## A SUMMARY OF SOME TYPICAL STEEL FAILURES IN MACHINE PARTS AND STRUCTURAL SECTIONS

*by*

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The study of service failures results in continued improvement in the use of metals. The experience gained in individual cases becomes of general value when a fundamental concept of the cause can be derived. In this way engineers have learned to avoid notch effects and other stress raisers while other concepts such as stress corrosion are not so well defined.

The examples given herein are taken from mill laboratory files and present a summary of the circumstances of the failures with the probable causes. Division is made into three types of failures for the purpose of this discussion but it is not intended as a classification of all types of failures.

### FATIGUE FAILURES

A considerable number of metal failures are classified as being of the fatigue type. The stresses involved are of the cyclic type and usually a considerable time elapses in the service life before failure occurs. Also a greater part of the service life is past before any damage is visible by usual inspection methods. The fracture is characterized by a pattern which indicates the focal point of the failure and its progression across the section. While in some cases a part may be considered to have fulfilled its life expectancy, in others failure may be premature, because of unfavorable selection of material or heat treatment, accidental abuse during fabrication, installation, or service. The following examples are given to illustrate different causes of unsatisfactory performance.

(1). **Failure of Pins in Conveyor Chains**

*AISI* Type 420 Stainless Steel

| *C* | *Mn* | *P* | *S* | *Si* | *Cu* | *Ni* | *Cr* | *Mo* |
|---|---|---|---|---|---|---|---|---|
| .36 | .32 | .017 | .015 | .23 | .09 | .16 | 12.92 | .01 |

*Photograph*—New pin with some failed parts shown in Plate 1.

Failure occurred in some cases after only one day of service. Hardness was 52 Rockwell C across the section. The degree of hardness was considered excessive and recommendation was made to change the grade to AISI type 410, low carbon 12% Cr stainless steel, and to heat treat to about 38 Rockwell C for the application.

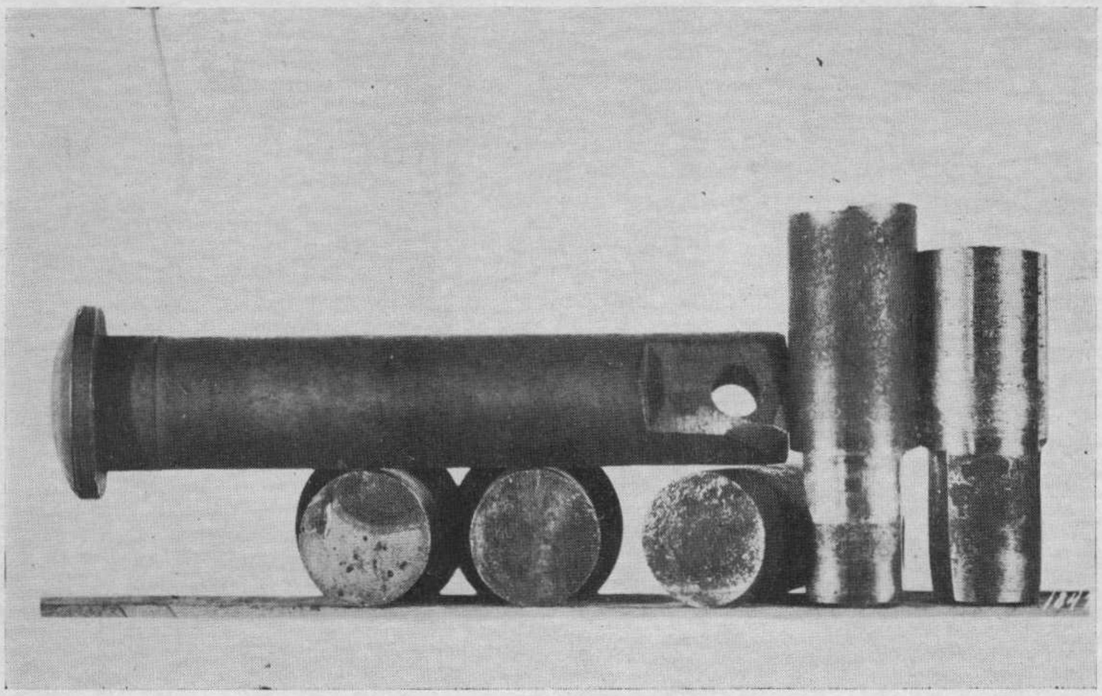
(2) **Serivce Failure of a Torque Converter Drive Shaft**

*AISI* 4145 H Grade Steel

| *C* | *Mn* | *P* | *S* | *Si* | *Cr* | *Mo* |
|---|---|---|---|---|---|---|
| .45 | .71 | .017 | .007 | .28 | .99 | .19 |

It was reported that failure had occurred after four years service in oil well drilling equipment.

*Hardness Tests*—285 Brinell at surface, 277 Brinell at centre



#3 #2 #2 #4 #5

**Plate—1**

New pin #1 with parts of pins failed in service. Note fatigue type failure in sample #3 and areas of wear in samples #4 and #5. Magnification 3/4 X

*Microstructure*—Acicular structure characteristic of a normalized and drawn condition.

From visual examination it was apparent that failure resulted from fatigue cracking which propagated transversely across approximately two thirds of the section before complete failure. The origin of cracking was located by the concentric arcs on the broken end at a point near the keyway as indicated by the arrow in the photograph. Considerable circumferential galling was also noted at the line of fracture. Although the keyway corners appeared to have ample radii it was believed that the combination of the galling and the concentration of stresses around the keyway resulted in the fatigue failure.

(3) **Pull Back Rod Failure**

*AISI* 9440 Grade Steel

| *C* | *Mn* | *P* | *S* | *Si* | *Ni* | *Cr* | *Mo* |
|---|---|---|---|---|---|---|---|
| .39 | 1.06 | .021 | .025 | .51 | .27 | .32 | .13 |

*Hardness Tests*

212 Brinell at surface

207 Brinell at center

**Microstructure**—Ferrite and pearlite of rather coarse grain ranging from #1 to #6 and averaging #4 according to the A.S.T.M. rating chart.

The hardness values and the microstructure indicate that the rod had been slow-cooled after forging and had been given no subsequent heat treatment.

The failure was caused by fatigue cracks which originated at heavy abrasion marks or gouges on the key slot surface near the ends. These gouges may have been caused by improper fitting of the key. In addition to correcting this condition it was recommended to use AISI 4140 or 8640 steel heat treated to obtain a fine grain structure and a surface hardness of approximately 300 Brinell.

(4) **Broken Rail Joint Bars**

*Typical chemical analysis*—C.44 Mn.67 P.025 S.025 Si .047

*Photograph of failures*—Plate—2.

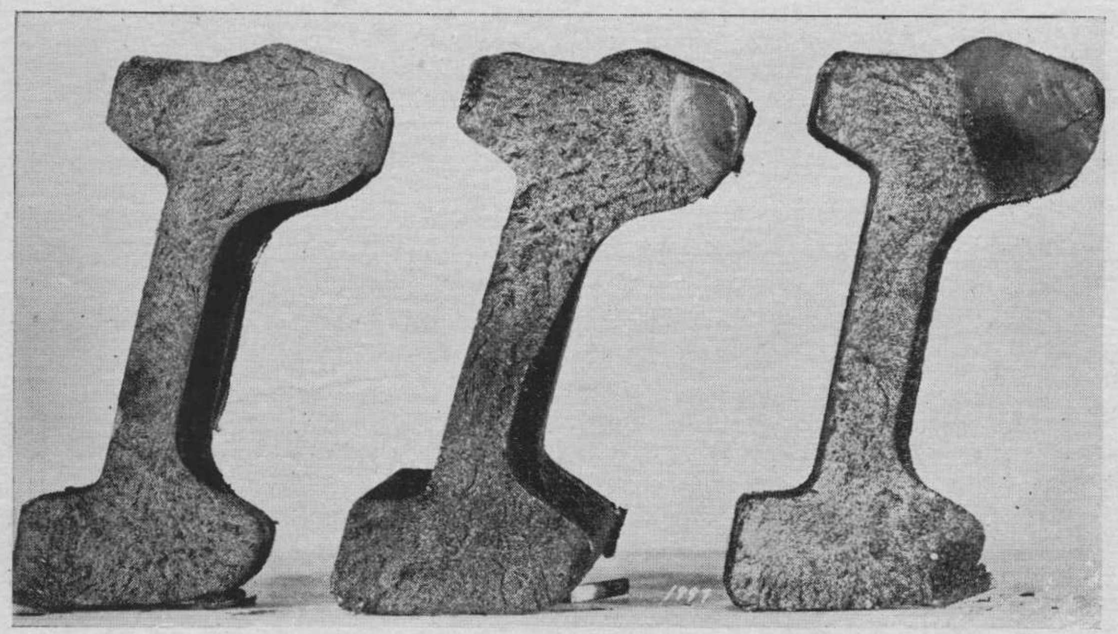
*Hardness Tests*—Head, web, and toe values ranged from 152 to 248 Brinell in eight bars.

*Microstructures*—Considerable variations were noted in the amounts of ferrite in grain boundary networks enveloping fine pearlite colonies.

*Mechanical Properties*—Considerable variations in strength values were found with only two of eight failed bars satisfying the specification requirements of 70,000 p.s.i. yield point and 100,000 p.s.i. tensile strength.

The eight failed joint bars were made during the years 1943-46 and the failures occurred during 1950. Visual examination of all eight bars showed that the failures started in the head zones by fatigue cracking followed by sudden rupturing through the remainder of the sections. This is illustrated in the photograph. Pickling in acid revealed secondary cracks on both head and toe adjacent to the fractures in all bars. This condition was apparently caused by the battering associated with the movement of the rail ends. The stressing effect of this movement was indicated by the metal which was upset into the space between the rail ends.

An improvement in the uniformity of physical properties and microstructures would be expected to result in improved service life. However, it was not certain that failures from



**Plate—2**

Photograph showing Various Degrees of Fatigue Penetration before Complete Failure of Rail Joint Bars.
Magnification X 9

fractures would be prevented since it was found that some of the failed bars were within specifications.

It was recommended that a change in design should be considered in order to prevent the upsetting or pinching of metal between the rail ends.

Information obtained later tended to corroborate this recommendation. Experience has shown that bars which have been removed from service in-order to grind out small cracks, apparently do not fail when placed back in service. It is believed that the removal of metal by grinding eliminates the contact of the bar with the rail ends and thus prevents the pinching and upsetting of metal.

(5) **Failure in the Main Shaft of a Mechanical Stirrer**

*AISI* type 304 Stainless Steel

| *C* | *Mn* | *P* | *S* | *Si* | *Cu* | *Ni* | *Cr* | *Mo* |
|---|---|---|---|---|---|---|---|---|
| .06 | .36 | .019 | .011 | .39 | .03 | 9.60 | 19.04 | .05 |

*Photographs*— Fractured section shown in Plate 3a

Macro-etched section shown in Plate 3b.

*Hardness tests* 176 Brinell at surface

161 Brinell at center

*Microstructure* Normal fine grain austenite structure was severely coarsened by welding operation resulting in grains as large as 0.16″ actual maximum dimension.

The sample represented one of four similar failures which had been encountered over a period of about three years in a lot of sixteen stirrers for aniline dye and starch baths.

The transverse macro-etch, Plate 3a, revealed areas which were coarsened apparently by the heat of welding. In the photograph this is evident for the zone on the right at a weld location. The zone on the left is believed to have been coarsened by a weld not included in the sample.

The fact that there are fine-grain zones intervening between the coarse-grain areas and the welds possibly may be explained on the basis of stress and thermal gradients which resulted in favourable conditions for grain growth. The presence of a stress gradient, such as that resulting from cold drawing of the bar, could not be confirmed because the welding assembly had been stress-relieved.

Grain coarsening is known to produce an adverse effect on the toughness of steel but no data are available to allow estimation of the loss caused by the extreme corsening in the subject sample. However, it is evident from the photograph that the fracture failure was of the progressive or fatigue type.

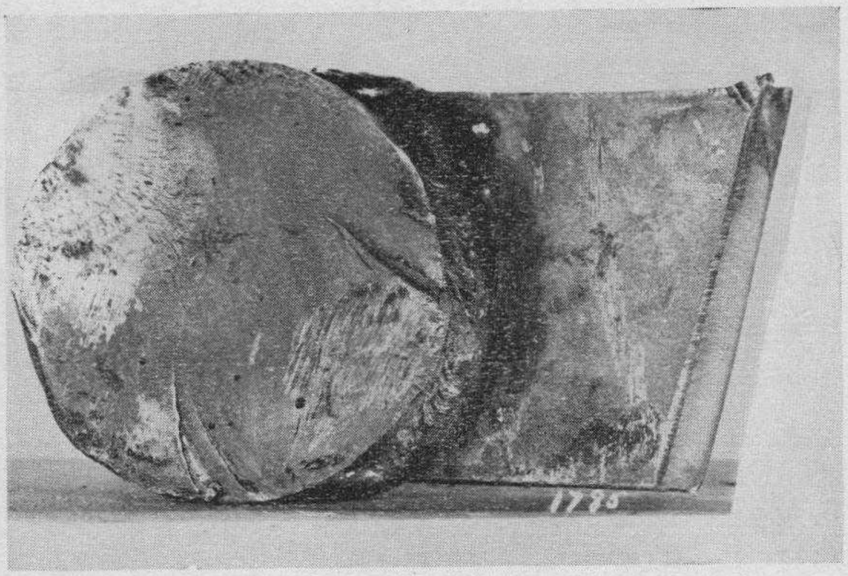
The point of origin was in a coarsened zone as evident by comparison of Plate 3a.

The coarsening is believed to be associated with long welding time. It was noted in the section as polished for metallographic examination that there was a space between the stirrer blade and the shaft, and the weld depended entirely on the fill and fusion of the weld metal. A better fit at this point would facilitate the welding operation and improve the weld by allowing fusion of the blade with the shaft.

(6) **Crane Hook Failures**

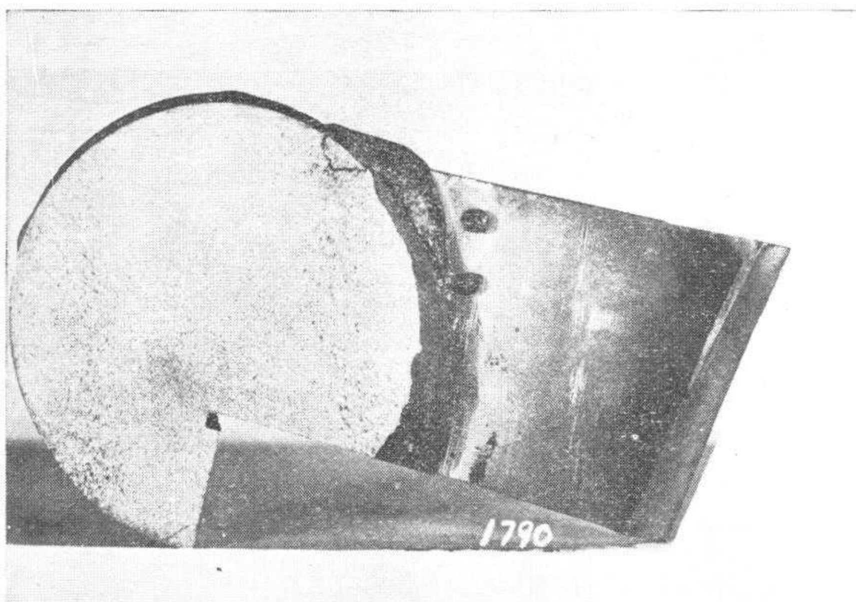
*AISI* C 1035 Steel

| | *C* | *Mn* | *P* | *S* | *Si* | *Cu* | *Ni* | *Cr* | *Mo* | *V* |
|---|---|---|---|---|---|---|---|---|---|---|
| Hook#1 | .17 | .36 | .009 | .017 | .14 | .09 | .16 | .08 | .05 | nil |
| Hook#2 | .32 | .84 | .013 | .030 | .20 | .02 | .03 | .04 | .01 | nil |




**Plate—3a.**

Stirrer Shaft as Received Showing Progressive Nature of Failure. XI




**Plate—3b.**
Macro-Etched Cross-Section Adjacent to Failure. XI

*Microstructure* Both samples had coarse grain structures of pearlite and ferrite.

The two samples examined included the top threaded ends of the hooks showing the fractures. These were of the progressive type originating in the base of the threads.

The 2 sample conforms to the AISI C 1035 grade which was specified for the application but the #1 sample was C 1017 grade. Furthermore neither sample appeared to have had a normalizing heat treatment as specified, because coarse grain structures of pearlite and ferrite were observed metallographically in both samples.

The location of the fractures in the V-threads resulted from stress concentration and recommendation was made to decrease this effect by redesign of the thread contour.

(7) **Premature Failures of Back Up Arbor Rolls**

*Chemical Analysis:*

| *C* | *Mn* | *P* | *S* | *Si* | *Ni* | *Cr* | *Mo* |
|---|---|---|---|---|---|---|---|
| .23 | .60 | .015 | .015 | .18 | 3.48 | 1.57 | .20 |

Each of three rolls had broken at the journal adjacent to the body of the roll and the fracture was at approximate right angle to the longitudinal axis.

Examination of the fractures indicated that they were of the progressive type. The concentric circular lines associated with this type of fracture indicated the points of origin to be below the surface.

The nuclei for the progressive fractures were readily apparent as flakes which was made adjacent to the fracture.

Failures which are caused by defective steel are not common because preliminary testing usually eliminates such material from use.

## FAILURES BY CRACK PROPAGATION

Brittle failures of ductile structural steels somctimes occur in structures which apparently have not been subjected to static loading in excess of normal. In studies of such cases it is advantageous to determine the point of origin of the failure especially when the fracture may extend for many feet. Closer study of a limited zone can then be made to determine whether an original steel defect or some alteration of the normal metal has caused the failure. The following examples are given to show how this procedure was used.

(8) **Failure of a Wale Beam in a Breakwater**

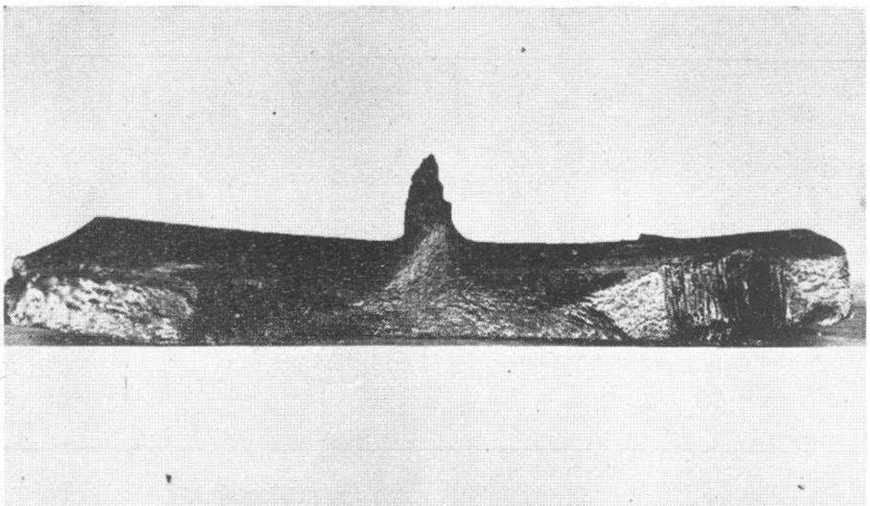
*Chemical Analysis*

| *C* | *Mn* | *P* | *S* | *Si* |
|---|---|---|---|---|
| .24 | .70 | .011 | .028 | .05 |

*Photograph* Area of initial failure shown in Plate 4.

*Tensile and Bend Tests*

| | Tensile Strength *p.s.i.* | Yield Point *p.s.i.* | % *Elongation in* 8'' | 180'' *Bend* |
|---|---|---|---|---|
| | 68,610 | 41,310 | 25.2 | Ok-no cracking |
| Specification | 60,000/ 72,000 | — | $\frac{1,500,000}{\text{T.S.}} = 21.9$ | |



Fracture in Flange of CB-103 x 72# Beam
Note area of initial failure between torch-cut hole and left edge. Magnification X .8

**Plate—4**

| *Hardness* | *Rockwell B* | *Equivalent Brinell* |
|---|---|---|
| average | 78 | 144 |
| at edge of torch-cut hole | 98 | 288 |

The failure occurred by sudden rupturing through most of the beam section during a severe storm. The sample for examination included the failure but had to be saw-cut to separate the parts and expose the fracture. Part of the fracture is shown in Plate 4 and it may be noted that the left zone, between the torch-cut hole and the edge of the flange, had been worn smooth. This indicates that failure had occurred through this zone at some time prior to the rest of the rupturing. Metallographic examinations along this first section of the failure showed the normal microstructure of ferrite and pearlite. A condition which may have acted unfavorably and initiated the failure, was noted in the rough irregular contour of the torch-cut holes. These irregularities would result in stress concentration which together with the increase in hardness noted above would favor the start of a crack at one of the holes. Although it is common practice to torch-cut holes as was done in this case, the harmful effects noted could be avoided by a smoother cut or by reaming.

(9) **CB.Section Ruptured in Service as a Walking Beam.**

*Chemical Analysis*

C.125 Mn.64 p.008 S.032 Si.06

*Hardness* 123 to 126 Brinell

Complete failure had occurred through one flange and the web of the beam weldment. The failure was typical of others which had occurred previously. The weldment was used as a walking beam in oil well pumping service. It may be noted that failure extended across the flange at the reduced width where 90° corners were produced by torch cutting. At one corner the point of origin was defined by concentric rings on the fracture face indicating an initial progressive type failure.

The normal microstructure consisted of fine lamellar pearlite and ferrite but at the torch-cut edge a zone of martensite was detected. The association of the torch-cut corners and the progressive type fracture across the flange indicate that the failure originated in the metal affected by the torch cutting. The abrupt change in section located stress concentrations in the hardened zones and caused a fatigue or progressive crack to develop. It is obvious that the strength of the beam would be considerably reduced by the decrease in flange width from 10″ to 7″. If this reduction was required by the design of the walking beam assembly, it should have been done by flaring to avoid sharp corners and consequent points of stress concentration. As an added precaution torch-cut zones could have been post-heated to decrease the hardening effect.

(10) **Failure of a Channel in a Riveted Compression Member of a Bridge.**

*Chemical Analysis*

C.24 Mn.48 p.015 S.029 Si.06

*Tensile and Bend Tests*

| Tensile Strength p.s.i. | Yield Point p.s.i. | %Elongation in 8″ | 180° Bend |
|---|---|---|---|
| 65,840 | 37,130 | 25 | Ok-no cracking |

It was learned that the original section, over 50 feet long, was trucked about 250 miles to the bridge site during winter with sub-zero temperatures prevailing and continuing during erection. Since the subject member of the bridge was designed as part of a compressive member and a tension failure had occurred, it was believed that the flange had been subjected to some shock before being placed in the structure.

Macro-etching of the flange sections revealed that several very shallow tears had started in the skirted areas on the sides of the rivet holes. It was observed microscopically that the skirted metal was severely cold worked while the area adjacent to it had a lesser amount decreasing to the normal structure of ferrite and pearlite. The total depth of cold worked area including the skirted zone was approximately .03".

The severely cold worked skirted areas are not abnormal for punched rivet holes but under conditions of impact or suddenly applied high stress such areas would serve to start cracks. The notch effect of small tears in cold worked metal would be most detrimental in the sub-zero weather. Thus it seemed likely that some impact force was responsible for the failure prior to erection.

## CORROSION FAILURES

Corrosion of structural low alloy and carbon steels is considered a natural occurrence and protective coatings are commonly used. However, when stainless steels are used it is quite often incorrectly assumed that corrosion may no longer be a problem. Accordingly, failures of stainless steel cause much concern. Occasionally it is a combination of conditions that cause the failures. Sometimes the most suitable type of stainless steel has not been selected for the application or the fabrication methods cause unfavourable alteration of a normally satisfactory structure. The following examples illustrate a few of these possibilities.

### (11) **Thread Fitting Failed in Service in a Pressure Assembly**

*AISI* Type 316 Stainless Steel

| *C* | *Mn* | *P* | *S* | *Si* | *Cu* | *Ni* | *Cr* | *Mo* |
|---|---|---|---|---|---|---|---|---|
| .06 | .55 | .030 | .016 | .69 | .14 | 12.68 | 18.93 | 1.84 |

*Photograph* Part as sectioned for macro-etch testing is shown in Plate 5.

A threaded fitting developed internal cracks after being put into service in a pressure assembly. Five parts had been machined from a two foot length of 3" diameter centerless ground bar stock. It was reported that three parts leaked immediately and two parts were satisfactory in service. The pressure assembly was operated in a temperature range of 400 to 600° F. at 10,000 p.s.i. pressure. Materials contained were compounds of phosphorus, aluminium, silicon, and sometimes chlorine.

The macro-etch tests as shown in the photograph revealed radial internal cracks. Two of the branch-like cracks penetrated the surface of the shaft at the junction with the threaded section but this is not visible in the photograph. The leakage probably occurred at these two points of failure.

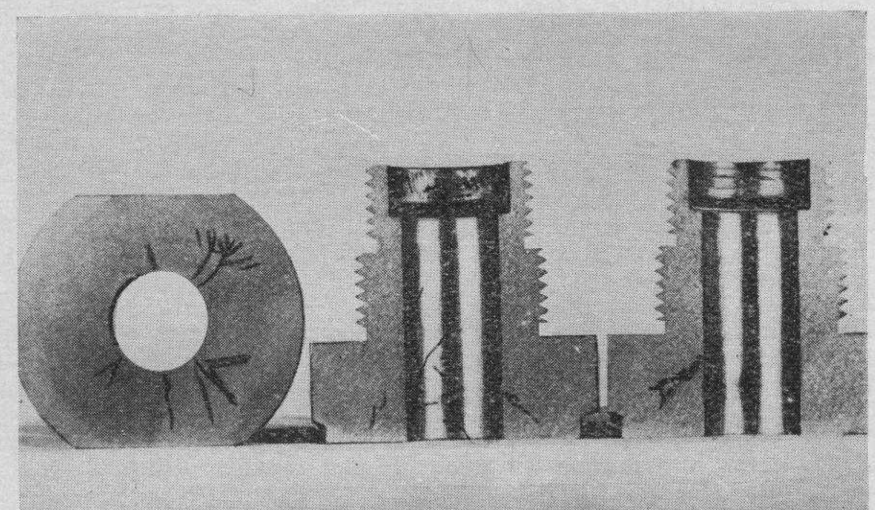
Metallographic examination in the zone of the failure revealed intergranular cracks outlining grain boundaries in a network pattern. The microstructure was austenite with numerous ferrite stringers. The steel was in the annealed condition as indicated by the fact that there were no undissolved carbides.

The cause of failure was not definitely established but the presence of chlorides, heat and pressure are known to be unfavourable factors in resistance to stress corrosion. On the basis of the metallographic examination and the conditions known to exist during operation, it is believed that the failure was the result of stress corrosion.

### (12) **Failure in Service of a Water Turbine Ring.**

*AISI* Type 403 Stainless Steel

| *C* | *Mn* | *P* | *S* | *Si* | *Ni* | *Cr* |
|---|---|---|---|---|---|---|
| .10 | .41 | .017 | .007 | .37 | .19 | 12.88 |



Macro-Etch Tests of Sectioned Fitting Which Failed in a Pressure Assembly.

Magnification X1.

**Plate—5**

*Photograph* Sample containing transverse cracks shown in Plate 6.

*Hardness* 321 Brinell

A water turbine ring developed a series of transverse cracks after nine months service. The material had been cold formed from a 2″×6″ rolled section to a 15′ diameter ring. The ring was oil quenched from 1700°F., tempered at 100°F and shruck fit on a turbine rotor.

Magnaflux testing revealed the radial discontinuity running longitudinally as shown on the transverse face of the sample. In addition, hairline-indications parallel with the originally noted cracks, 2, 3 and 4 were observed in one keyway, but are only slightly apparent in the photograph.

Metallographic examination showed a tempered martensite structure with numerous ferrite stringers. The failures were intercrystalline and branched.

The cause of failure was not definitely determined because of lack of information regarding such variables as operating temperatures, stresses in the turbine ring and water source supplied to the turbine. However, the type of failure was characteristic of stress corrosion.

(13) **Severe Corrosion of a Stainless Steel Coupling**

*AISI* Type 303 Stainless Steel

| *C* | *Mn* | *P* | *S* | *Si* | *Ni* | *Cr* | *Mo* |
|---|---|---|---|---|---|---|---|
| .09 | .99 | .017 | .280 | .45 | 9.10 | 17.86 | .43 |

The coupling had been in service immersed in sulphurous liquid. After only a short period of time, the part had been so weakned and deteriorated by corrosion that it had to be removed from service.

Metallorgraphic examination revealed an austenitic microstructure with no undissolved carbides but with a heavy concentration of sulphide inclusions throughout. The cracks were transgranular.

It was considered that the failure was associated with the fact that type 303 stainless steel is not suitable for service in a sulphurous liquid. It was recommended that a grade such as type 316, 18-8 Mo, stainless steel be used.

(14) **Failure of Nozzles in the Extrusion of Zinc into Die Castings**

*AISI* Type 303 Stainless Steel

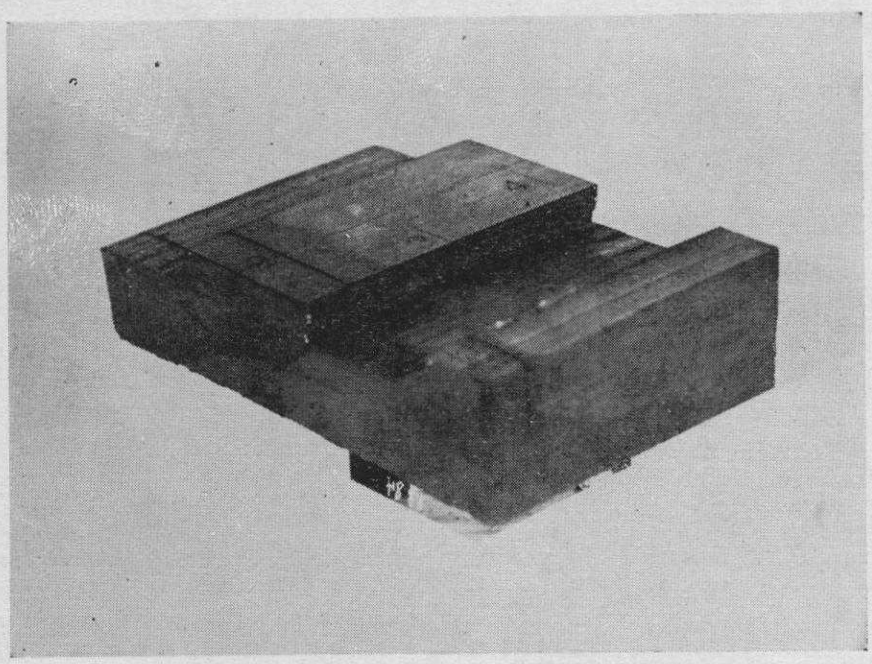
| | **C** | **Mn** | **P** | **S** | **Si** | **Cu** | **Ni** | **Cr** | **Mo** | **Se** |
|---|---|---|---|---|---|---|---|---|---|---|
| **Satisfactory Nozzle** | **.07** | **1.08** | **.176** | **0.014** | **.66** | **.23** | **9.64** | **17.76** | **.15** | **.31** |
| **Failed Nozzle** | **.07** | **.84** | **.160** | **.012** | **.65** | **.03** | **9.60** | **18.00** | **.07** | **.31** |

*Photograph:* View of half section of nozzle in plate 7 showing the point of failure.

One nozzle failed very rapidly after only six extrusions because of penetration of the wall thickness by the molten zinc. The other, which was secured for comparison, had been in service for approximately six months without failure.

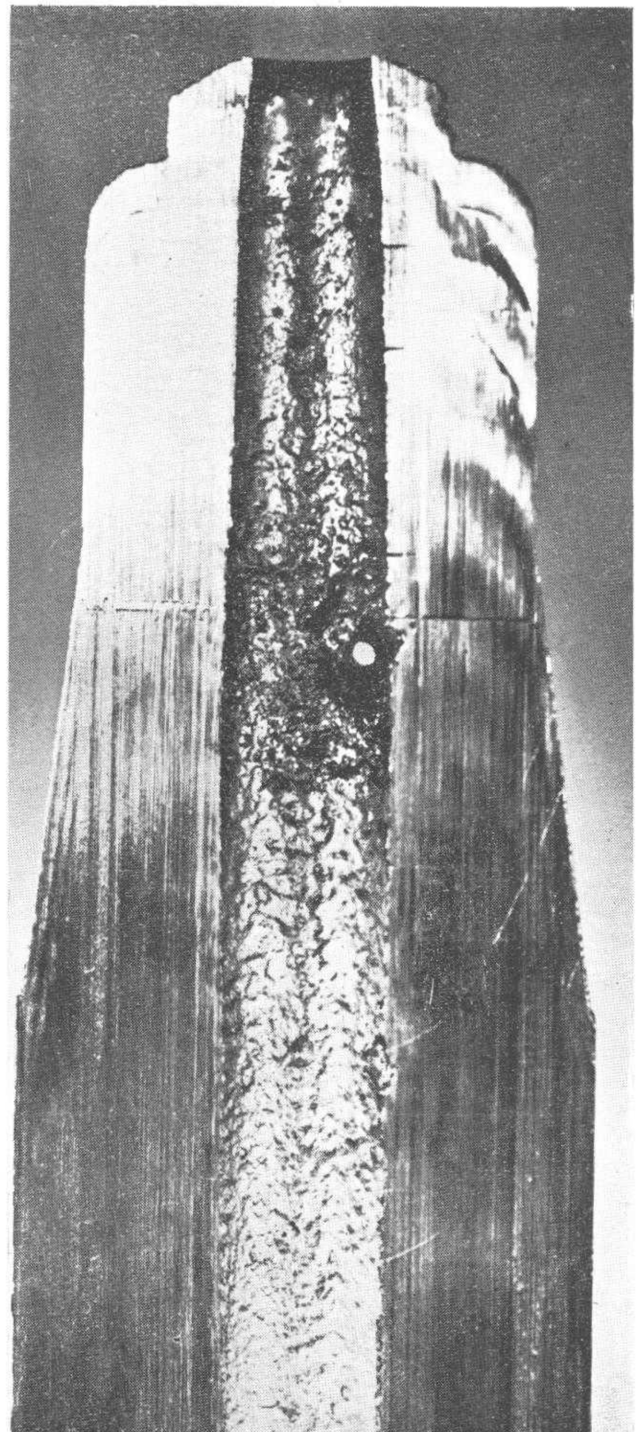
The chemical analysis of the two nozzles were very similar except for manganese and the residual copper and molybdenum contents but these differences did not appear to be significant.

Longitudinal macro-etch tests revealed sound quality in both. The satisfactory nozzle showed coarse grain structure contrasted to fine grain in the failed nozzle. This difference was also observed in the microstructures but was not believed to be of significance in this application.



**Plate—6**

Water Turbine Ring Sample as Magnafluxed to Show Cracks.
Magnification X 8



**Plate—7**

Half Section of Stainless Nozzle Showing Point of Penetration by Molten Zinc in Extrusion Process.

Magnification X 1.

In metallographic examinations the zinc penetration was found to be progressive along the inner wall. It appeared that penetration occurred by formation of a zinc-iron alloy. In the failed nozzle the layer of zinc plus zinc-iron alloy measured about .027″ deep while in the satisfactory nozzle a maximum of .010″ depth was found with some portions free of penetration. Both nozzles had microstructures consisting essentially of austenite but the failed nozzle had excessive carbide precipitation compared to practically none in the satisfactory nozzle. This was a good indication that the failed nozzle had been heated to a considerably higher temperature than the other.

It is reported in the literature that the attack of iron by zinc begins at about 420°C. (788°F.) and increases rapidly with rise of temperature. The zinc was extruded through the subject nozzles supposedly maintained at a temperature of 720° to 760°F. by means of heating with gas flames directed on the tapered OD of the nozzles. Since other characteristics such as chemistry and soundness were very similar, it appears probable that excessive operating temperatures accounted for an accelerated rate of zinc-iron alloy formation in the failed nozzle. The rapid penetration of the zinc-iron alloy formation to the surface was probably related to the temperature gradient existing between the nozzle bore and the heated surface. A point of higher temperature along the bore probably was the location of an accelerated attack which progressed along the temperature gradient at increasing rate as the point of heating was approached.

Because of the critical temperature conditions existing in the service of the nozzles and because of the mutual solubility of zinc and iron, the application of stainless steel for this purpose cannot be guaranteed. For possible successful operation it appears essential to control temperature precisely at the minimum required for the die-casting operation and also to heat the nozzle as uniformly as possible.

1. J.W. Mellor, "A Comprehensive Treatise on Inorganic and Theoretical Chemistry," Vol. XIII, P. 543.