The Erosion of a Cobalt-Chromium Alloy by Liquid Impact [and Discussion]

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IX. The erosion of a cobalt–chromium alloy by liquid impact

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[Plates 24 to 27]

Severe erosion occurs in the leading edge of the moving blades at the exhaust end of large steam turbines. It is customary to fit a shield of some hard material such as Stellite 6 to reduce the rate of damage.

Metallographic examination of specimens tested on a simulative rig showed that the erosion damage occurring was similar to that found on shields removed from service. This rig was therefore used to study the early stages of erosion in a cobalt-based alloy (Stellite 6).

Specialized optical and electron metallographic techniques were used to study the microstructural changes occurring. Considerable deformation was observed in the matrix at a very early stage, without metal removal. At this time fissuring could also be seen at some carbide/matrix interfaces. As testing continued small pits were seen to form, generally adjacent to carbides. The growth of these pits was then studied.

From these observations the following four-stage mechanism is proposed for erosion in Stellite 6:

(1) Matrix deformation by slip.
(2) Cracking at carbide–matrix boundaries.
(3) Propagation of these cracks under repeated loading.
(4) Intersection of crack fronts allowing material removal.

1. Introduction

The blades in the last row of a low pressure steam turbine operate in conditions (about 1·0 Lb./in.^{2} (abs.) and 37 °C) which exposes them to erosion attack. The formation and behaviour of the water droplets which lead to this erosion has been described by Gardner (1963). The slow moving droplets which result from condensation on the preceding stator blades are struck by the rotating blades and the repeated impact causes erosion damage on the blading material. In order to reduce this damage the leading edge of a low pressure blade is normally shielded with a more erosion resistant material. One currently used shielding material is a cast cobalt-base alloy (Stellite 6).

1·1. *Examination of service blade*

The extent to which damage can occur is shown in figure 1, plate 24. The blade in this figure was removed from service after 30250 h running with a tip velocity of 1400 ft./s. The protection on it was provided by a number of lengths of cast Stellite 6. Examination showed that at the tip the blade and shield had been eroded away. Extensive erosion damage was also observed in the remaining portion of the first shield. Numerous craters were found on the shields lower down the blade.

Metallographic examination of sections taken from the eroded shields revealed a normal cast structure of cobalt/chromium alloy dendrites in a carbide eutectic. Figure 2 (*a*), plate 24, shows several cracks radiating from a typical erosion pit.

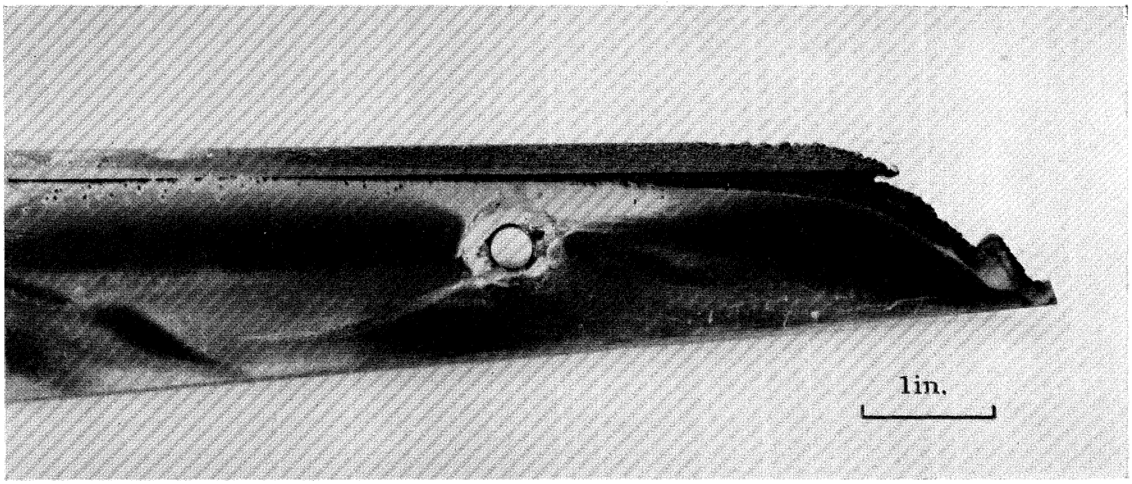
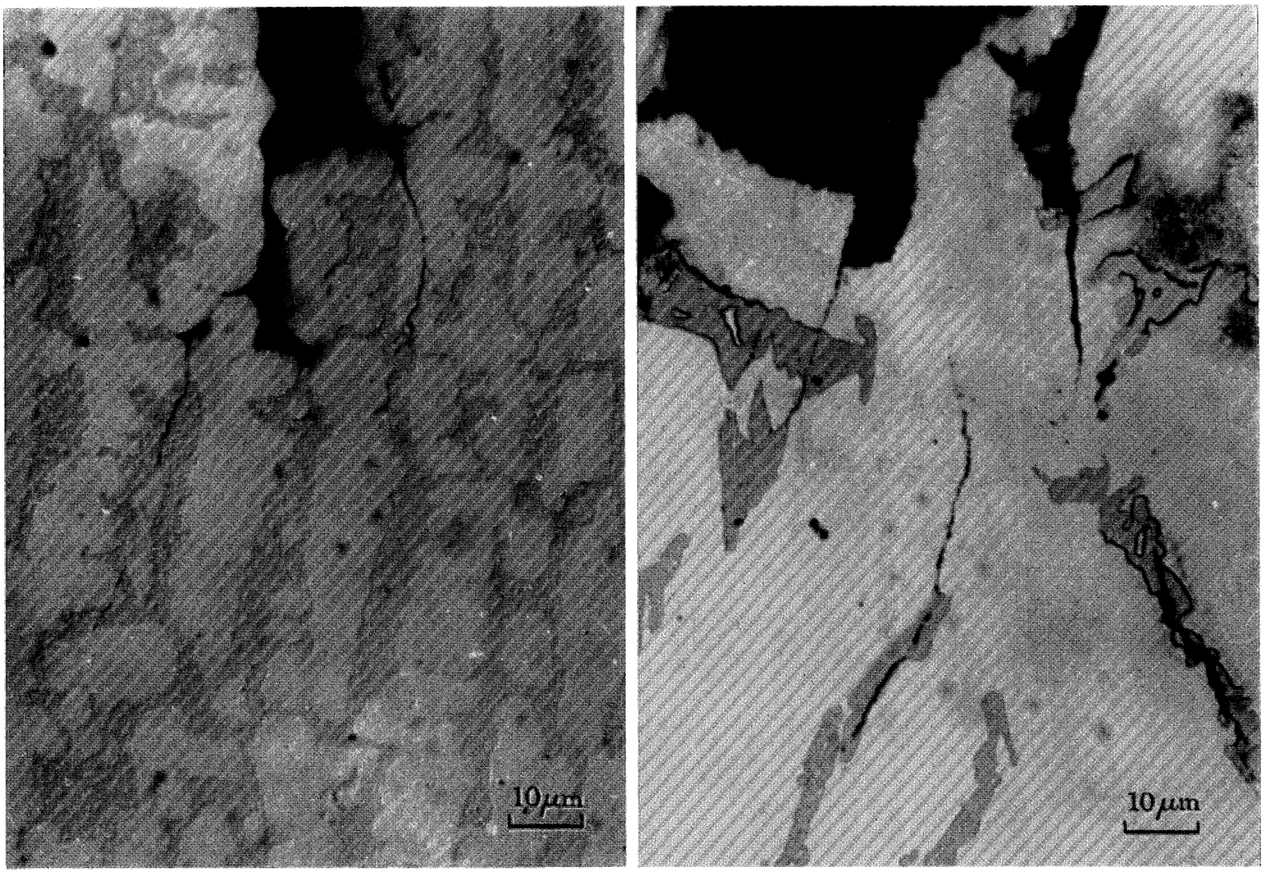


FIGURE 1. Stellite shielded low pressure blade after 30250 h service.



(*a*) (*b*)

FIGURE 2. (*a*) Cracking associated with erosion pit in cast Stellite 6 erosion shield. (*b*) Cracking associated with erosion pit in cast Stellite 6 erosion test specimen.

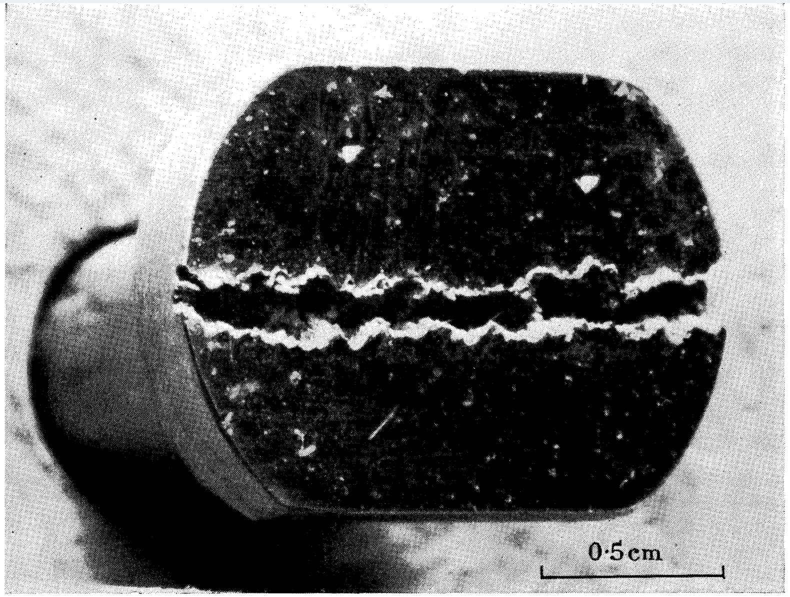


FIGURE 5. Specimen after erosion testing.

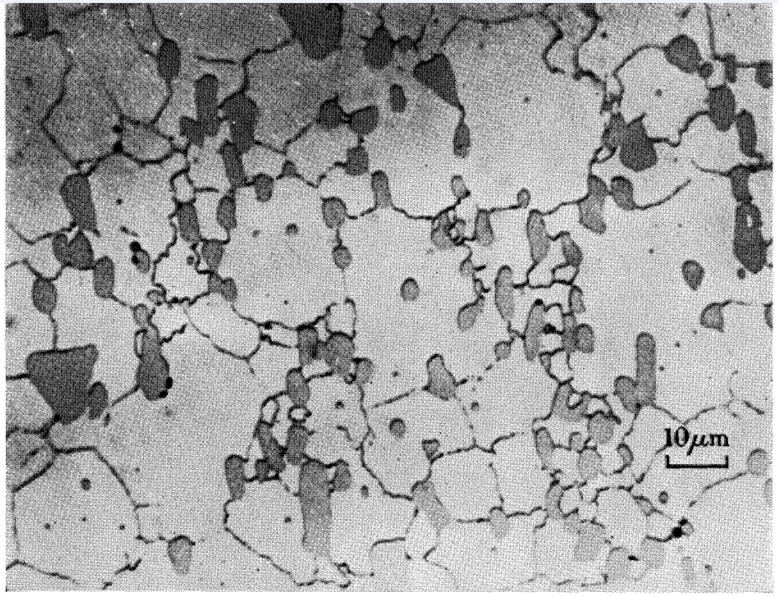


FIGURE 6. Typical structure Haynes alloy 6B (etched).

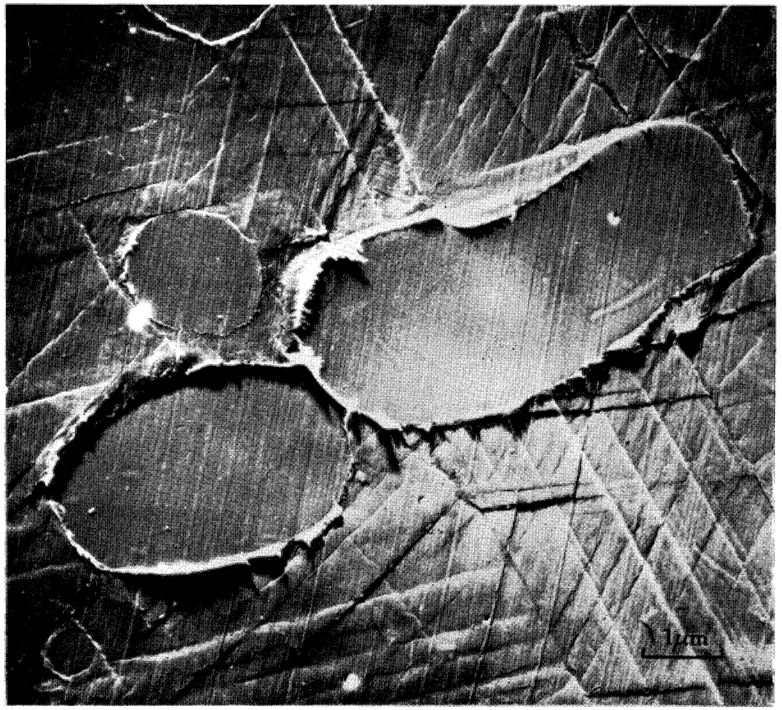


FIGURE 8. Cracking at carbide/matrix interfaces.

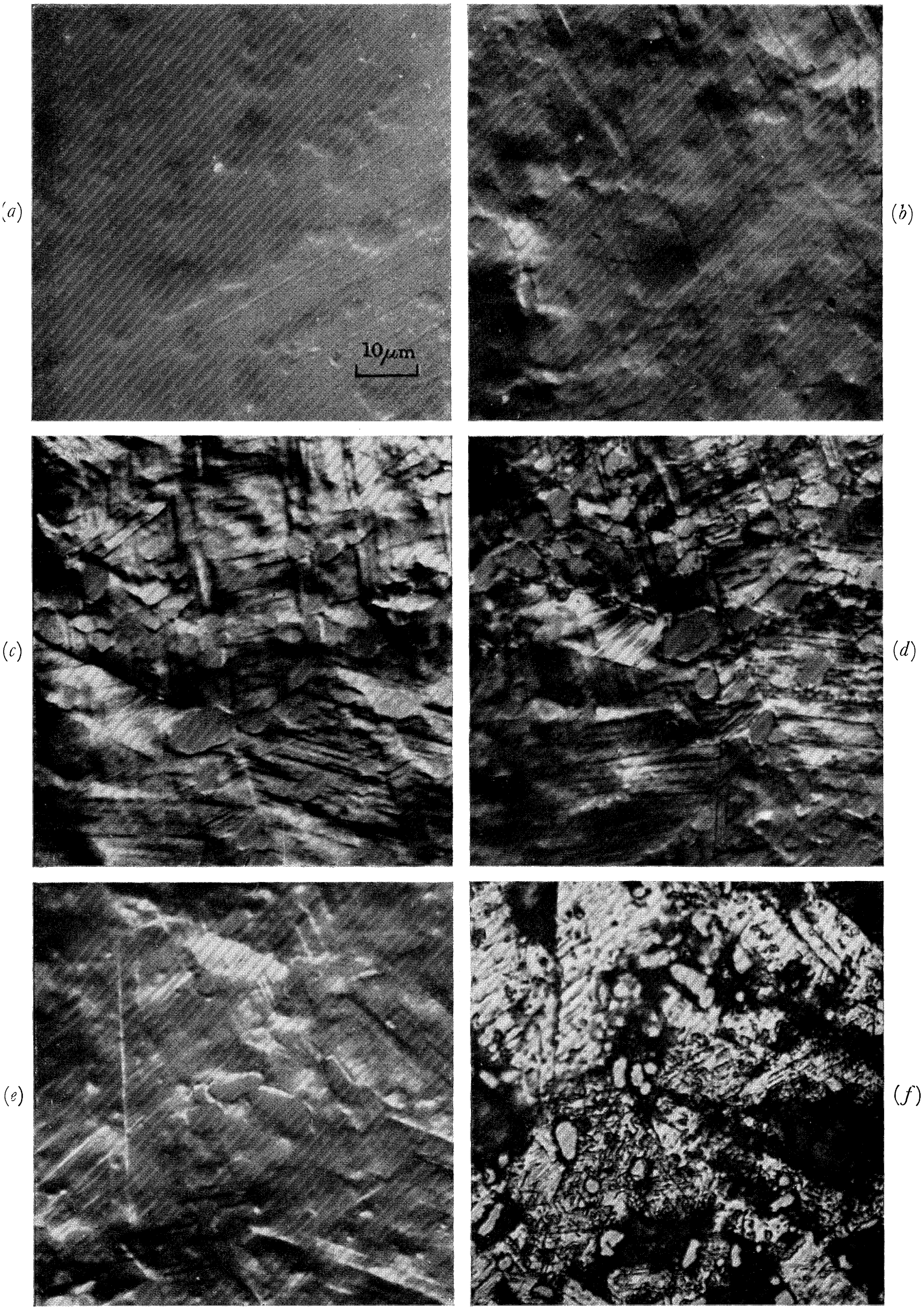


FIGURE 7. Development of erosion damage on surface of Haynes 6B specimen tested at a velocity of 1030 ft./s.

(*a*) 0 impacts (field 1)
(*b*) 3000 impacts (field 1)
(*c*) 40000 impacts (field 1)
(*d*) 90000 impacts (field 1)
(*e*) 3000 impacts (field 2)
(*f*) 90000 impacts (field 2)

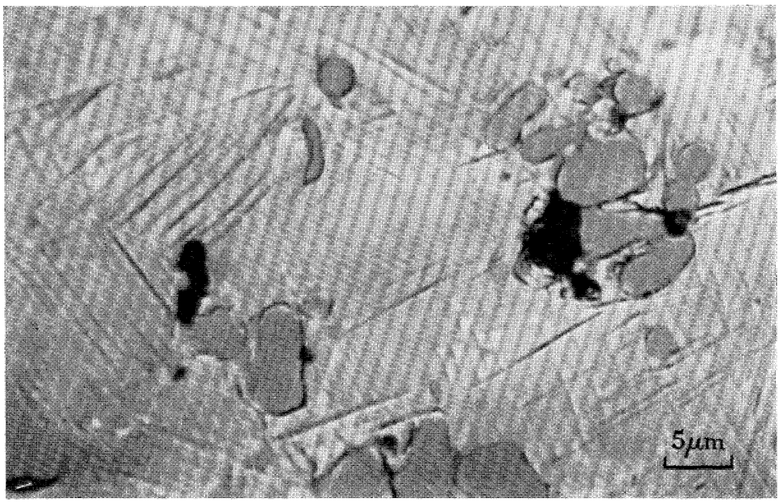


FIGURE 9. Cavities left by loss of carbide particles at specimen surface.

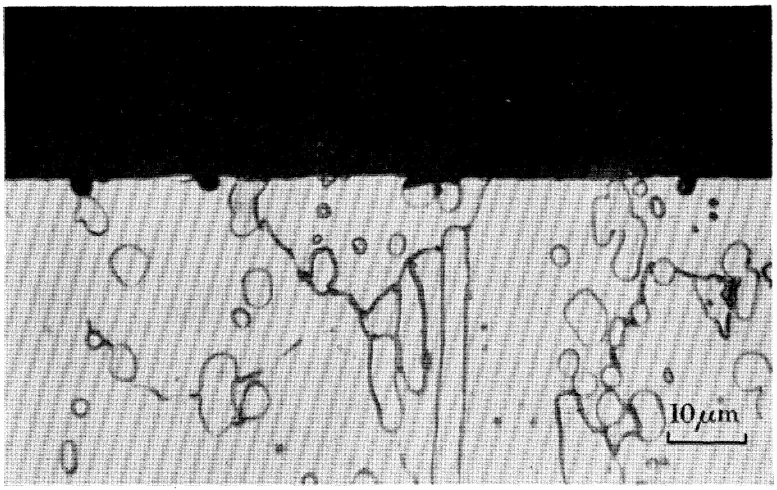


FIGURE 10. Section through eroded surface showing cavities left by carbide particle loss (etched).

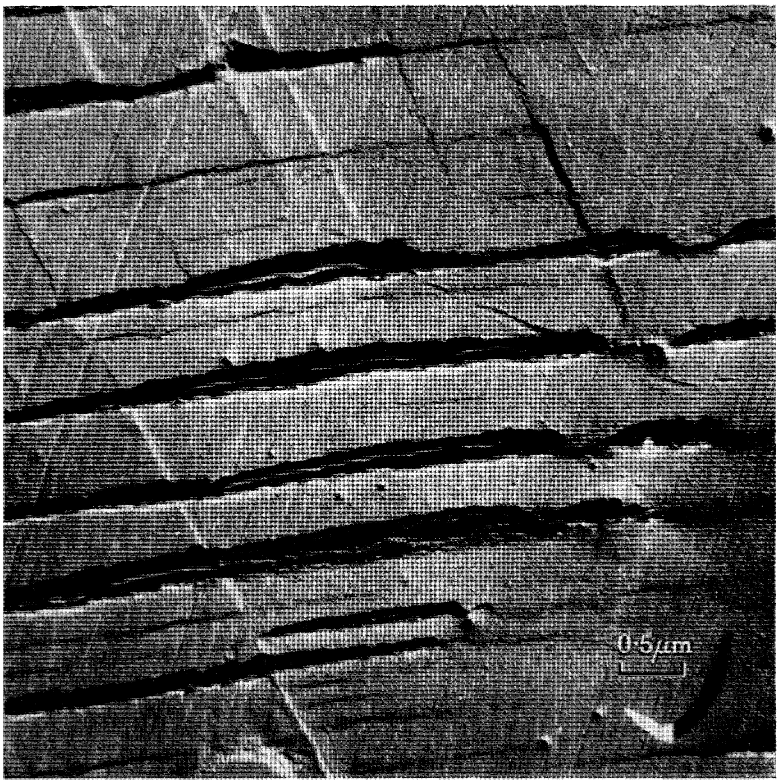


FIGURE 11. Intrusion formation at slip lines.

1·2. *Laboratory tests*

It has been necessary to carry out testing to obtain an understanding of the process of erosion in a steam turbine and also to compare the erosion resistance of possible materials. For this purpose a test rig has been constructed by the Steam Turbine Research Department of English Electric Co. Ltd. in which a specimen is subjected to repeated impacts by a water jet. From figure 3 it will be seen that there are four specimens attached to the periphery of a disk and each is struck by a transverse jet of water on each revolution. The test is carried out at a pressure of about 0·5 Lb./in.^{2} (abs.) and the speed of rotation can be adjusted to give linear velocities of the specimen varying from 500 to 2000 ft./s. The diameter of the water jet is $\frac{1}{64}$ in. It is customary to test a pair of specimens in each material and to include also a pair of specimens of a standard material for reference purposes.

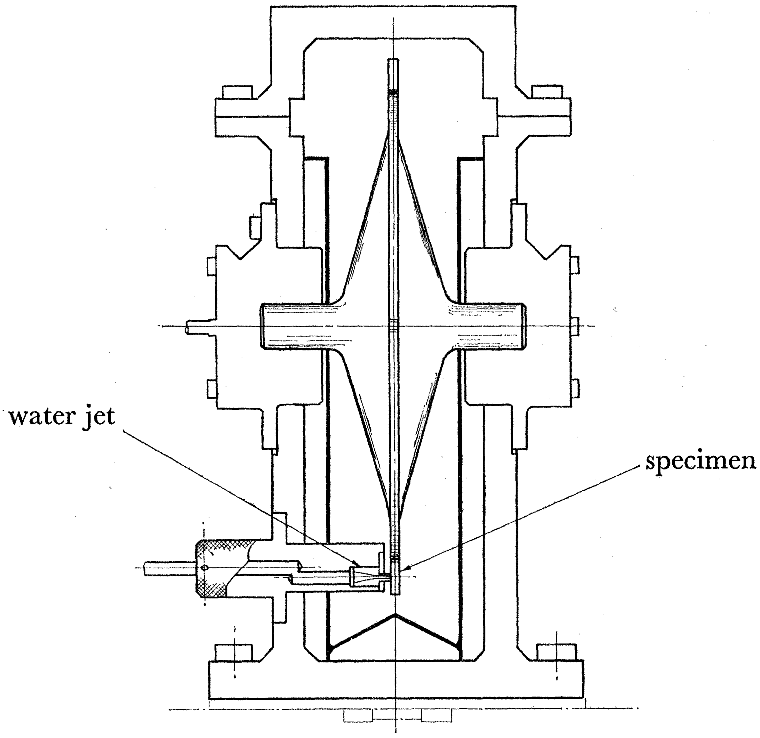


FIGURE 3. English Electric erosion test rig.

During the test the specimens are removed periodically for examination and weighing. A graph can then be produced relating weight loss (reciprocal of erosion resistance) to number of impacts (running time). Testing is generally carried out at 1400 ft./s for a period of 200 000 impacts; a typical curve is shown in figure 4.

After testing to 200 000 impacts a deep track of erosion damaged material can be seen in the test face as indicated in figure 5, plate 25. In the cobalt–chromium alloy being considered here the track is approximately 0·030 in. wide and 0·020 in. deep. Metallographic examination of sections taken from this area of damage indicates the presence of pits and cracking which show similarities to those observed on shields removed from service (figure 2 (*b*)).

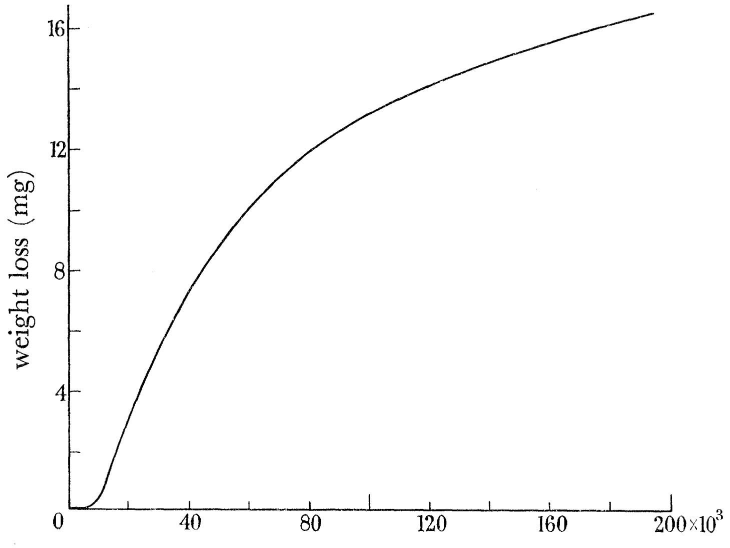


FIGURE 4. Typical erosion curve for Stellite 6.

2. DEVELOPMENT OF EROSION DAMAGE

Although normally used in the cast condition for erosion shields this cobalt–chromium alloy can also be obtained in the wrought condition (Haynes alloy 6B).

The overall erosion resistance of both forms is very similar but since the latter has a more uniform distribution of carbides (figure 6, plate 25), better homogeneity, and no shrinkage porosity, it was thought to be more suitable for a detailed metallographic study. The typical chemical analysis of both alloys is given in table 1.

TABLE 1. TYPICAL ANALYSIS (%)

	Co	Cr	W	C
cast alloy (Stellite 6)	66	26	5	1
wrought alloy (Haynes 6B)	61	29	5	1

In order to study the effect of water jet impact loading on the surface of the material it was necessary to examine specimens which had not suffered extensive damage. This means that the specimens were in the 'incubation period' of figure 4, during which the weight loss is insignificant. Tests for this purpose were carried out at 1400 ft./s for exposures of 5000 to 12000 impacts. A wider range of exposures was also covered at 1030 ft./s to examine the changes in greater detail. The amount of damage after 70000 impacts at 1030 ft./s appeared to be similar to that found after 10000 impacts at 1400 ft./s.

2·1. *Procedure*

Prior to testing, the surfaces were polished using standard metallographic techniques. All fine polishing was carried out using diamond pastes, the final polish being $\frac{1}{4}$ μm. Care was taken to avoid flowing which results in work hardening of the surface. After exposure to the required number of impacts the specimen surfaces were examined by optical and electron microscopy. Optical microscopy was carried out by means of the Nomarski interference contrast technique which has high vertical resolution (Nomarski & Weill 1955), and electron microscopy using two stage Formvar/carbon replicas shadowed at 45° with Au/Pd. In certain cases sections were prepared through the eroded surfaces for optical microscopy.

2·2. *Metallographic examination*

The wrought alloy has an equiaxed fine grained structure in which elongated carbides, mainly WC and Cr_7C_3, are present in a single phase matrix (figure 6, plate 25). Examination of the surface prior to test shows a dispersion of carbides approx. 7 μm diameter in the matrix (figure 7 (*a*)).

Figure 7, plate 26, indicates for two typical fields the progress of erosion damage on the surface of a specimen tested at 1030 ft./s as seen under the optical microscope.

After 3000 impacts (figure 7 (*b*)) extensive slip patterns can be seen, indicating deformation of the surface. It has been found that the surface scratches present on the material before test are still visible after these first few impacts, therefore no material has been lost at this stage. As testing continues the slip patterns remain basically the same but become more definite and certain slip lines become persistent.

The erosion track present after 40000 impacts has been shown by Talysurf measurements to consist of a shallow, shouldered, depression some 4 μm below the general level of the specimen surface. At this stage a few small pits can be detected, adjacent to carbides (figure 7 (*c*)). With further testing larger pits develop. One seen in the upper left of figure 7 (*d*) has appeared in an area where considerable slip had occurred close to a carbide cluster. It should be observed that some of the small pits previously noted have not enlarged significantly. The development of pitting is also shown by comparing figure 7 (*e*) and (*f*), which show major pitting appearing on certain pronounced slip lines and among carbide clusters.

Repolishing and etching of a specimen given 40000 impacts has produced no evidence of mechanical twinning or deformation banding. Microhardness surveys were carried out on several tracks. The results, in table 2, show that work hardening has occurred.

TABLE 2. REICHERT MICROHARDNESS SURVEY ON HAYNES ALLOY 6B EROSION SPECIMEN (30 g LOAD)

	eroded (Kg/mm^2)	uneroded (Kg/mm^2)
carbide	710	700
matrix	543	464

In order to examine in detail some of the features observed in the series of optical micrographs in figure 7, electron microscopy was used. Examination of replicas taken from a specimen after 5000 impacts reveals the presence of cracks at the carbide/matrix boundaries (figure 8, plate 25). These cracks propagate along the boundaries with increasing exposure so that by 40000 impacts separation at these boundaries is visible optically and, as seen in figure 9, plate 27, loss of some particles results.

Sections taken through the erosion track at this stage show that the formation of surface cavities results from the loss of the less deeply seated carbides (figure 10, plate 27), others being slightly depressed. Cleavage cracks have also been observed in some surface carbides.

Electron microscopy has also revealed the presence of intrusions along certain slip lines after 10000 impacts (figure 11, plate 27). With increasing exposure these slip lines tend to broaden and the damage along them becomes more pronounced.

It is of interest to note that cracking at the carbide/matrix boundaries appears to occur before the formation of slip line intrusions. When the erosion has proceeded to the stage of relatively large scale material loss, initiation is generally in the region of carbide clusters, and results in localized cratering; the maximum measured depth being 150 μm. With increasing numbers of impacts these craters tend to overlap and extend both in depth and in area until a well developed groove has been eroded in the specimen surface. Sections taken through specimens at advanced stages of damage indicate that material loss occurs by the intersection of transgranular cracks.

3. Discussion

X-ray diffraction analysis indicates that the matrix of the wrought cobalt–chromium alloy is a mixture of face-centred cubic and hexagonal close packed structures. The initial effect of water drop impact is to produce deformation of the surface. Examination shows that this deformation occurs by a slip process. From the angular relation of the slip lines it is thought that deformation may occur in the (111) or (1101) planes of the matrix. With increase in the number of impacts persistent slip lines are observed on the surface of the specimen and subsequently intrusions can be seen. It has been shown that these features are associated with the early stages of fatigue (Forsyth 1963).

Damage in the form of cracking at the boundaries between the carbide particles and the matrix has also been found. This appears to occur after the slip line formation but prior to the development of intrusions. It has been shown that cobalt and its alloys have low stacking fault energies (Habraken & Coutsouradis 1965) and hence the matrix has a low capacity for the relief of strain by cross-slip. It is suggested, therefore, that separation at the boundaries occurs in order to accommodate the actual deformation strains. Propagation of these cracks has been shown to result in the loss of the less deeply seated carbides; the shearing action of the outward flowing water after each impact observed by Bowden & Brunton (1961) may assist in the removal of these particles. There is some evidence that with increasing testing time such sites extend preferentially by loss of matrix material from their periphery. At this stage there is no significant weight loss.

Both cracking at the edges of particles and intrusion formation in the matrix proceed concurrently in the early stages. The removal of material at the later stages of damage appears to be a result of the intersection of transgranular cracks causing gross material loss. It is not known at present whether these cracks originate at the carbide/matrix boundaries or at the intrusions nor the extent to which their propagation is dependent on fatigue.

4. Conclusions

The following stages have been observed during the erosion of a cobalt–chromium alloy by liquid impact:

Slip deformation and work hardening of the specimen surface.
Cracking of interfaces between carbide particles and the matrix.
Intrusion formation at certain slip lines as a result of cyclic stressing.
Material removal by the intersection of transgranular cracks.

The authors acknowledge permission of the Group Director of Research of the English Electric Co. to publish this paper.

References (Marriott & Rowden)

Bowden, F. P. & Brunton, J. H. 1961 *Proc. Roy. Soc.* A, **263**, 433.
Forsyth, P. J. E. 1963 *Acta Metall.* **11**, 70.
Gardner, G. C. 1963/1964 *Proc. Inst. Mech. Eng.* **178**, 593.
Habraken, L. & Coutsouradis, D. 1965 *Cobalt*, **26**, 10.
Normaski, G. & Weill, A. R. 1955 *Revue Métall., Paris*, **52**, 121.

X. Discussion

F. G. Hammitt (University of Michigan)

How do you know that there is *zero* weight loss in the cratering phase? Is this by surface measurement of weight loss? Our examination of cavitation-produced craters with a precision surface measurement seemed to show that the raised ridge did not fully account for the volume of the crater. However, this result is somewhat uncertain since we found that there was some raising of the surface even out to 20 radii, so that a very slight error in surface height measurement would alter our conclusion.

G. P. Thomas

Surface profile measurements suggest that, in the early stages of erosion, there is no weight loss, and this is further supported by the fact that initial surface characteristics, such as polishing marks, can still be identified in the impact area.

A. W. O. Webb (Stone Manganese Marine Ltd.)

Mr Thomas differentiates between alloys with body centred cubic structures and face centred cubic structures in respect to the mode in which they fail under conditions leading to cavitation-erosion, the body centred cubic alloys forming cracks with characteristics rather similar to those of fatigue cracks and the face centred cubic materials forming open depressions. What range of materials has Mr Thomas examined to lead him to the conclusion that the difference lies in the lattice structure of the materials under test and not to differences in some other property such as hardness or proof stress?

G. P. Thomas

As a rough generalization we can say that annealed face centred cubic metals are usually more ductile than those of body centred cubic form. Face centred cubic structures generally rupture by ductile shearing whilst body centred cubic structured are more prone to brittle failure. In the particular examples quoted, we found that this rough classification also held for failure by erosion. This is not to say, however, that by altering the mechanical properties of either structure one could not alter the mode of failure. Whether one gets ductile or brittle behaviour will depend on the structure and on the mechanical properties of the particular alloy.

D. Tabor, F.R.S.

In a later paper (p. 221 below) Dr Brooke Benjamin and Professor Ellis show by a most elegant analysis that cavitation can be immensely effective in producing surface damage. I should therefore like to ask whether this may not be the mechanism responsible for the damage observed with low velocity impacts between solids and drops or jets of liquid. Low velocity impacts would provide adequate time for several compressive and reflected tensile stresses to occur before the liquid had flowed away. This would presumably favour conditions for the formation and collapse of cavities. In this way damage could occur even when the pressures due to the simple hammer blow theory were in themselves too small to produce deformation. In a similar way this might explain Dr Joliffe's observation that mercury gives less damage than expected—because of the high surface energy of mercury it may be more difficult for reflected tensile stresses to produce cavities in it than in, say, water.

G. P. Thomas

We have considered the possibility that cavitation may be responsible for part of the deformation in low velocity liquid impact by a mechanism of the kind suggested by Dr Tabor. There are a number of experimental observations, however, which indicate that cavitation is not the prime cause of deformation in the early stages of erosion. The water hammer experiment, described in the paper, in which compression waves were sent through a liquid which itself was under a positive pressure produced damage identical with the first stages of erosion. In this experiment the liquid was carefully examined for signs of cavitation and none were observed. It was concluded that depressions could be produced in the absence of cavitation and that their appearance was a function of the properties of the solid rather than the liquid.

If the damage at low velocities was due to cavitation one might expect small heavily deformed pits. In metals we get small smooth depressions, and perhaps more important, in non-metals there is no evidence of small pits, depressions, or ring cracks. The fractures which are observed are along the outer boundaries of the impact area. The fracture patterns are simply related to the symmetry of the drop, but not to the symmetry of a collapsing cavity.

A. A. Fyall (R.A.E., Farnborough)

Deformation of metals occur at lower speeds than expected. How important is the effect of centrifugal loading imposed by the apparatus? Erosion is noted at lower threshold velocities than normally measured.

G. P. Thomas

We have not taken into account effects due to centrifugal loading. There must be some effect of course, but this is not apparent from the distribution of the damage. The amount of deformation in the direction of stressing is the same as that in other directions. The lower threshold velocities are probably due to methods of measuring damage. We consider erosion damage occurs with the first detectable signs of plastic deformation of the surface. At this stage, weight loss measurements would not indicate damage.

G. Rowden

Could Mr Thomas give some indication as to the number of impacts for a given impact velocity, at which the various stages in the development of damage, as noted in his paper, appear? Are the number of impacts required to produce a given amount of damage the same for different crystal systems?

G. P. Thomas

The stage of development of the deformation for a given number of impacts varies considerably of course with the impact velocity, the specimen and its original condition. In the copper specimens referred to, which were of hardness V.h.n. 65, eroded at a velocity of 50 m/s, the depressions were apparent after as few as 10^3 impacts, slip lines and grain boundaries being observed after about 10^4 impacts. Large pits began to develop after 5×10^4 impacts and material was removed after about 5×10^5 impacts. There seems little significant difference for different systems, at these low velocities, in the number of impacts required to produce a given amount of damage, provided all other factors are equal, although this needs fuller investigation.

A. Smith

Were the tests referred to by Mr Thomas carried out under atmospheric conditions or under vacuum?

G. P. Thomas

The experiments mentioned were carried out at atmospheric pressure. Experiments at reduced ambient pressures have been carried out, Hancox (1962, Ph.D. Thesis, Cambridge), and these suggested that the rate of erosion was not markedly altered between atmospheric pressure and a pressure of 2·5 cmHg.

J. H. Brunton

I think it is very interesting that intrusions are observed under repeated impact. It seems to suggest that the initial stages of deformation are in some ways similar to the initial stages of fatigue failure. Did Dr Marriott observe corresponding extrusions?—or possibly find evidence of the removal of extrusions by liquid flow?

The second question I have is, did Dr Marriott carry out erosion at very low impact velocities where general yielding would not occur? If so, did he find that deformation first occurred locally, producing small depressions in the manner outlined in Mr Thomas's paper?

J. B. Marriott and G. Rowden

In answer to Dr Brunton's first question, extrusions have not been seen and it is probable that they would be removed by the rapid outflow of water on impact. It has been observed that the intrusions become more readily detectable and apparently broader as testing proceeds; the tearing action of the water may partly account for this.

Regarding the second question, testing has been carried out at velocities down to 600 ft./s which imposes a stress of $17\frac{1}{2}$ tons/in.^{2}. Small depressions have been seen in specimens tested at 1400 and 1030 ft./s by the Nomarski technique of optical examination. These depressions are observed during the development of the slip pattern and are generally adjacent to a carbide; a typical depression can be seen above the larger carbide located near the centre of figure 7 (*c*) of our paper. In the test to 600 ft./s a fine slip pattern evolved but the test was discontinued before any depressions were observed.

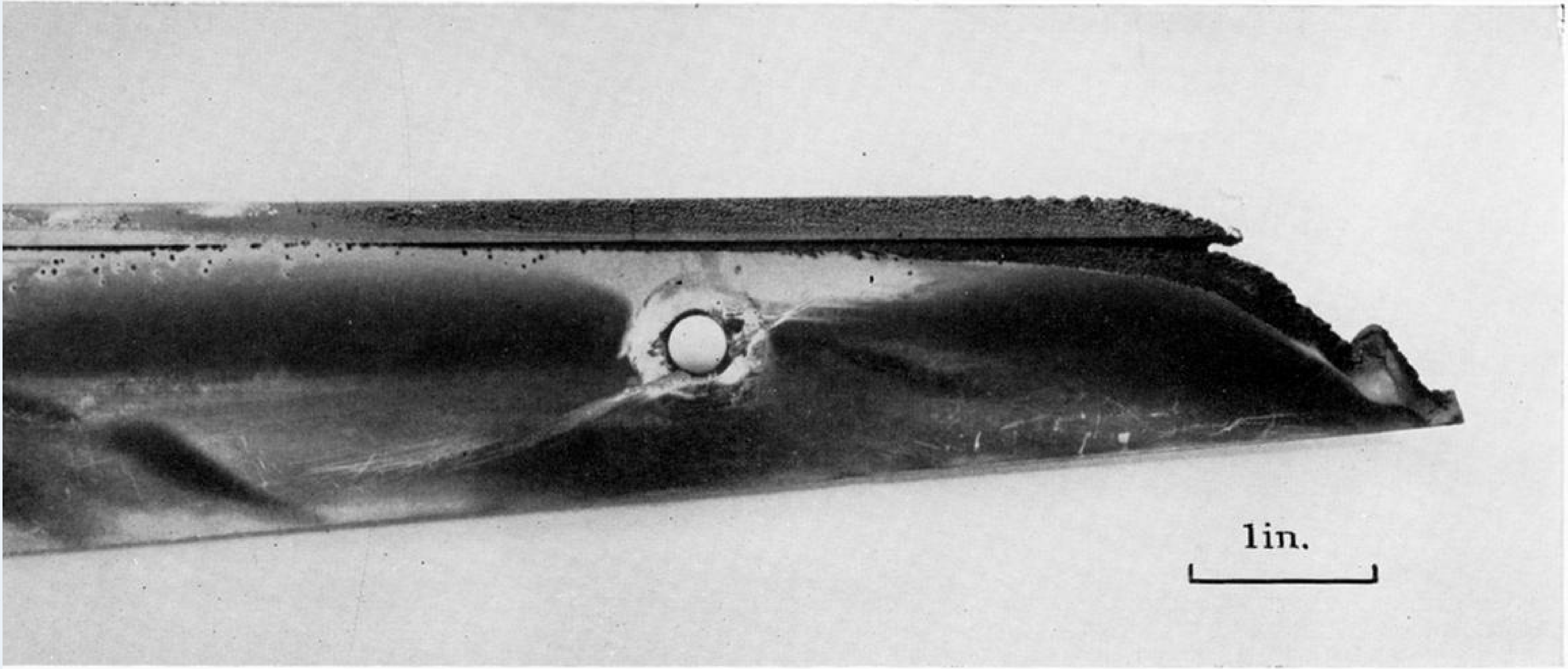
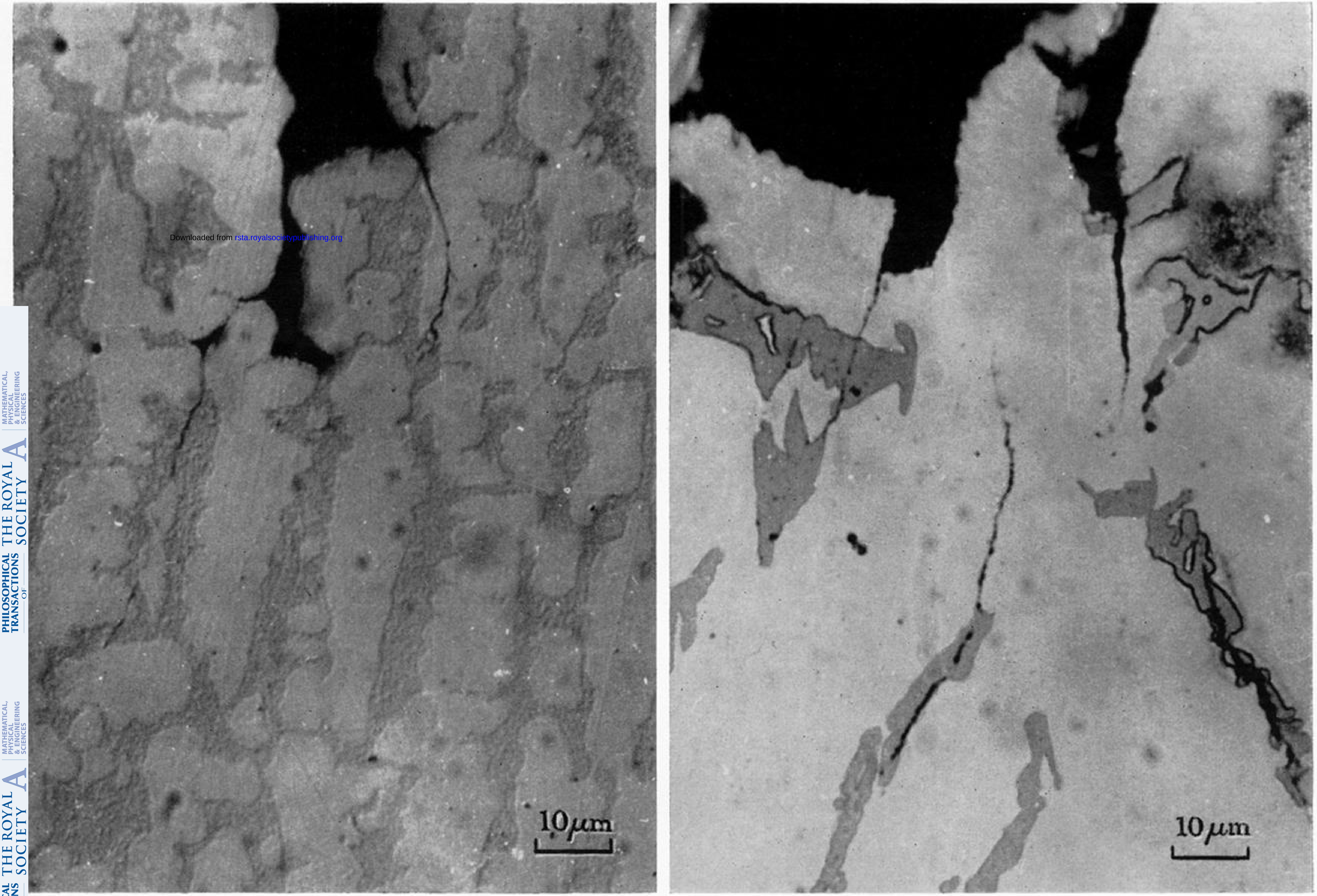


FIGURE 1. Stellite shielded low pressure blade after 30250 h service.



(*a*) (*b*)

FIGURE 2. (*a*) Cracking associated with erosion pit in cast Stellite 6 erosion shield. (*b*) Cracking associated with erosion pit in cast Stellite 6 erosion test specimen.

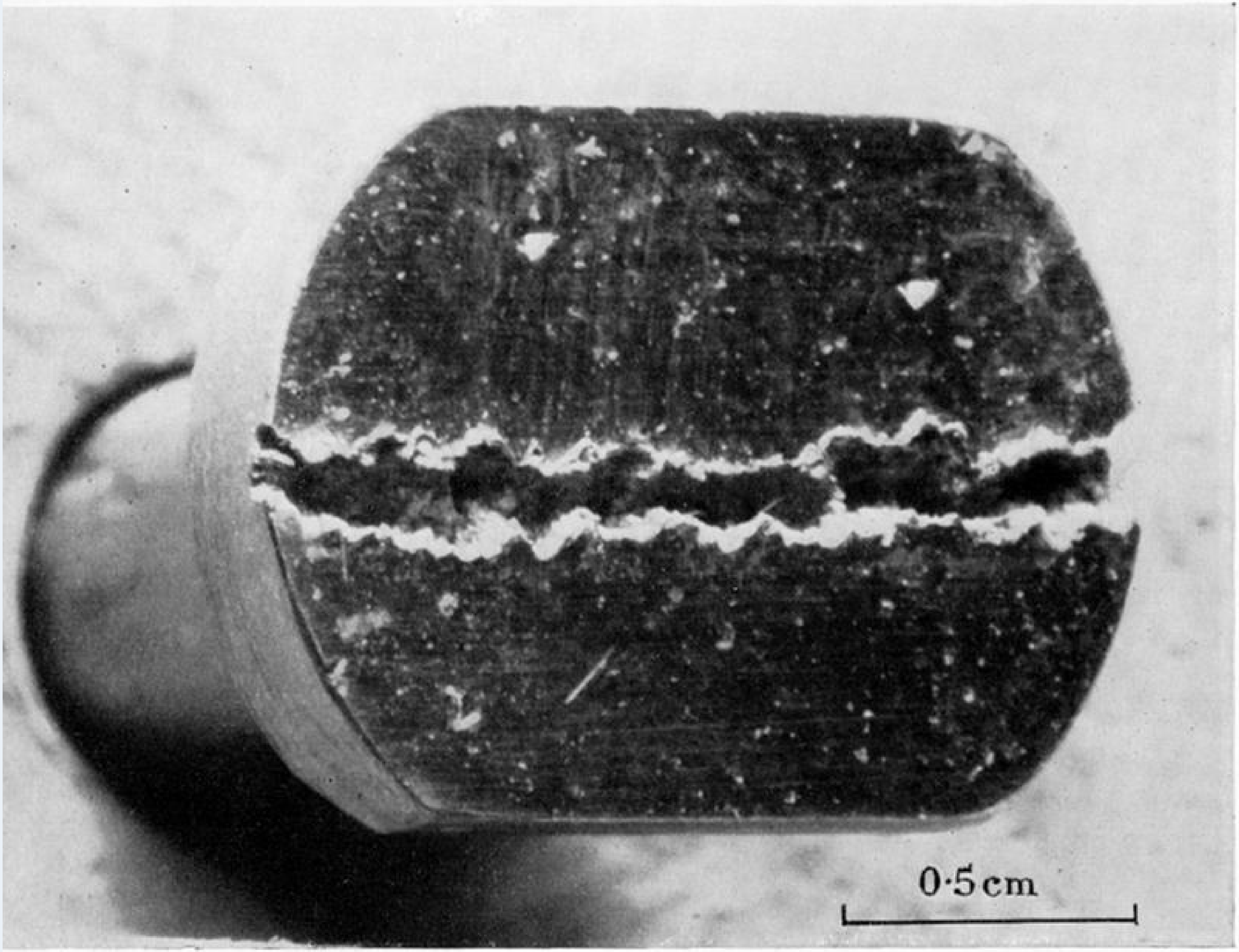


Figure 5. Specimen after erosion testing.

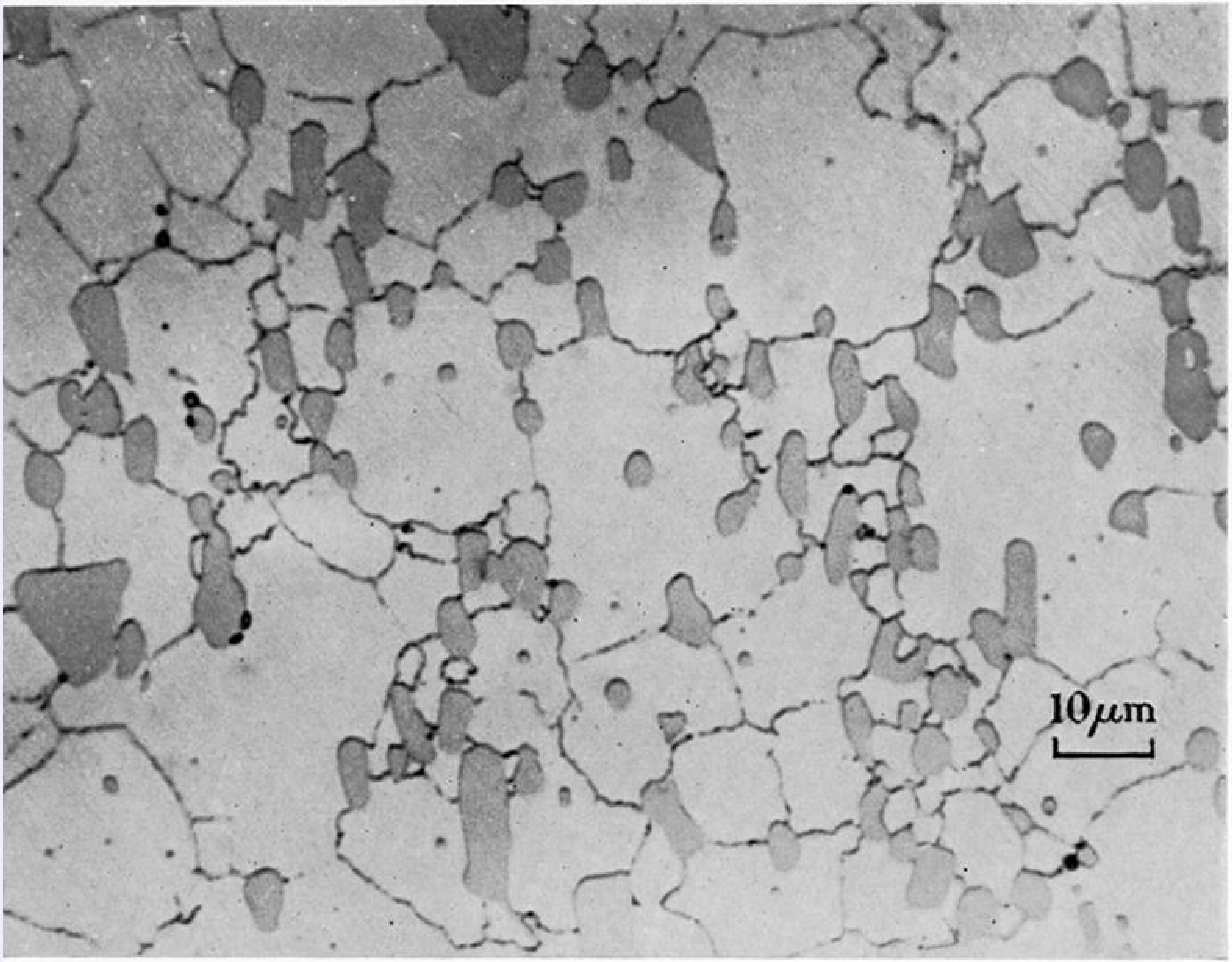


FIGURE 6. Typical structure Haynes alloy 6B (etched).

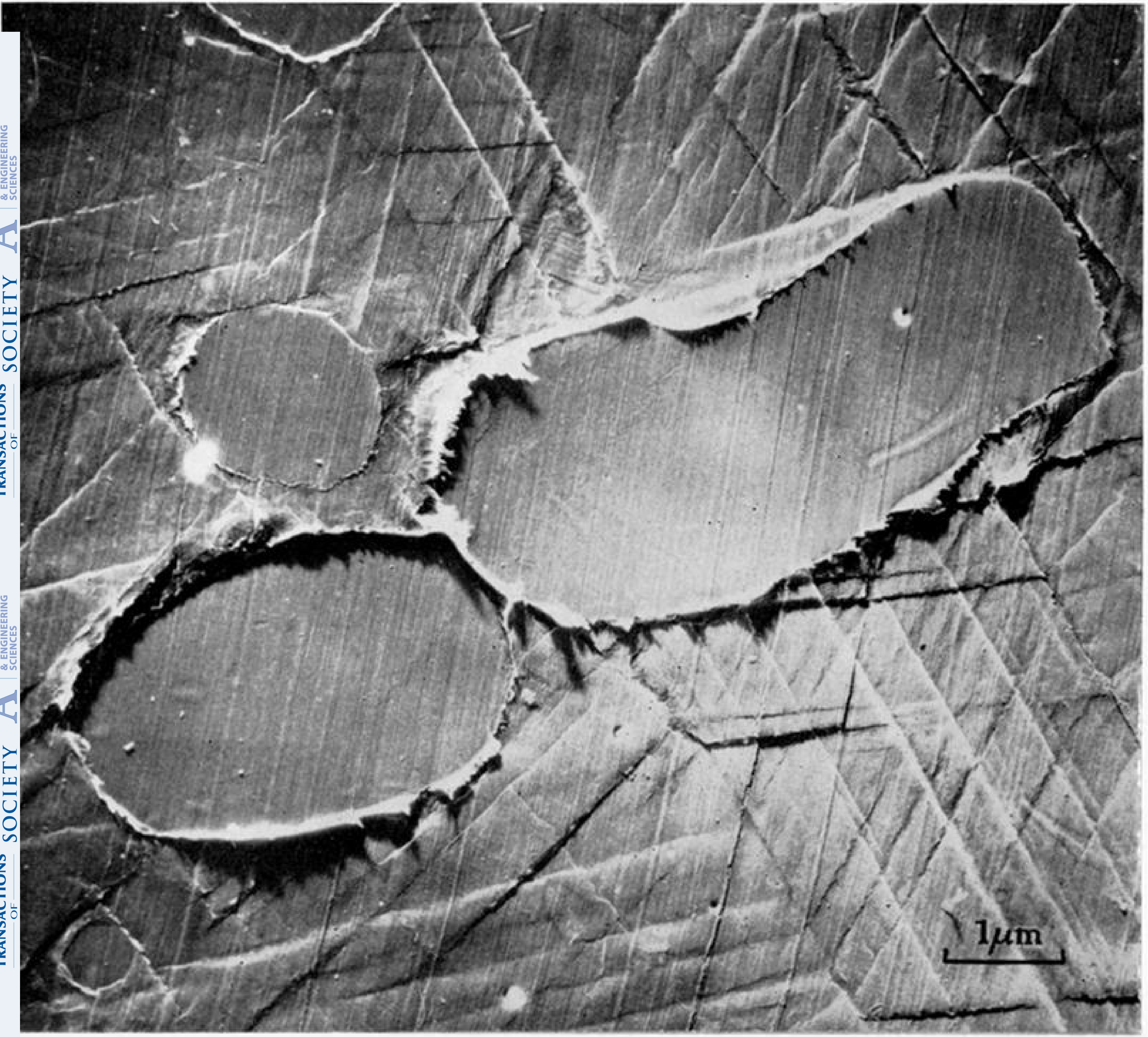


FIGURE 8. Cracking at carbide/matrix interfaces.

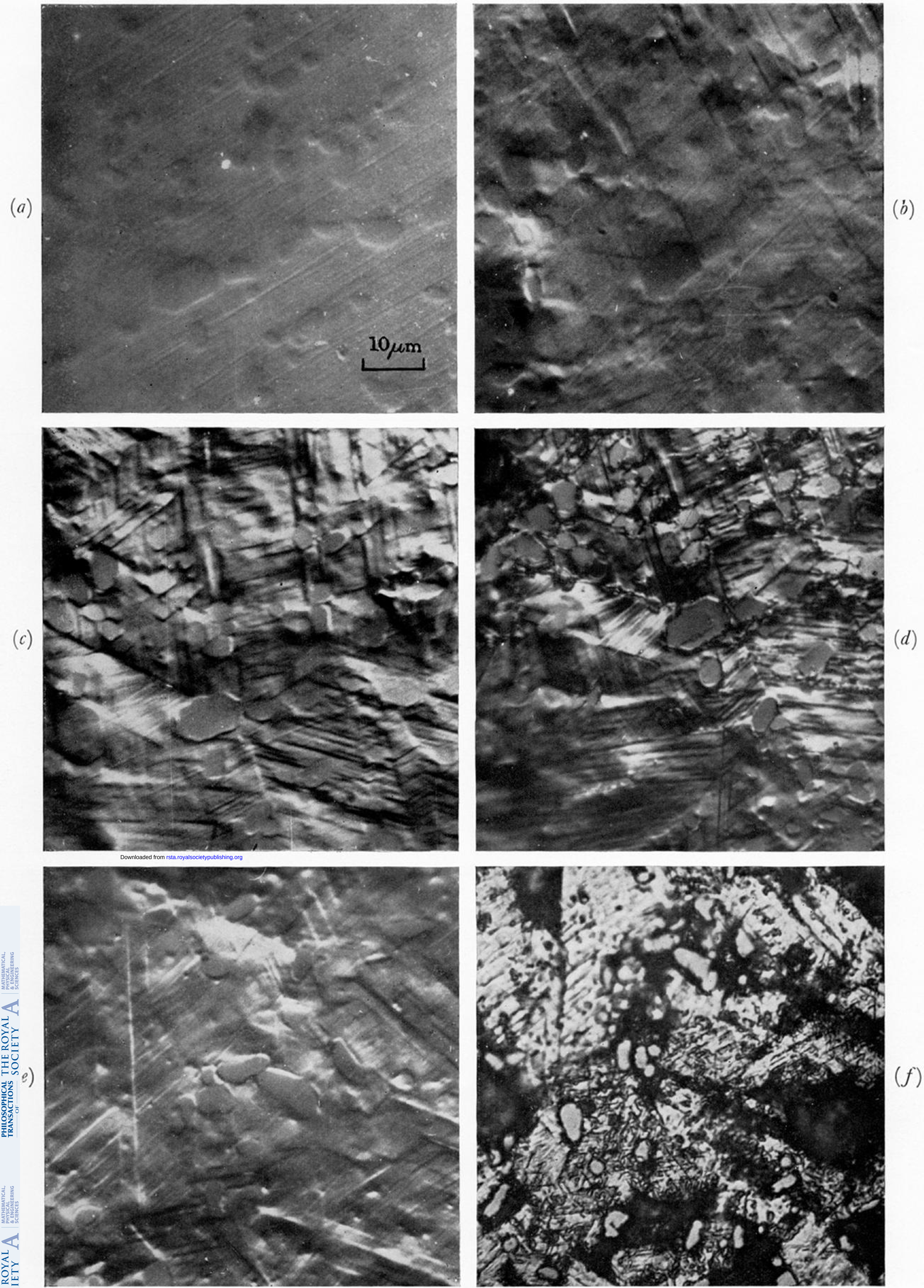


FIGURE 7. Development of erosion damage on surface of Haynes 6B specimen tested at a velocity of 1030 ft./s.

(*a*) 0 impacts (field 1)	(*d*) 90000 impacts (field 1)
(*b*) 3000 impacts (field 1)	(*e*) 3000 impacts (field 2)
(*c*) 40000 impacts (field 1)	(*f*) 90000 impacts (field 2)

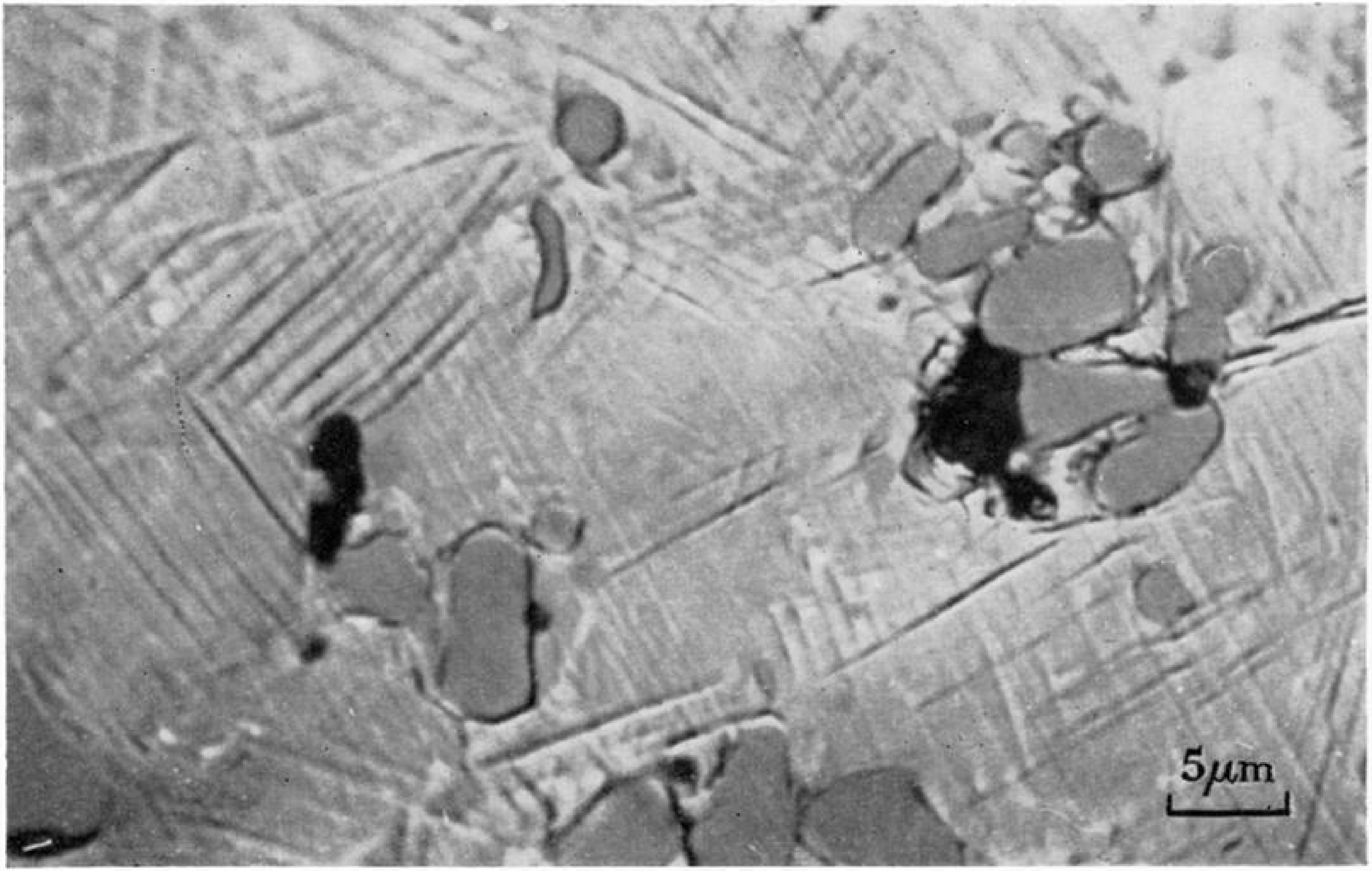
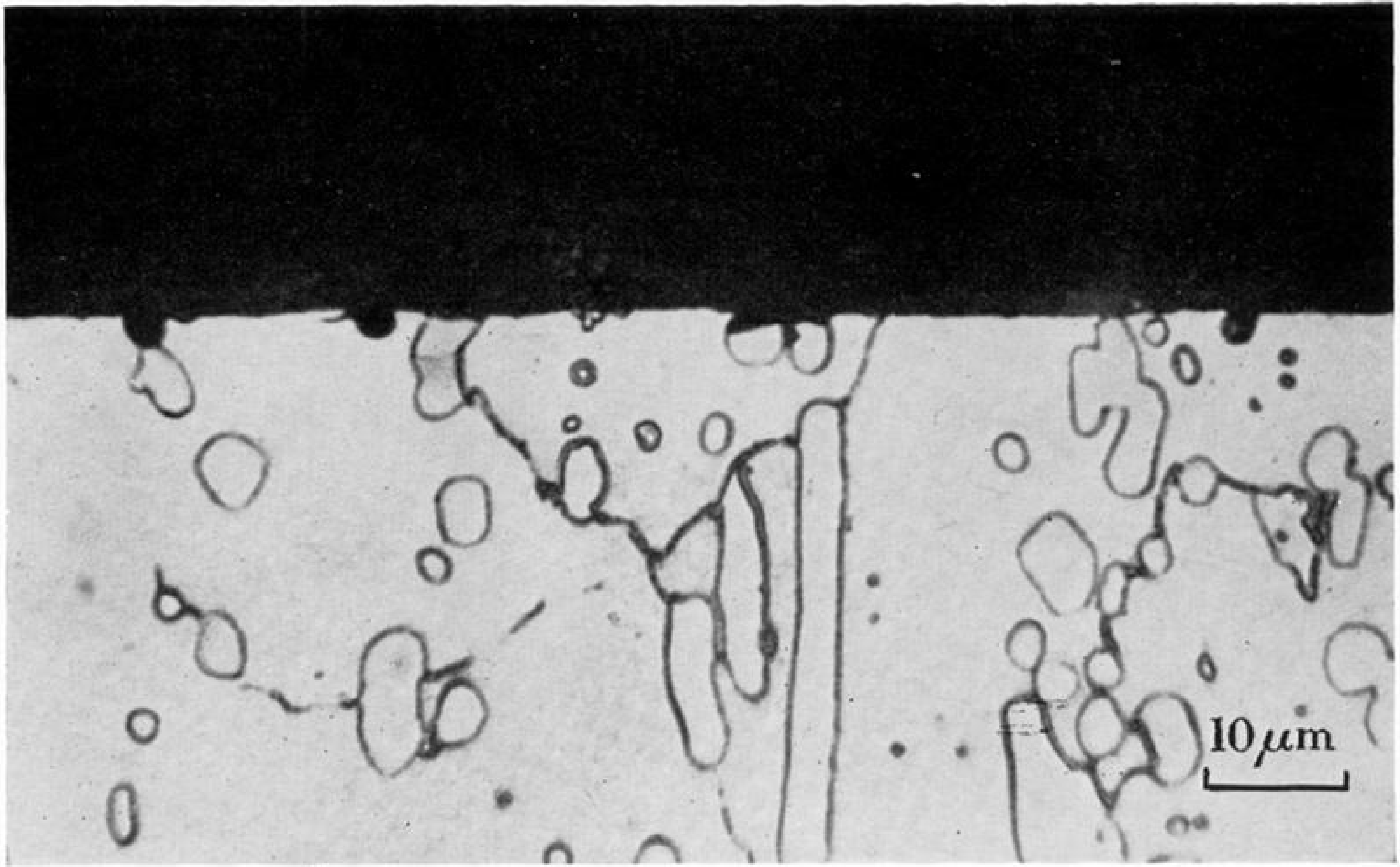


FIGURE 9. Cavities left by loss of carbide particles at specimen surface.



IGURE 10. Section through eroded surface showing cavities left by carbide particle loss (etched).

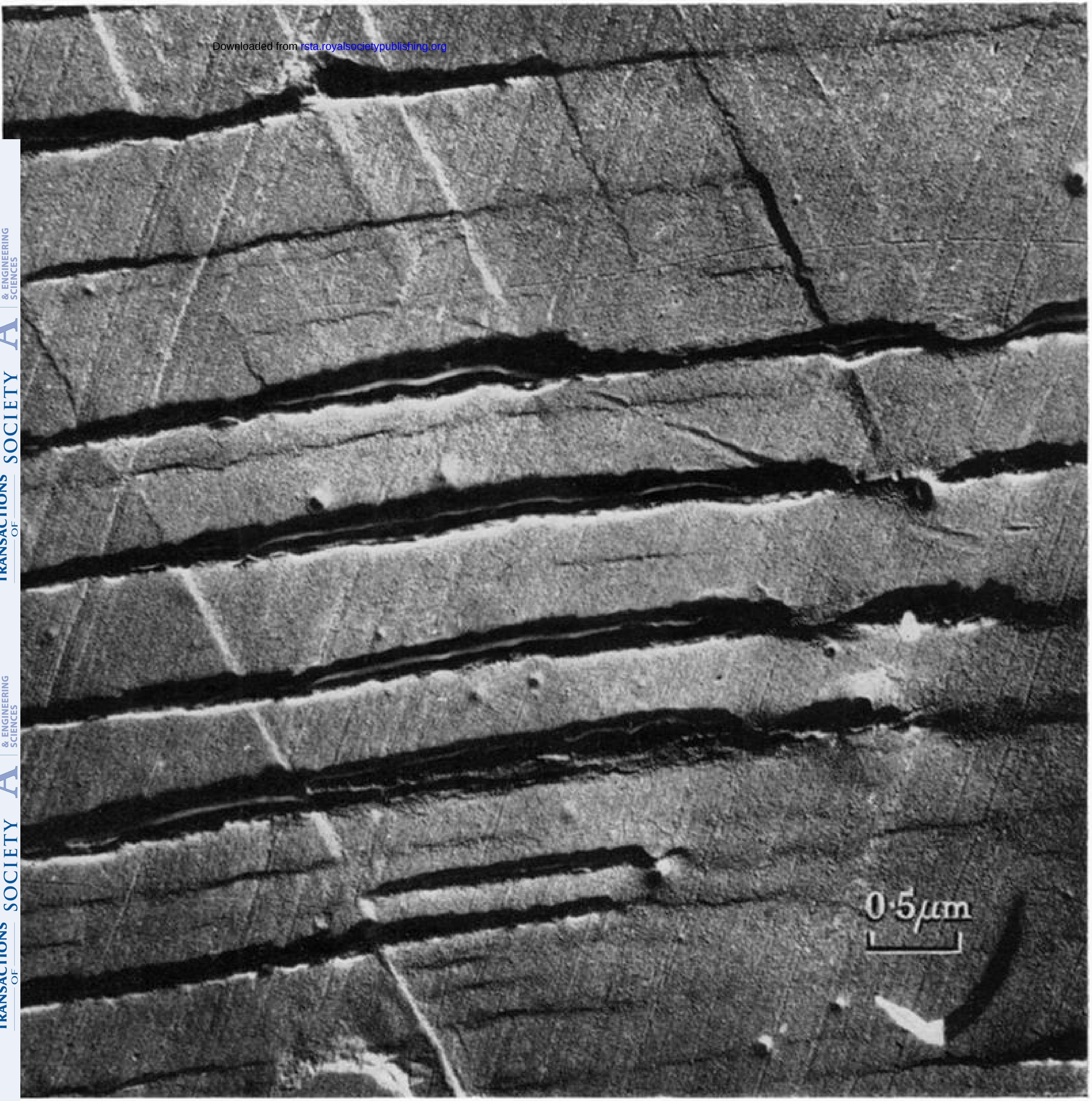


FIGURE 11. Intrusion formation at slip lines.