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EVALUATION OF FAILED SUCTION-ROLL HEAD FROM THE DRIVE END OF THE NO. 3 PRESS OF THE NO. 5 PAPER MACHINE AT PORT ALBERNI, B. C.

by

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PHYSICAL METALLURGY DIVISION

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SUMMARY OF RESULTS

Non-destructive tests and microexamination of fracture surfaces and sections at Dominion Engineering Works, plus examination of specimens at the Physical Metallurgy Division, lead to the conclusion that the suction-roll head failed by fatigue. The failure started in and near the reentrant angle between the spigot and the flange. High stress concentration due to an inadequate fillet, a corrosive medium and the presence of heat-affected zones incidental to the weld repair of the spigot adversely affected the service life of the head.

The head was made of an AISI 1030 steel forging of satisfactory quality and properly oriented flow lines.

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INTRODUCTION

On November 18, 1964, a letter was received from Mr. E.N. Walton, Manager, Central Engineering, MacMillan, Bloedel and Powell River Limited, requesting that the Physical Metallurgy Division arrange to observe the metallurgical investigation of a fractured suction-roll head at Dominion Engineering Works Limited and to submit an independent report concerning the failure of this roll head from the drive end of the No. 3 press of the No. 5 paper machine at Port Alberni, B.C. Accordingly, the auther visited the Lachine, P.Q. plant of Dominion Engineering Works (D.E.W.) on November 25th and 30th and then reported to MacMillan, Bloedel and Powell River Limited (M.B. and P.R.) by letters dated November 27th and December 2nd, as well as by Internal Report PM-V-64-27 dated December 7th.

The present report includes the results of an examination of a portion of the roll head at the Physical Metallurgy Division and benefits from receipt of more information from M.B. and P.R. However, the findings expressed in this report are in substantial agreement with the preliminary findings.

It must be emphasized that this report deals essentially with the metallurgical aspects of the failure. Other factors are involved, as indicated in the brief description of the function of the roll head and its service history which follows. These set the metallurgical aspects in perspective.

The No. 5 Paper Machine and the No. 3 Suction-Roll Head

The No. 5 paper machine is a 324-inch newsprint machine custom-built by D.E.W. for M.B. and P.R. for installation at Port Alberni, B.C. It is understood that it is one of the two largest paper machines in the world. It was designed to produce paper at rates up to 3000 feet per minute. The machine is the largest ever built by D.E.W. and although it is similar to some smaller machines made by D.E.W. it was individually engineered.

After leaving the Fourdrinier the wet paper, supported on cloth, is conveyed through the No. 1 and No. 2 suction-press roll sections. The self-supporting paper is then conveyed through the No. 3 suction-press section at pressures of 350 to 360 pounds per lineal inch. The No. 3 suction-roll shell is made of stainless steel and is 330 inches long with an inside diameter of 40 inches. The shell heads are designed with a spigot which fits into the shell and a flange which is studded to the shell.

Figure 1 (from M.B. and P.R.) indicates the shape and dimensions of the spigot and flange. It also shows the studding arrangement. It is understood that D.E.W. specifies that the reentrant angle between the spigot and the flange have a 6/32-inch radius.

The author was informed verbally that the roll heads were made of forged 1040 steel by a sub-contractor. It was understood that rolls for previous smaller machines had been cast of lower carbon steel.

Service History of the No. 3 Suction-Roll Heads

September 1963 to December 1963 (3 months):

Roll #845, the original roll, was operated until about 25 studs were found to be broken in the front (undriven) head. Records from M.B. and P.R. do not mention any trouble with the rear (driven) head during this period.

The spigot-to-shell fits were then checked and it was decided that adequate interference fits had not been achieved, despite preassembly at Lachine. The actual measurements were not obtainable. Consequently, a spare roll was installed and Roll #845 was sent to Burrard Drydock where the spigot of the front and of the rear head were machined-down and then built-up to achieve a nominal 0.014-inch diametral interference fit with the roll shell.

A record of the instructions given to Burrard Drydock by D.E.W. was not obtainable.

September 2, 1964:

After about three months of accumulated operation the spare roll failed. Details were not provided. Roll #845 was returned to service.

October 8, 1964:

Roll #845 was removed from service, completely restudded and returned to service. This was the institution of a 45-day restudding program of preventive maintenance. The 45-day cycle was based on the fact that each of the two previous roll failures (occassioned by failure of studs) had occurred after 90 days of operation. No cracking of the rear head, itself, was reported at the time of the October 8th restudding.

The studs installed on October 8th had rolled threads, a reduced waist and other features which made them superior to those originally installed. However, failure of these studs, on the drive end, showed the following alarming pattern:

October 16	-	#13 stud loose	- tightened
18	-	#14 stud loose	- tightened
29	-	#22 stud broken	- replaced
	-	#13 stud loose	- replaced
	-	(# 14 stud replaced as a precaution)	
November 2	-	#12 stud broken	- replaced
	-	#13 stud broken	- replaced
	-	#14 stud stripped threads in shell	
	-	(#11 and #15 studs replaced as a precaution	
4	-	#13 stud broken and roll head cracked - roll removed from service.	

There were no broken studs in the front end of roll #845 following October 8th.

EXAMINATION AT DOMINION ENGINEERING WORKS

Fracture Surfaces

At D.E.W. Dy-Chek and Magnaflux techniques were used to locate a tight crack along the 90-degree reentrant angle, between the spigot and the flange, for a distance of 61 inches between stud holes No. 8 and No. 28. The crack was at, or very close to, the apparently unfilleted reentrant angle. The Dy-Chek indication was discontinuous near the ends of this cracked region indicating that the crack was either discontinuous or extremely tight near the ends.

The Dy-Chek penetrated completely through the section, a distance of about 1.75 inches. The crack which was observed on the exterior root between the flange and the main body of the head was not as tight as the crack along the reentrant angle. The root crack was also shorter extending for 36 inches between stud positions No. 14 and No. 22. There was some evidence of multiple cracking along the root crack and near stud position No. 17 a fragment between cracks was missing.

Although the Dy-Chek penetrated completely through the section, the angle of dip of the observed cracks suggested that two independent cracks, as suggested on Figure 1 were involved in the failure.

The spigot and flange portion, containing the detected crack or cracks was severed from the main body of the head by torch cutting.

Figure 2 (from D.E.W.) shows a transverse cross-section of the severed part. This cross-section, through stud position No. 27-3/4, has been etched in nital to reveal macroscopic details of the weld repair on the spigot and to reveal the internal soundness of the forging in this region. The crack extends from the reentrant angle to a depth of about 3/8 inch. The etch showed that the weld passes were laid in sequence from the end of the spigot toward the reentrant angle; the reentrant angle lies in a region affected by heat during welding and the forging is internally sound. Deeper etching of similar sections revealed that the forging flow lines were favourably oriented at almost 90 degrees to the direction of propagation of the reentrant angle cracks. The forging flow lines were unfavourably oriented with respect to the secondary crack or crack length which was open on the exterior root.

Figures 3a and 3b (from D.E.W.) show the exposed fracture surface between studs No. 13 and No. 24. The whole of the fracture surfaces were coated with a dark adherent coating of corrosion product and possibly residue from black liquor. Nevertheless, it was obvious that failure had initiated at several points along the 90-degree reentrant angle between the spigot and the flange. Characteristic "beach" markings on the fracture surface showed that multiple fatigue fracture had initiated midway between "anchoring" studs. Unfortunately, the photographs do not show these markings clearly. Visual inspection of the surfaces showed a series of convex scallops pinned to the surface at each stud position. Figure 3a shows one of these scallops or "clamshells" on the left end between studs No. 13 and No. 14. As these fatigue cracks progressed they inevitably overlapped and merged together. The ridges or hackle marks, especially evident close to each stud hole in Figure 3a, are traces left where individual cracks, in slightly different planes, abruptly joined together. The separate fatigue cracks apparently grew and merged into one large crack which progressed, between studs No. 13 and No. 24, to within 1/4 inch of the exterior root of the flange and the main body of the head. This large primary crack is shown exposed in Figure 3a.

The nature of the crack surface shown in Figure 3b is not unequivocably understood, except that it was not a primary cause of failure and its existence depends on the primary fatigue crack. It is either a continuation of the primary fatigue crack, in which case a change of direction was determined by changes of the pattern of stress distribution which brought the crack into alignment with forging flow lines, or it is a separate secondary crack which propagated from the exterior. (Refer to Figure 1).

The important information read from the fracture markings is that the failure initiated at many points in or very near the reentrant angle between the spigot and the flange.

Fillet of the Reentrant Angle

The reentrant angle between the spigot and the flange did not have a readily noticeable fillet, at least in relation to the generally poor surface finish. Lathe marks were clearly evident on the spigot and the flange indicating that the surfaces had been "as-machined" when the head was installed.

Corrosion

The spigot and flange surfaces were corroded. However, visual examination of the surfaces did not reveal any characteristic corrosion-fatigue cracks or fissures in the surfaces.

EXAMINATION AT PHYSICAL METALLURGY DIVISION

Specimen

A half-inch cross-sectional slice of the fracture region was removed by sawing with one side passing through stud hole No. 17. This section and the location of specimens removed for microscopic examination are shown in Figure 4. It is understood that the microstructure of an adjacent slice was studied at D.E.W.

Chemical Composition

Chemical analysis of drillings, the location of which is shown in Figure 4, gave the following results in weight percent:

C	Mn	Si	S	P
0.32	0.73	0.215	0.009	0.009

Spectrographic analysis of the weld overlay gave the following semi-quantitative results:

Si	Mn	Mg	Cr	Al	V
0.82	1.23	0.007	0.06	0.004	0.02

Mo	Cu	Ti	Ni	Co
0.05	0.13	0.005	0.08	0.006

It is evident that the main body of the head was not made of AISI 1040 steel. Rather, its composition conforms closely to AISI 1030 steel. The weld metal appears to rely on silicon and manganese to develop adequate tensile strength at a low carbon level.

Macrostructure

Figure 4 shows the forging flow lines as they are related to the reentrant angle. The main i.e. the primary part of the fracture transversed the flow lines almost at right angles. The small final or secondary part of the fracture occurred in a plane of the forging flow lines. (The planes of the flow lines represent planes of weakness relative to other planes in the forging, just as grain in wood represents planes of weakness and low resistance to initiation and propagation of fracture.)

There was virtually no visual evidence of plastic deformation along the fracture surfaces.

The specimens removed for microscopic examination are shown in Figure 5. The specimens have been mounted in bakelite and polished and etched for microscopical examination. On macroscopic examination this etching shows the extent of the weld deposits and the extent of the attendant heat-affected zones.

Specimens #1 and #2 of Figure 5 show the sharpness of the reentrant angle. They also show that the metal in the vicinity of the reentrant angle has been structurally altered by the welding procedure. Specimen #3 shows a heat-affected area on the flange surface beyond the reentrant angle.

Microstructure

Relevant microstructures, adjacent to the path of the fracture culminating in failure, are shown in Figures 6, 7, 8 and 9.

Figures 6, 7 and 8 show that the failure started in microstructures produced as a result of heating incidental to the weld repair of the spigot. Also, the fillet in the reentrant angle is shown to have a nominal radius of only 1/32 inch. The failure initiated on the flange side of the fillet (Figures 6 and 7) and in the fillet on the flange side (Figure 8). Two incipient primary cracks are also shown in the centre of the fillet of Figure 7.

In Figure 6 the main fracture and in Figure 7 the two incipient fractures originated in parent metal (as opposed to weld metal) which had been heated effectively to just above the upper critical transformation temperature, which for 1032 steel is about 1485°F. The structure at this temperature was fine-grained austenite which on cooling transformed to acicular and to grain-boundary ferrite and tc other transformation products such as bainites and fine pearlite. No martensite was observed in this fine-grained region. Untempered martensite was observed in the coarse-grained region immediately adjacent to the weld deposit.

In Figures 7 and 8 the primary fracture originated in parent metal which had been heated effectively to temperatures between the lower and upper critical transformation temperatures, which for 1032 steel is between about 1350 and 1485°F. In this temperature range the structure consists of ferrite and austenite; or, ferrite, spheroidized pearlite and austenite. The austenite within the critical transformation range has a higher than nominal carbon content. The fracture surfaces were too corroded, both generally and by pitting, to allow a determination of whether the path of the fracture had progressed primarily through or around the grains of ferrite and pearlite. It was observed that the path of each incipient crack, shown in Figure 7, was predominately intercrystalline. This is a characteristic of stress corrosion or corrosion fatigue. The width of the incipient cracks, at the fillet surface, is also suggestive of mild corrosion fatigue. However, Figure 9 shows that in its terminal region the primary crack is predominately transcrystalline. This is a characteristic of fatigue cracks.

Figure 9 shows that the secondary crack in the crack observed on the exterior junction of the flange and the main body of the head does not extend past the primary fracture in the fracture observed in the reentrant angle. Indeed the terminal end of the primary crack veered 90 degrees suggesting that the secondary crack is merely an extension of the primary crack. Contrary to this observation the "lap" on the secondary fracture shown in Figure 9 appears to have been formed by a crack progressing toward the primary fracture. The main portion of the section through the secondary fracture, not shown in Figure 9, was plastically deformed to a depth of several grains measured in from the fracture surface; also, this portion of the secondary fracture surface was corroded and pitted. The extent of the plastic deformation and of the corrosion did not indicate conclusively which way the secondary crack had progressed.

DISCUSSION OF RESULTS

Metallurgical examination of the failed head has shown four factors which may have contributed towards premature failure. These are the sharpness of the reentrant angle, the presence of a corrosive medium, the presence of heat-affected zones in and near the reentrant angle and the composition of the steel.

Of the above factors, the sharpness of the reentrant fillet (1/32 inch, nominal) is probably most deleterious. This is because stresses concentrate or intensify significantly in the immediate vicinity of such fillets. The observed fact that cracks initiated at so many separate points along the circumference of the reentrant angle between the spigot and the flange is a strong indication that the stresses in this region were abnormally high. The additional observed fact that the crack progressed almost through the head along a slowly advancing fatigue front indicates that the stresses which propagated the fatigue cracks were not relatively high. Together, these facts show the importance of an adequate fillet in the reentrant angle.

There was some indication that corrosion fatigue was a contributing factor in the initiation of cracks in the reentrant angle and even in the early stage of their propagation. The presence of very few incipient cracks in the reentrant fillet suggests that corrosion fatigue was not a necessary factor in the failure. In the final stages there was microstructural evidence that the primary fracture was predominately transgranular and therefore was propagating as a fatigue crack. Under the circumstances it is considered that corrosion fatigue, general corrosion and pitting corrosion were contributing factors of relatively minor importance in this particular failure.

Many of the heat-affected zones adjacent to the weld deposit are generally recognized to have inferior notch sensitivity in fatigue and inferior impact strength. In this particular case the structures formed by cooling of a partially austenitized structure are particularly suspect. It is probable that these structures have inferior notch sensitivity in fatigue. Certainly they have inferior tensile and impact toughness.

It was evident that the head had not been stress relieved after weld repair. This means that the heat-affected zone of the parent metal was left with residual tensile stresses due to thermal upsetting during heating and subsequent contraction during cooling. It is possible that such tensile stresses would lower resistance to any crack-inducing situation.

Chemical analysis showed that the head was made of 1030 rather than 1040 steel. The unnotched fatigue limit of 1030 in this component would be about 10 per cent less than that of 1040 steel.

The forging was of reasonable quality considering its size and short production run. The flow lines in the forging were favourably oriented, being at 90 degrees to the plane of the primary crack. This used the anisotropic properties of the forging to best advantage in resisting the initiation and propagation of the primary crack.

CONCLUSIONS

1. The head failed by means of a fatigue mechanism. Stress concentration and a corrosive environment were contributary factors in the initiation and propagation, at least in the early stages, of the primary fracture.

2. The reentrant angle between the spigot and the flange had a nominal radius of only 1/32 inch.

3. The fatigue cracks which led to failure initiated in heat-affected zones in and near the reentrant angle. These heat-affected zones were produced when the spigot was resurfaced.

4. The failed heat was made of 1030 steel rather than 1040 steel.

5. The forging was of good quality. In particular, the flow lines were well oriented in the region of the reentrant angle.

ACKNOWLEDGEMENTS

At D.E.W. Messrs R. Thompson, P.H.B. Hamilton, R. W. Dunton and R. Vadas were cooperative not only in furthering the examination, but also in providing background material and photo macrographs

Messrs E.N. Walton and W.A. Burton of M.B. and P.R. provided essential background material and records of service history.

Metallography at P.M.D. was done by Mr. G.D. Ayers.

DKF:ac

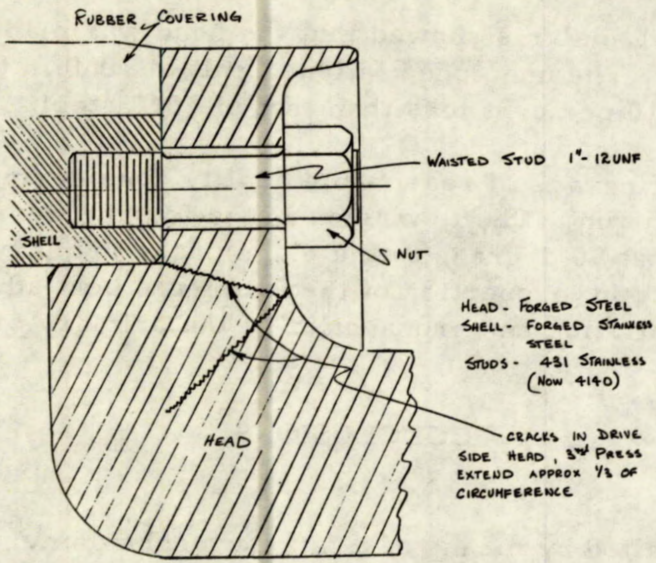


Figure 1. Cross-Section of the Head: Shell Joint (courtesy of M.B. and P.R.).
Note: A blind crack, as indicated on the drawing, was not found to exist.

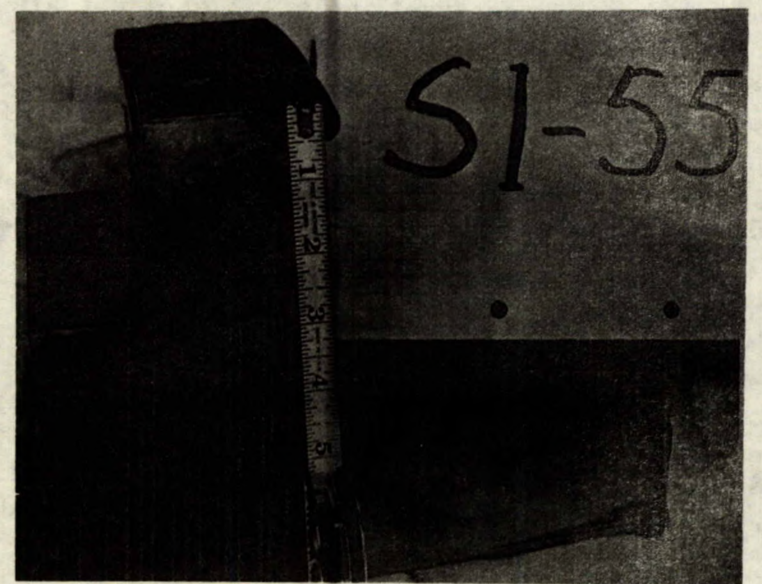
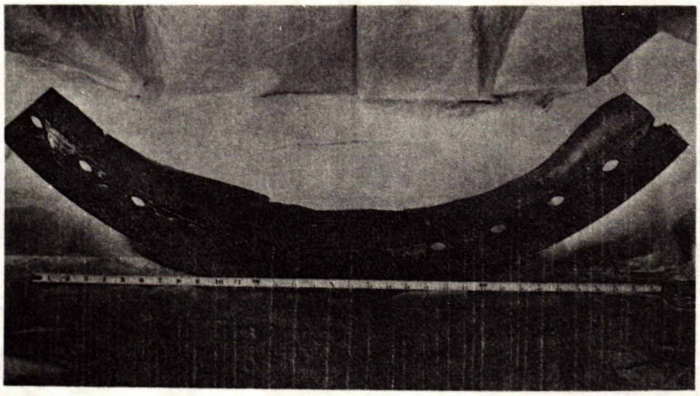
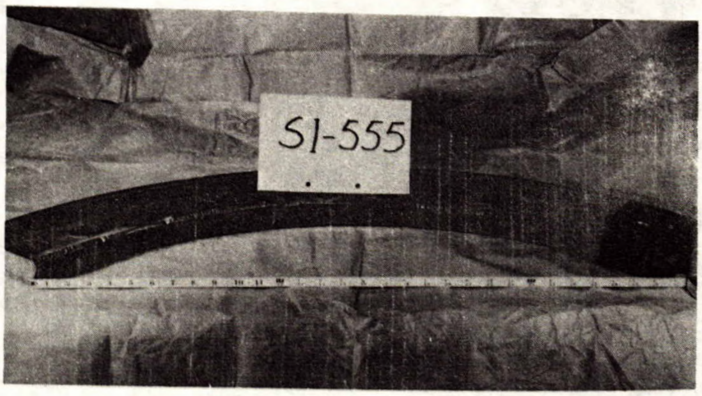


Figure 2. Transverse Cross-Section at Stud Position No. 27-3/4, Through the Spigot and Flange of the Failed Head. Etched in nital. (Courtesy of D.E.W.)



(a)



(b)

Figure 3. Exposed Fracture Surfaces Between Stud No. 13 (on the left) and Stud No. 24 (on the right). Cleaned in alcohol. (Courtesy of D. E. W.)

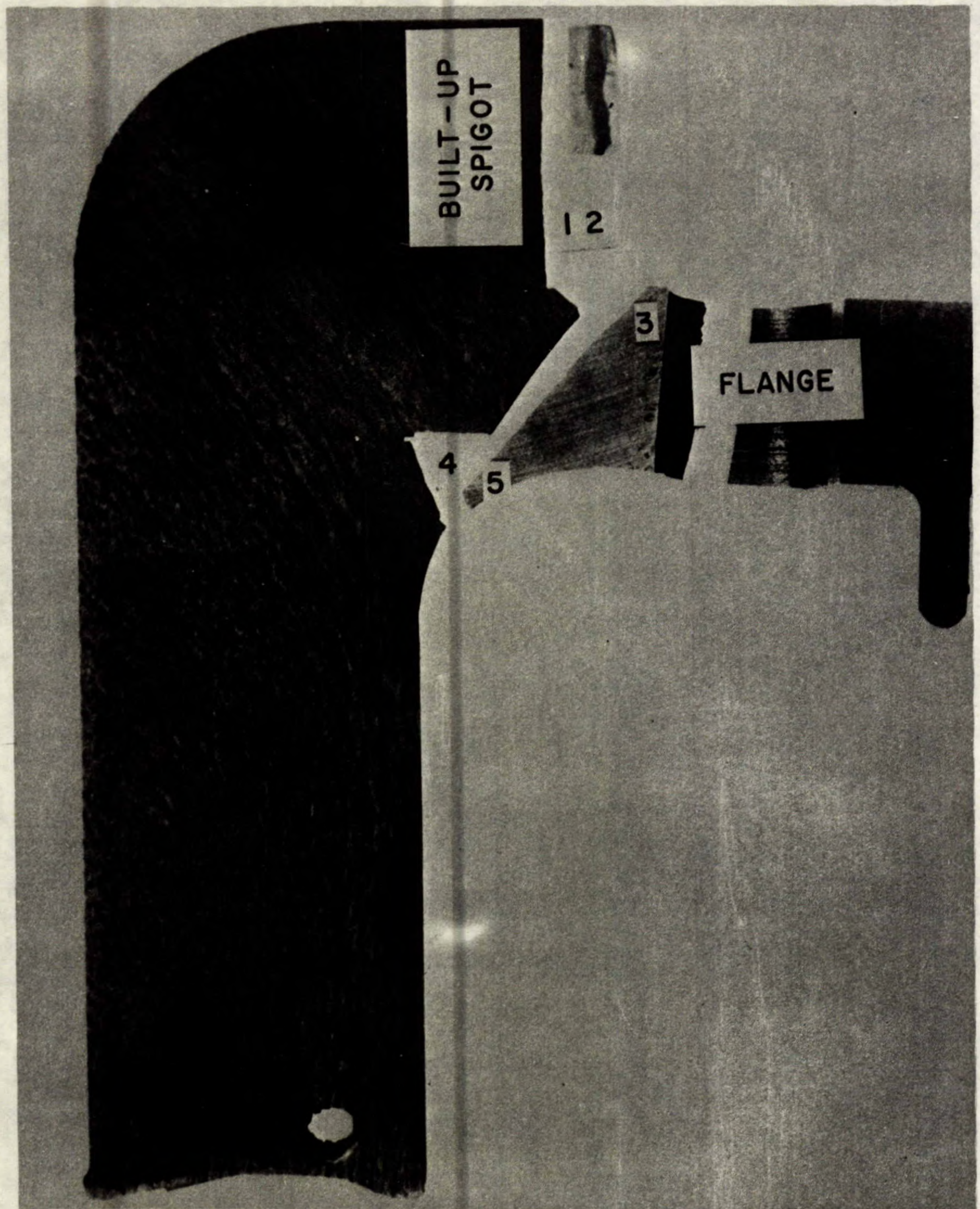


Figure 4. Section Through Spigot and Flange, Passing Through Stud Hole in No. 17, Which Was Examined at the P.M.D. Deep etched.

The locations of five specimens removed for microscopical examination are indicated. Etching in 1:1 HCl and water at 160-180°F has revealed the forging flow lines.

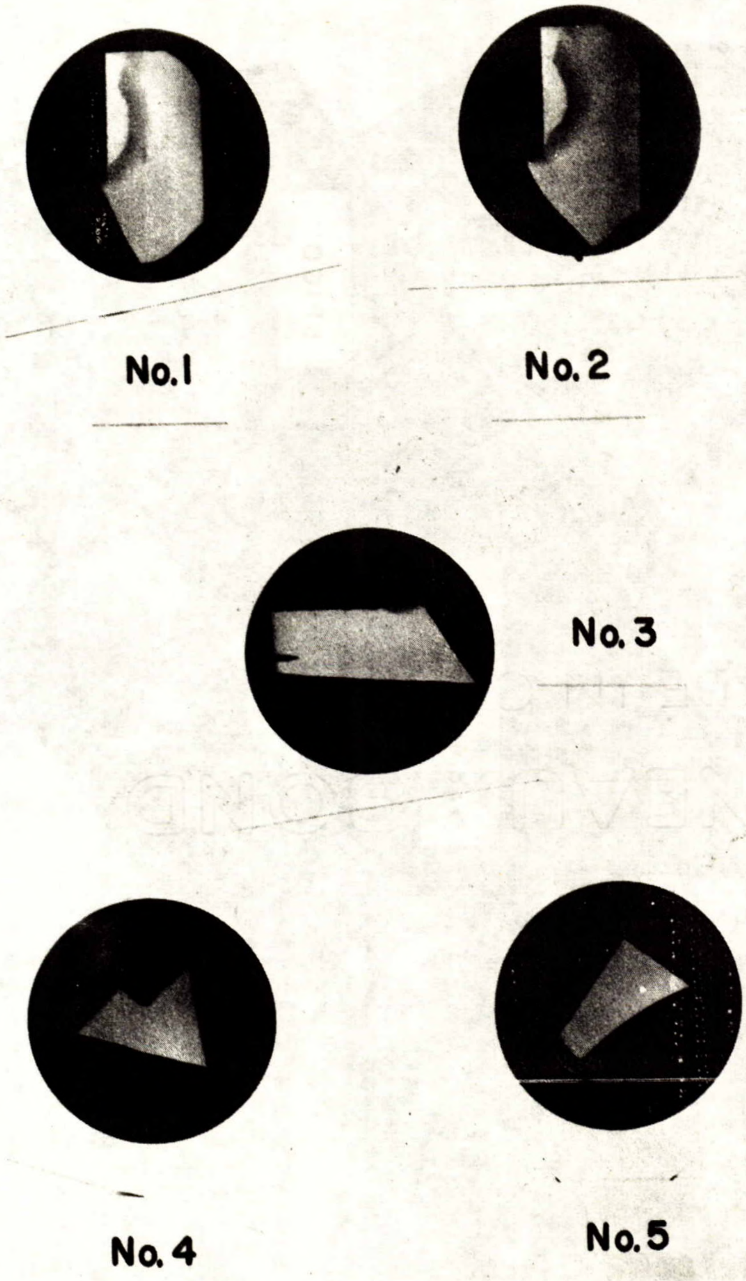


Figure 5. Specimens Prepared for Microscopical Examination. Etched in nital.

In No. 1 and No. 2 observe the weld deposit (light grey) and the heat-affected zones (darker greys) which affect the region of the reentrant angle. In No. 3 observe the heat-affected zones on the flange.

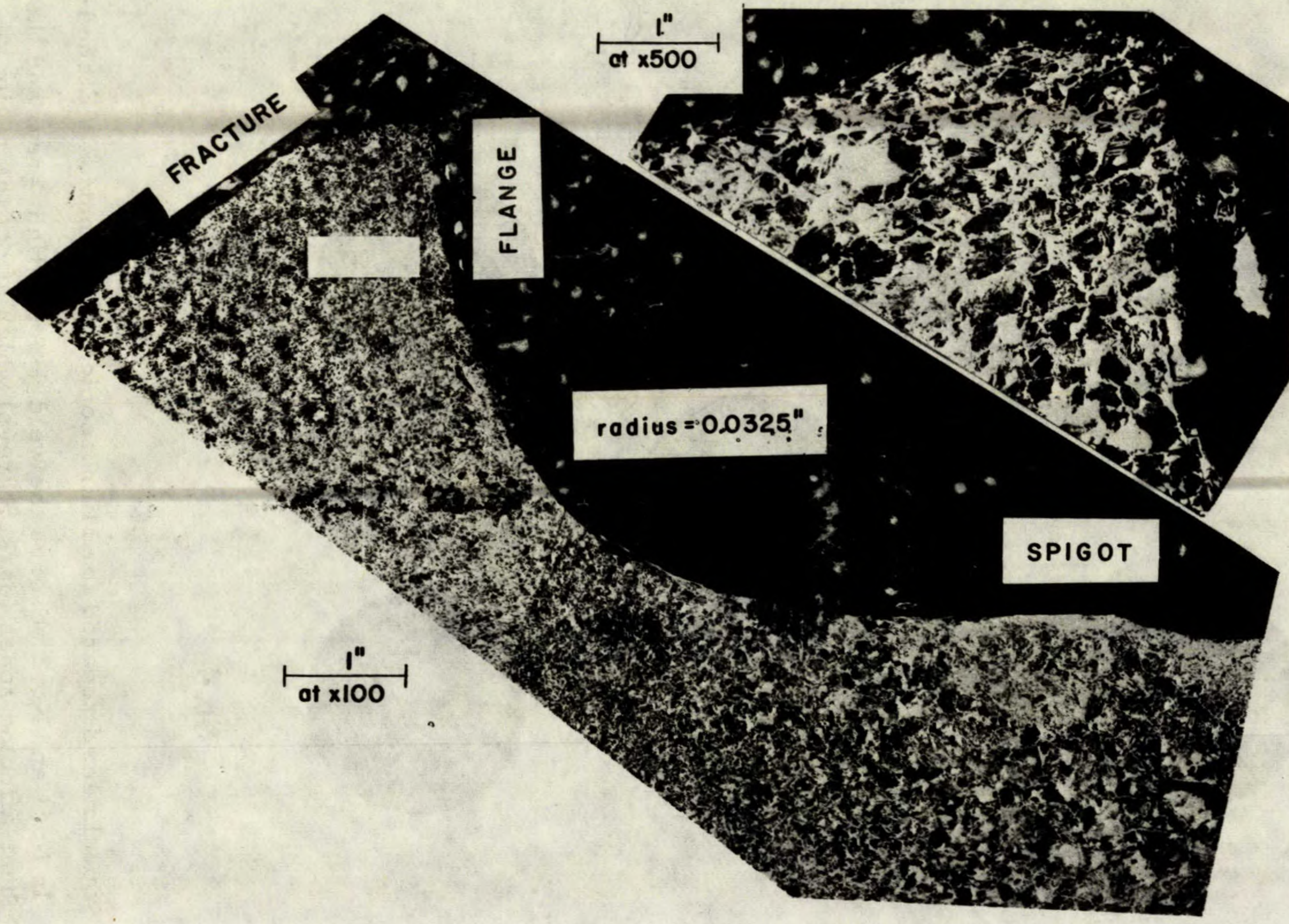


Figure 6. Reentrant Angle Region of Specimen No. 1. Nital etch. X100 and X500 (inset).

The fracture initiated in a region which, during the repair, was effectively heated to above the Ac_3 temperature (just above 1485°F).

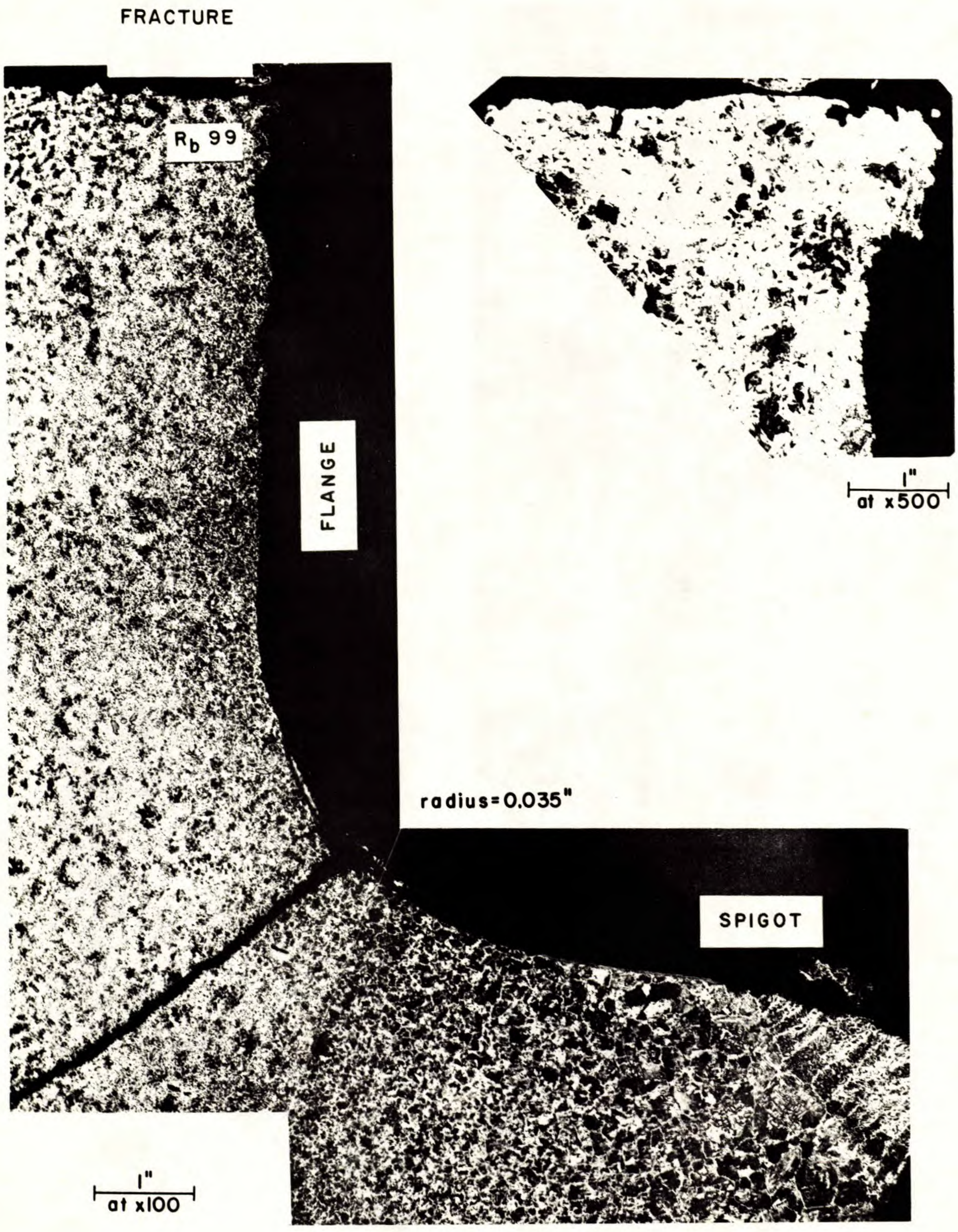


Figure 7. Reentrant Angle Region of Specimen No. 2. Nital etch. X100 and X500 (inset)

The fracture developing to failure initiated in a region which was effectively heated close to but below the Ac3 temperature (just below 1485°F) allowing partial transformation (high carbon regions) to austenite. The incipient cracks occur in a region similar to that in which the crack of Figure 6 occurred.

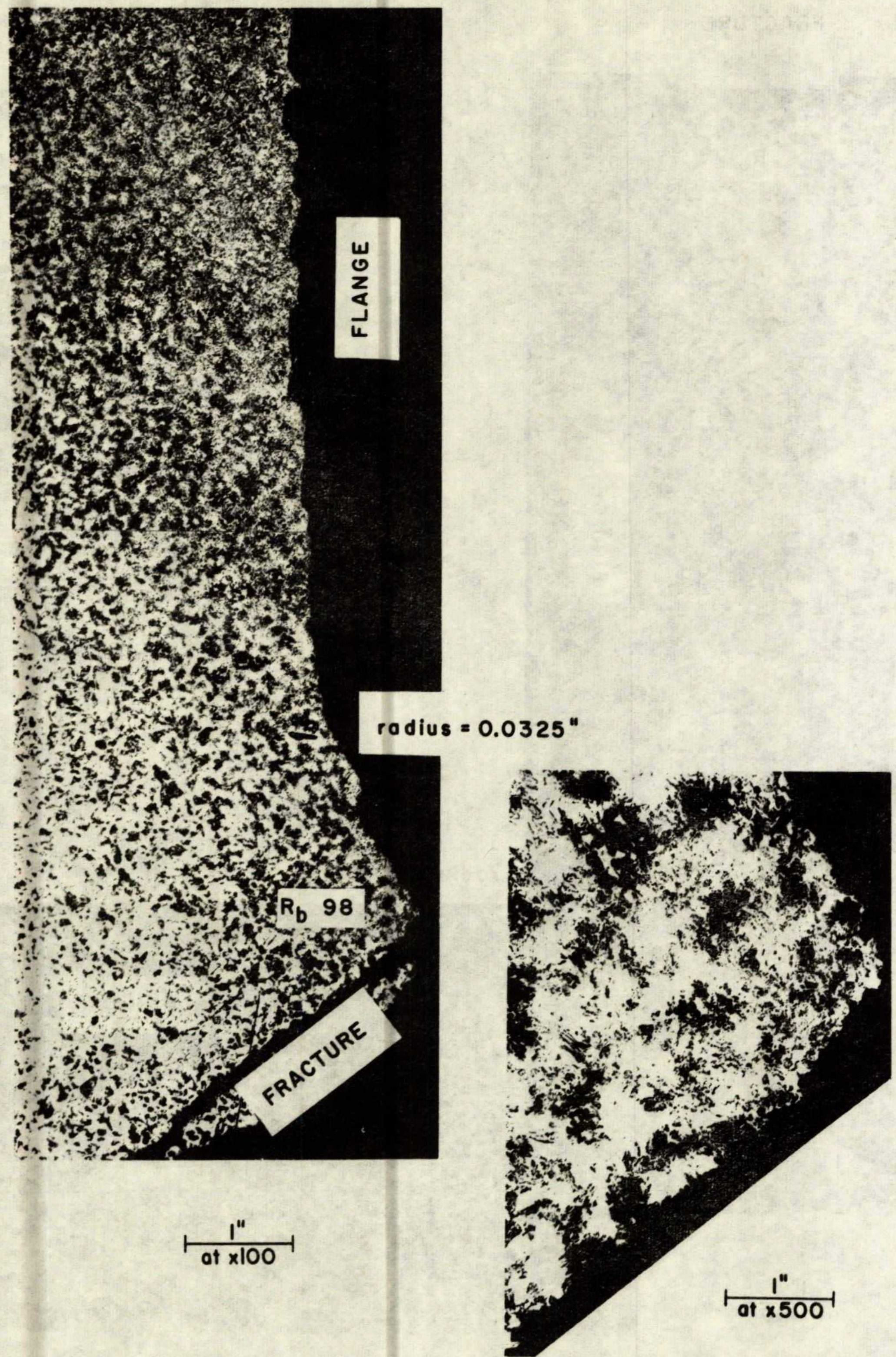


Figure 8. Flange Region near Crack of Specimen No. 3. Nital etch X100 and X500 (inset).

The fracture initiated in a region which, during repair, was effectively heated just over the Ac_1 temperature (just over 1350°F)

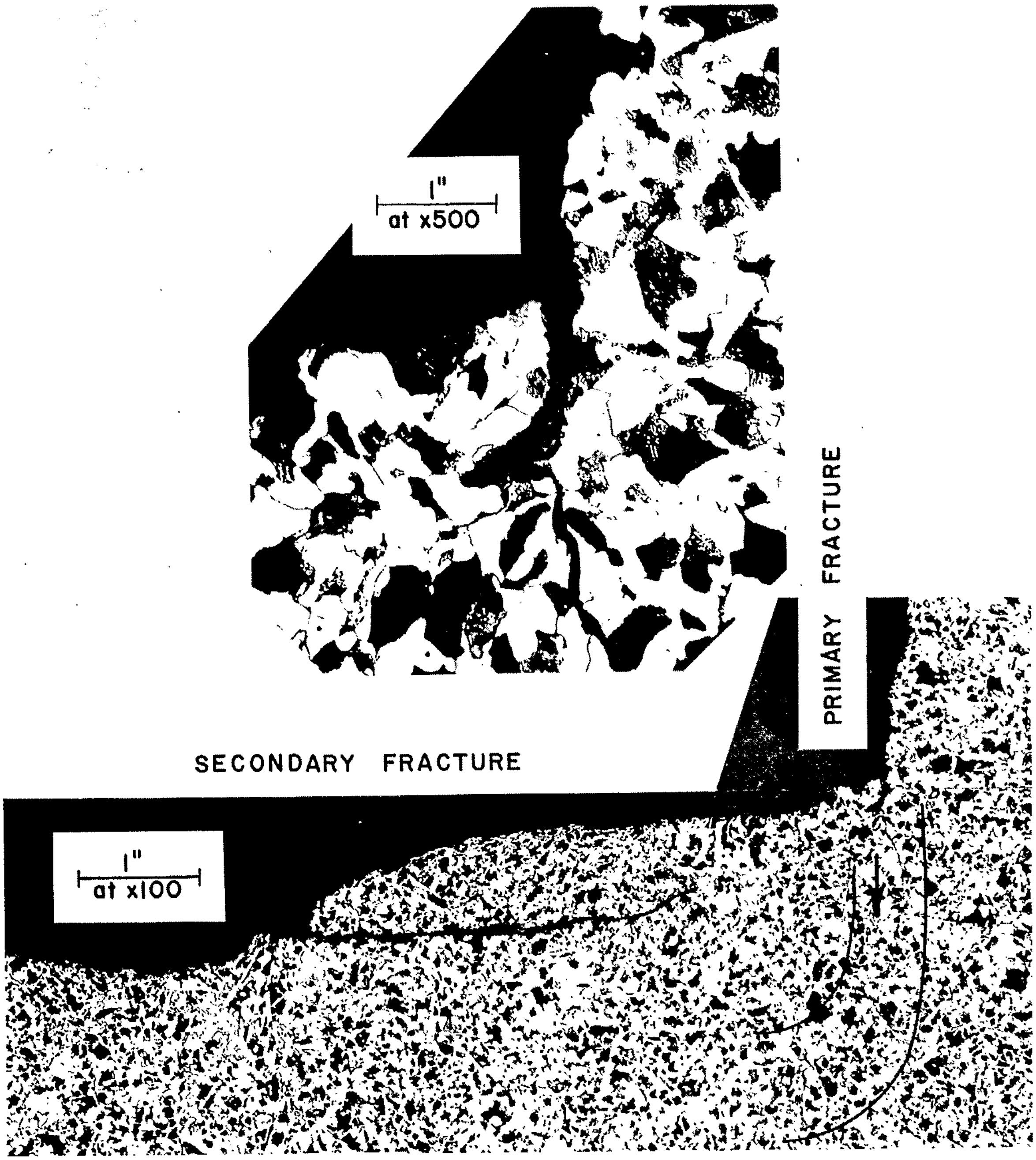


Figure 9. Terminal Region of Primary Fracture Showing "Junction" with Secondary Fracture. Nital etch. X100 and X500 (inset).