FAILURE ANALYSIS
Case Histories and Methodology

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Dr. Riederer-Verlag GmbH
American Society for Metals

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Dr. Riederer-Verlag GmbH
Stuttgart, West Germany

American Society for Metals
Metals Park, Ohio 44073

Library of Congress Catalog Card No. 83-71811

ISBN: 0-87170-171-5

SAN 204-7586

Printed in the United States of America

PREFACE TO TRANSLATION

The translation of **Das Buch der Schadensfälle** by Dr. Friedrich Karl Naumann provides a vast collection of case histories that will greatly expand the available literature on failure analysis. Every attempt was made to retain the author's intent, description, and analysis of these studies. Editorial license was only exercised to clarify particular passages or to supplement the German text, e.g. providing equivalent American alloys or general chemical compositions in order to make the book more readily usable to the metallurgical engineering community in the English speaking countries. In several instances, Dr. Naumann has referenced German standards or test procedures. If the reader desires more information on an particular item, clarification or information can be obtained from the following sources:

1. **DIN – English Translations of German Standards,**
   Beuth Verlag GmbH
   P. O. Box 1145
   D-1000 Berlin 30
   Federal Republic of Germany

2. A. **Stahl – Eisen Prüfblatt,** test sheet of
   Verein Deutscher Eisenhüttenleute, 1961,
   Verlag Stahleisen mbH

   B. **Stahl-Eisen-Werkstoffblatt,** materials reference sheet in
   Taschenbuch der Stahl-Eisen-Werkstoffblätter, 3rd. Ed., 1980,
   Verlag Stahleisen mbH

   C. **Werkstoff-Handbuch Stahl und Eisen,** 4th Ed., 1965,
   Verlag Stahleisen mbH
   P. O. Box 8229
   D-4000 Düsseldorf 1
   Federal Republic of Germany

We have the pleasant duty of recognizing the assistance of many people during the preparation of this translation. First, we gratefully acknowledge the encouragement and technical support provided by the American Society for Metals; particularly Messrs. William H. Cubberly and Timothy L. Gall. Likewise, our thanks are extended to the Dr. Riederer-Verlag, in particular Mr. H. Schneider, for the many ways of rendering support and assistance. Additionally, the supplemental descriptions and correspondence with the author, Dr. Friedrich K. Naumann, have clarified technical issues throughout the text and were extremely helpful and greatly appreciated. We would like to thank the management and experts at Failure Analysis Associates at Palo Alto, California, for their support and encouragement throughout the technical review.

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PREFACE

This book will assist those producers and users of machines, apparatus, or structures who are concerned with an analysis of failures and an elucidation of their causes. It is based primarily upon the experience of the author and therefore must by necessity be limited to failures of iron and steel parts. But even within the framework of this large territory, no complete description of the manifold phenomena can be given. To compensate for this, individual cases or specific areas that may be of technical or economic significance, but not yet of general knowledge, will be described in some detail.

The description will be supplemented by instructions on how an investigation should be prepared and conducted in order to be most successful. The book is organized in such a way that the time sequence proceeds from planning and production to actual service of the parts in which the defects that lead to failure originate.

The book has been prepared from the point of view of the materials scientist and metallographer. It was suggested first by Professor Dr. G. Petzow, the editor-in-chief of the journal **Praktische Metallographie/Practical Metallography.**

The investigations were conducted in large part at the Max-Planck-Institut für Eisenforschung, Düsseldorf. The author is indebted to his colleagues who assisted in the examinations. This is particularly true for Mr. Ferdinand Spies, who not only took part in conducting the various investigations, but also assisted in the selection of failure cases and preparation of illustrations.

Düsseldorf, 1980

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1. Examination

Failure analyses are useful not only for adjudications of legal disputes, but also because the elucidation of their causes facilitates the prevention of future failures.

Research has also benefited to a large extent from failure analyses. A fountain of knowledge has been gained from precipitation and corrosion phenomena in research that was based upon investigations of aging and corrosion failures in boiler plates and pipes.

1.1 Preparation of Examination

Before we proceed with this analysis, some introductory statements should be made. Often a metallographer or materials testing engineer receives a piece of steel from someone who has sustained damages with the request to determine chemical composition, strength or other properties. The fact that a failure analysis is desired, is often not even mentioned. Therefore, as a rule, the questions asked do not serve those interested in the origin of the failure. They presuppose that the cause is already known to the inquirer, so that all he needs is confirmation. But if this is not the case, the answer may be meaningless. In such a case a cursory look by a materials specialist is more useful than many an irrelevant inquiry.

The following may be helpful to illustrate the point. A **chain** manufacturer sent a piece of 3 mm wire asking whether it was made of open hearth or Bessemer steel. Further questioning elicited that the wire could not be welded in a resistance-butt welding machine. The manufacturer was asked to send a piece of a chain with poorly welded links. No weldable comparison wire could be sent because manufacture had only recently begun and no welds had so far been successful.

It was immediately apparent from the chain links that a welding error had occurred. Metallographic investigation served to confirm this. **Figure 1.1** shows a longitudinal section through the weld of a link. The weld seam was completely open. On either side of the joint zone, craters were visible. Apparently these were current contact points. From the fine structure **(Fig. 1.2)** it can be seen that the steel had elongated grains at the joint. This confirms that this part was not heated to a high enough temperature, whereas high resistance at the current entry points heated these areas to partial fusion and apparently hardened them in spots. In this case the material was erroneously thought to be at fault. Any answer to the original question, even if such were possible, would not have been of any help to the manufacturer. But the findings now made it possible for him to remedy the situation.

Another failure analysis, in which the answer to the question posed could not contribute anything useful was the following. An armature factory sent a bushing with a screwed-on ring from the **safety valve** of a seagoing vessel with the request to establish the chemical composition, yield strength, tensile strength, elongation, and notch impact strength. The parts showed evidence of substantial pitting corrosion and were covered with a black crust. The ring was screwed on improperly and had cracked from the outside to the inside **(Fig. 1.3).** The thread was strongly corroded on both the male and female parts **(Fig. 1.4).** This was reason enough to assume that the failure had occurred due to stress corrosion (see also section 15.3.4.2).

Analysis showed that both parts consisted of a titanium-stabilized austenitic stainless steel with approx. 18 % Cr, 10 % Ni and 2 % Mo. Thus the material selection was correct for the proper function of the valve, as far as corrosion by the seawater was concerned. That made the determination of the mechanical properties superfluous, even if they could have been established in these parts, since they had no bearing on corrosion restistance. Metallographic investigation confirmed that this was a typical case of transgranular stress corrosion cracking **(Fig. 1.5).** The stress and deformation were caused by the improper threading of the ring. It was assumed that seawater acted as corrosive agent. This was confirmed by an analysis of the black crust. It contained 1.02 % C, 0.24 % S, and 0.45 % Cl. Carbon and sulfur may have originated in the lubricant, while the chlorine was introduced by the seawater.

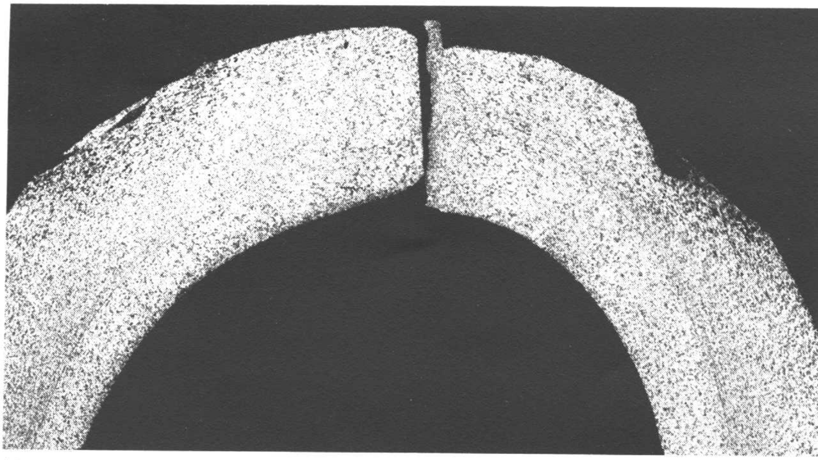
The principal cause of failure in this case was the improper thread engagement which caused high stress in the ring, bushing, and especially the thread. This failure, like the preceding one, could be explained by mere visual inspection of the parts. Analysis served solely to confirm that the right material was selected.

Another example: A messenger of a machine manufacturer arrived with a tooth that had broken out of a **pinion gear.** An inquiry was made to establish whether the material corresponded to a certain steel according to standards. To answer this question would have been of little use. Since it could be assumed that this was not the only tooth that had broken out of the gears, only an inspection of the entire assembly with all gears could show the primary tooth fracture. A single tooth, among many other damaged ones, was found that exhibited an incipient fracture with a typical fatigue failure structure. Only by examining this tooth, which had fractured first, and whose fracture affected all other damage, it was possible to establish the failure cause.

As can be seen from these examples, the materials testing engineer who is to analyze a failure, must be provided with all the information available. This is a prerequisite for any successful failure analysis. A personal discussion with all interested parties may be necessary and where indicated, the manufacturer of the failed part as well as the raw material producer should be consulted. A very important question, that almost always should be asked of the claimant, is what has been done differently in the present situation than before. This is especially important in cases where failure occurs suddenly and repeatedly after many years of satisfactory performance. The search for a deliberate or inadvertent change is often difficult, but it is of greater importance than the best examination. Questions and discussions of this type serve a purpose only if the parties will disclose all pertinent information.

It is also helpful to the investigator if he receives comparison parts together with those that failed and particularly those that have proven satisfactory in operation. The answer to the question at which stage of manufacture the failure occurred can often be answered by an examination of the raw material, if that is still available.

Finally, a visit to the plant of the claimant may be advisable for a better understanding of the function of the failed part and knowledge of the operational conditions to which it was exposed.



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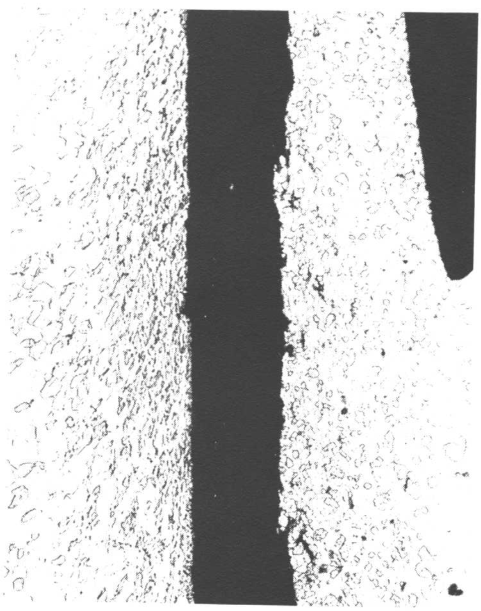

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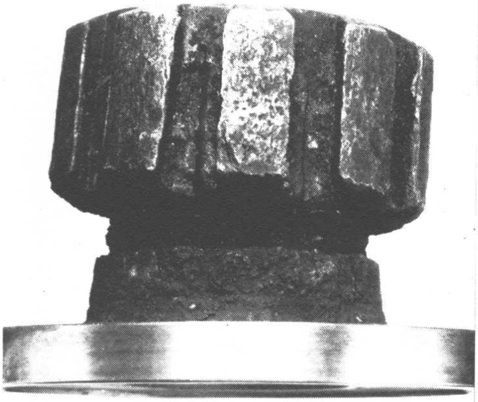
Fig. 1.1 and 1.2. Poor welding of a chain link, longitudinal section. Etch: Nital

Fig. 1.1. Overview 10 ×. Overheated and molten spots from current entry at both sides of non-bonded weld

Fig. 1.2. Elongated grain structure through cold deformation at welded joint. 100 ×



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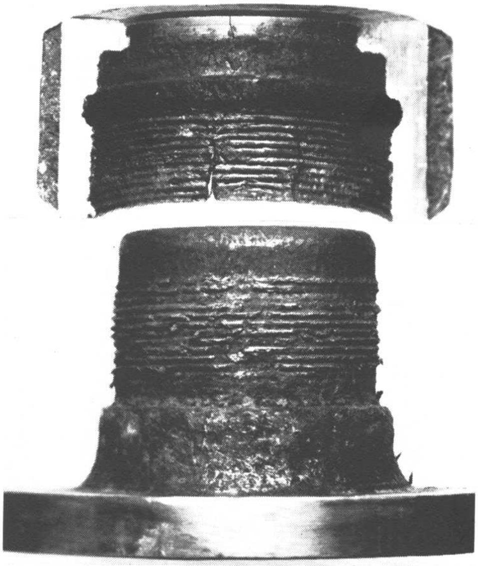

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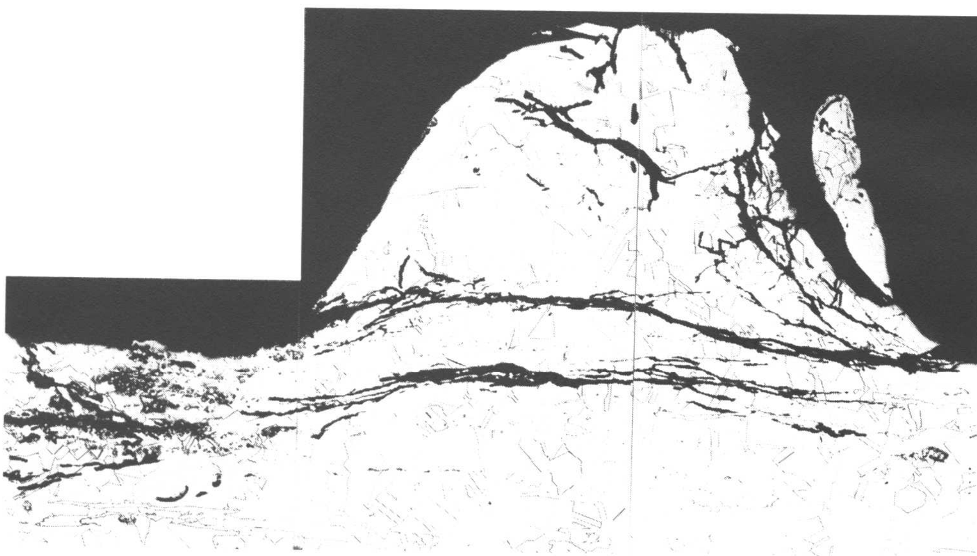

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Fig. 1.3 to 1.5. Ring from safety valve of seagoing vessel destroyed by stress corrosion

Fig. 1.3. External view. 0.7 ×

Fig. 1.4. Internal view after cutting open of the ring. 0.7 ×

Fig. 1.5. Longitudinal section through thread of bushing. Etch: V2A-etchant*. 85 ×

* For composition see Appendix II

1.2 Procedure

After the history of the failed object has been determined, the part itself should be thoroughly examined. Especially important are the state of the surface and in case of fractures, their origin and nature. If only one single broken specimen is available from which the configuration of the entire piece cannot be reconstructed, a sketch should be procured from which this can be determined.

The cause of many failures can be determined best by careful examination of the surface with either the naked eye, a hand-held magnifying glass, or a binocular microscope. High strength wires are especially sensitive to surface damage. An example:

Non-magnetic stainless steel wires of 0.7 mm diameter with approx. 18 % Cr and 12 % Ni (AISI type 304L) which were cold drawn to an ultimate strength of 1570 to 1770 MPa (228–257 ksi) frequently broke during a not specified "klanken test"* (a dynamic, free-handed loop tensile test) and occasionally during drawing. It should be noted that the wires predrawn to 1.5 to 1.25 mm diameter were subjected to an intermediate anneal in a continuous furnace, protected by an atmosphere of cracked ammonia at 1020 °C, but without removal of the stearate that had been used as lubricant. Initially the fracture occurred after minor cold working. There did not seem to be any relationship to the melting practice, nor was this probable, since the failure occurred sometimes in certain places of the same coil, while in others none occurred. But observation had shown that wires of 7 mm diameter were especially susceptible to such failure, while thicker of thinner wires were less susceptible. Also wires made of stainless steel with approx. 10 % Cr and 9 % Ni (type 302) showed less tendency to break, even though the leaner nickel austenite is less stable, than did wires made of more nickel-rich non-magnetic steel with approx. 12 % Ni (type 305). The wire manufacturer had exhausted all means of determining the cause of failure, and thus the Max-Planck-Institut für Eisenforschung was requested to undertake a special investigation and conduct micro-analytic and magnetic tests, as well as X-ray analyses.

During an interview and an inspection of the wire drawing plant the necessary samples were selected, namely satisfactory as well as defective coils of both steel types and various diameters. In addition, good and bad spots were also collected from coils that showed different behavior during drawing or during klanken testing.

The manufacturer's observation that even within the same coil local differences in tendency for crack formation had occurred, lead to the suspicion that the fractures had some connection with local drawing or surface defects. Before starting with the desired special testing program, all wires were examined over their entire length with a binocular microscope at twenty times magnification. Furthermore, at good and defective sites, klanken tensile tests of the dynamic type used by the manufacturer (designated in the following as klanken tear tests) were conducted and supplemented by static tensile tests using knotted round wires.

Regardless of the type of steel, heat to heat variation, or dimensions, surface defects of various kinds could be determined in those spots displaying poor klanken tear behavior, while the satisfactory sections were smooth **(Fig. 1.6)**. Failures were mostly initiated in longitudinal grooves **(Fig. 1.7)** where the wires sometimes developed cracks during drawing **(Fig. 1.8)**.

In the transverse section, surface defects showed up as rough spots or laps. **Figures 1.9 to 1.11** show these in comparison with a smooth surface. In one coil, sections were also made of some drawing defects in addition to the surface defects and the slight cracks originating from them. They were associated with surface carburization effects **(Fig. 1.12)**. Both satisfactory and unsatisfactory specimens showed the same structure of strongly deformed austenite with a small amount of elongated ferrite **(Fig. 1.13)**.

A comparison of all the manufacturer's observations with the results of many hundreds of klanken tear tests and the accompanying examinations showed the existence of a definite con-

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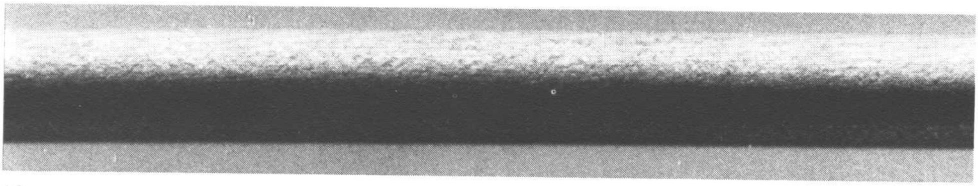
* see Appendix I

nection between the surface defects and failure during klanken tear testing. Finally it could be predicted from visual surface inspection whether the klanken tear tests would lead to fracture or not. The knotted round wire tensile tests, conducted according to a German standard procedure*, was less reliable than the klanken tear test.

According to these macroscopic tests, supplemented by only a few microsections, it could be established that the failures observed in these high strength wires after a minor increase in strength were caused by comparatively insignificant surface defects. In addition, crack formation during drawing was apparently promoted by carburization, which probably resulted from the adhering lubricant. Therefore it made no sense to conduct any further tests as per the original request.

* DIN 51214



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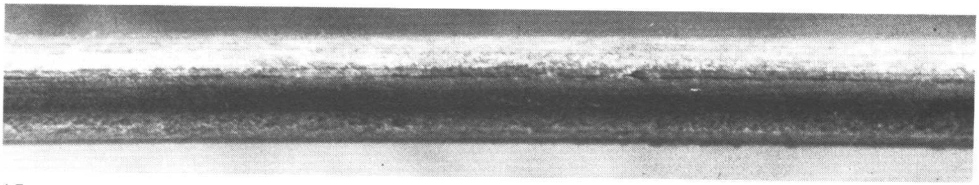

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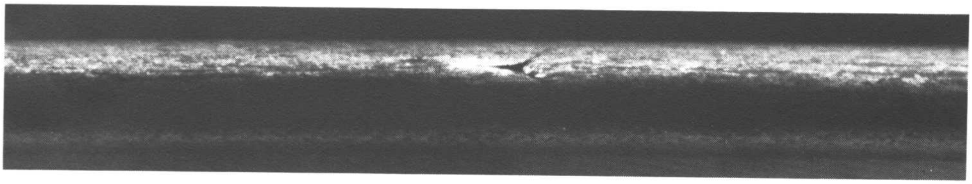

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Fig. 1.6. to 1.13. Austenitic steel wires drawn to high strength that broke in part during **klanken** tear test

Fig. 1.6. to 1.8. Surface view. 20 ×
Fig. 1.6. Smooth area
Fig. 1.7. Spot with groove
Fig. 1.8. Spot with incipient crack

Fig. 1.9. to 1.11. Unetched cross sections. 500 ×
Fig. 1.9. Smooth area
Fig. 1.10. Average condition
Fig. 1.11. Individual deep grooves

Fig. 1.12. Tensile crack at spot carburized by drawing lubricant. Etch: V2A-etchant. 200 ×

Fig. 1.13. Grain structure in longitudinal section. Etch: V2A-etchant. 500 ×

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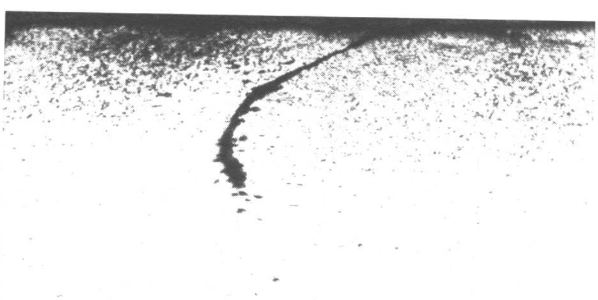

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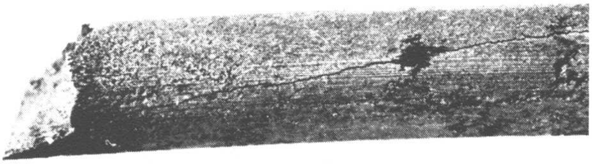
The cause of the frequent cracks of high strength tensile wires in a prestressed concrete structure could also be found merely by visual inspection of the wire surface. The cracks and fractures originated in small corrosion pits **(Fig. 1.14 and 1.15).** Such oxide pits act as very sharp notches especially under fatigue stresses. Stress concentrations form at the bases of these notches (see also section 15.3.4.2). The wires were of high quality, free of defects as established by metallographic and mechanical tests.

The previous examples have shown the importance of a preliminary thorough visual inspection of the defective specimens. For this purpose the materials test engineer should allow sufficient time. In almost all cases this effort will be worthwhile. This is particularly true of fractures (see also section 2.1). In addition to the location of the fracture origin and its structure, the surface condition at the origin of the fracture is of interest.

Prior to sectioning of the specimen, a photograph or sketch should be made in which the subsequent sections should be drawn in. All parts should be clearly designated, so that their position in the specimen can be reestablished later. The next failure analysis shows that errors can occur even at this stage, which may later produce defects.

A **bone drill** of stainless tool steel[1]) fractured during drilling of the marrow cavity in the leg of a patient which should be splinted subsequently by driving a pin through the fracture. The fracture propagated from a fatigue crack shown in **Fig. 1.16** and is designated with A2. At the fracture origin, the remains of a number could be seen **(Fig. 1.17)** which had been inscribed with an electrical engraving tool. The larger part of this number was on the unavailable opposite fractured part. The cross section of the drill was weakened at this point by a milled groove from whose edge another fatigue fracture propagated (A1). A longitudinal section through A2 showed that the material had melted and hardened during cooling. It also showed several incipient cracks **(Fig. 1.18).** This crack initiation led to the formation of the fatigue fracture. Any damage to the surface should be meticulously avoided, especially in specimens which are cyclically stressed.



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1.15

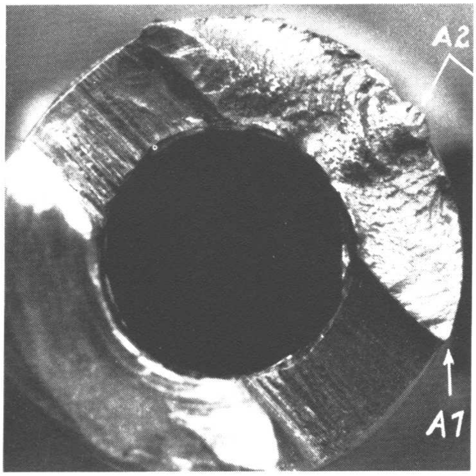
Fig. 1.14. and 1.15. Broken hard drawn high strength tensile wire of 4.5 mm thickness and 2160 MPa (313 ksi) strength. Fracture origin: Corrosion pits that were present already prior to assembly

Fig. 1.14. Surface, pickled with ammonium citrate solution

Fig. 1.15. Longitudinal section through corrosion pit, unetched. 80 ×

This may be illustrated by the following failure analysis:

A **rear-axle side shaft** of a truck broke during driving. It was said to consist of chromium-molybdenum alloy steel of AISI type 4140 and heat treated to 460 to 515 HB. The automotive manufacturer wished to find out if quality and heat treatment corresponded to standards. The fracture of the shaft was of a torsional nature that propagated from a small fatigue crack **(Fig. 1.19).** It originated in grinding grooves which in turn were caused by the grinding of a flat plane for a Brinell hardness test **(Fig. 1.20).** Such grinding grooves are deep notches at whose bottoms



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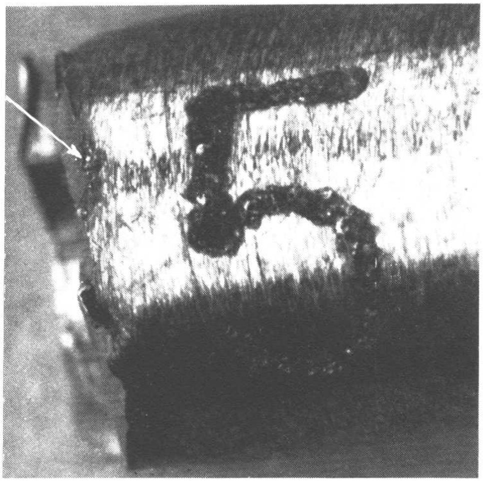

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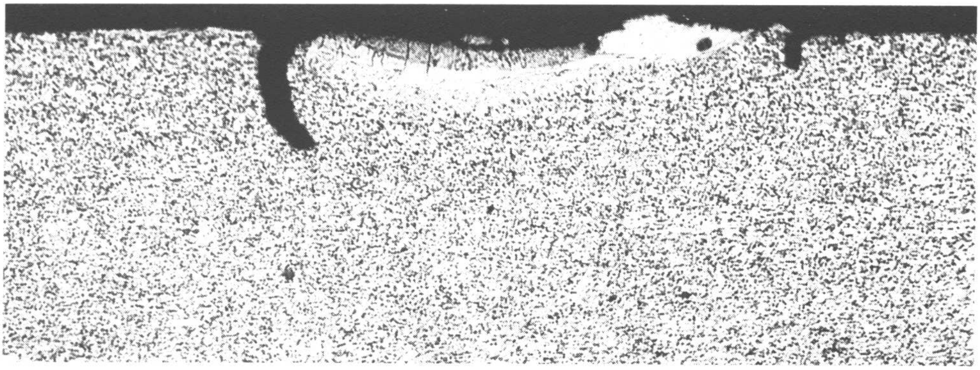

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Fig. 1.16. to 1.18. Bone drill broken by burn of electrical engraving tool

Fig. 1.16. and 1.17. Views 10 ×. Fatigue fracture propagated from A1 and A2

Fig. 1.16. Fracture plane

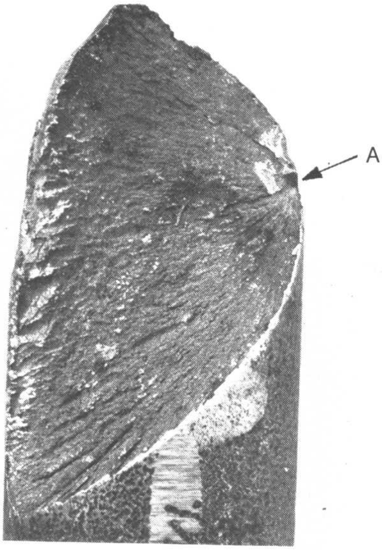
Fig. 1.17. Surface at fracture

Fig. 1.18. Microstructure at fracture origin A2. Longitudinal section. Etch: V2A-etching solution. 250 ×

high stresses concentrate (compare with section 2.1). Chemical and metallographic tests showed that steel quality and heat treatment were satisfactory. But the martensitic structure indicated that the tempering temperature was fairly low. In consideration of this fact, the hardness which ranged from 572 to 606 HV 10 was extremely high. The high hardness, although not damaging to a smooth surface, here prevented stress relief by deformation in the grinding grooves. The fracture therefore was caused by grinding grooves and the high notch sensitivity of the hard material.

Only after a thorough examination of the specimen from all sides, as well as taking of a photograph or making a sketch, test specimens can be prepared. In some cases it may be useful or necessary to resort to non-destructive testing or pretesting[2]).

The pieces should be inspected thoroughly during sectioning of the specimens for metallographic examination. Jamming of the saw or separating of the cut may indicate high residual stresses that are relieved through the section. Spark formation during grinding may point to the presence of certain alloying elements. During cutting and working of the specimens, slow reduction and adequate cooling are essential, especially in the case of hard or high work-hardening steels. These precautions may prevent formation of cracks whose origin might later be subject to misinterpretation (see also section 8.2)[3]). For the same reason pickling with hydrogenating acids is an unsuitable method for exposing cracks or developing the primary microstructure in these steels (see also section 9.1)[4]). Magnetic particle testing or the dye penetration method and primary etching with copper ammonium chloride solution according to Heyn are preferable in these cases.



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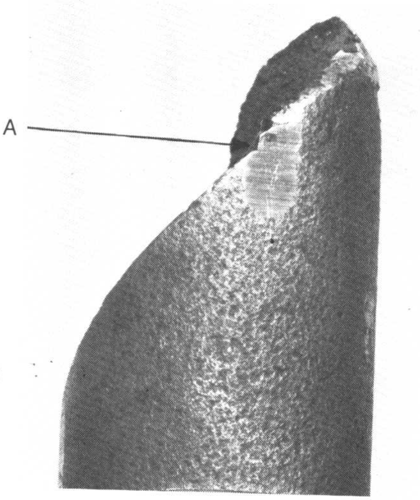

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Fig. 1.19 and 1.20. Rear axle side shaft with torsion fracture originating at grinding mark (A). 1 ×

Fig. 1.19. Fracture

Fig. 1.20. Surface at fracture origin