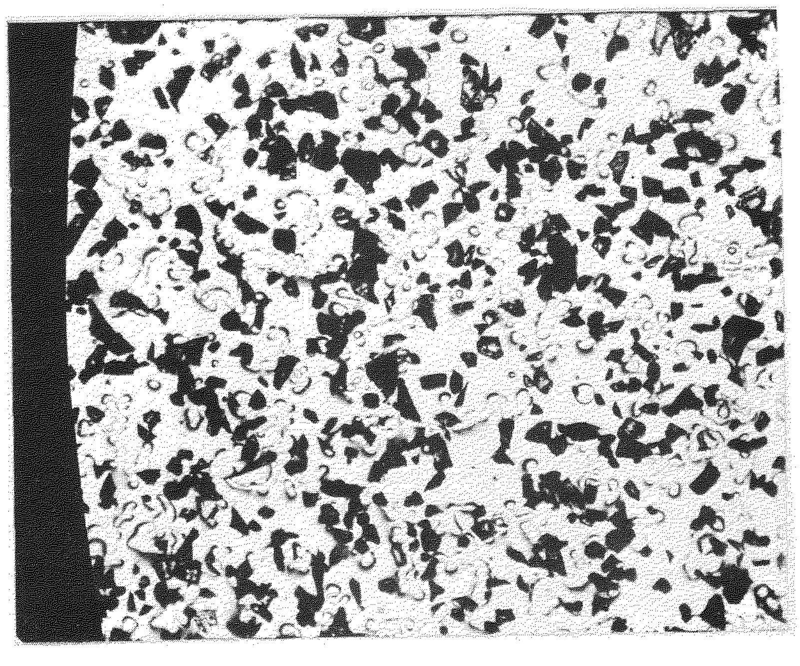


Fig. A.7. Nº 500 Carborundum band (coverage about 0·35.)

PHOTOMICROGRAPHS OF SPECIMEN ROUGHNESS BANDS (x 100)

FIGS. A8 & A9.

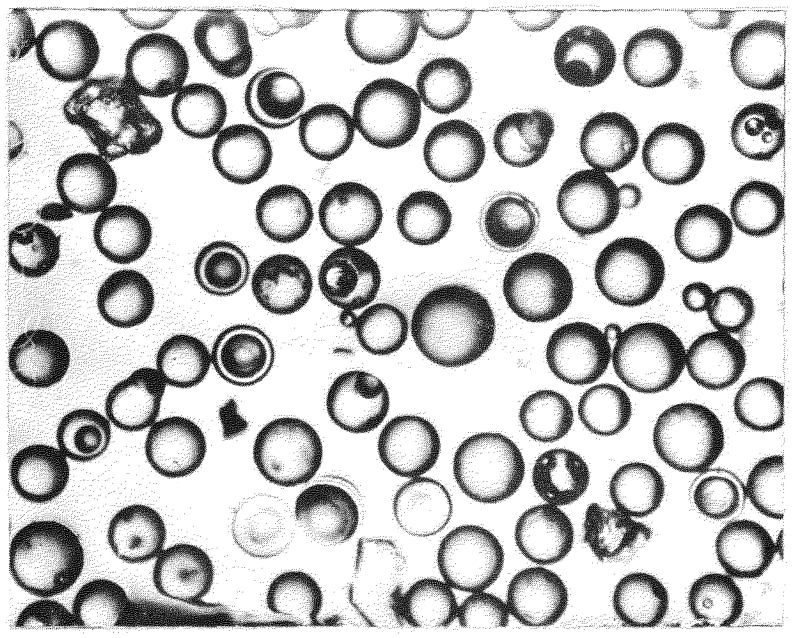


Fig. A.8. N° 140–200 Ballotini band (coverage about 0·45.)

N.B. Coverage is higher than for band used in tests. The carborundum grains are due to contamination of the sieve.

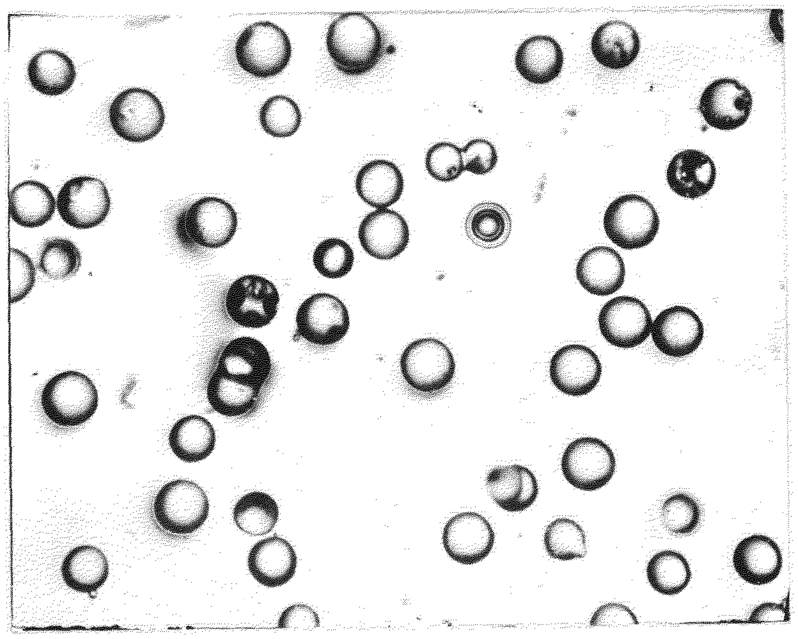


Fig. A.9. N° 200–240 Ballotini band (coverage about 0·15.)

N.B. Not used in present tests.

PHOTOMICROGRAPHS OF SPECIMEN ROUGHNESS BANDS (x 100)

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