

SERVICE FAILURES OF ENGINEERING METAL COMPONENTS

By

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ABSTRACT

Machines of conventional design often suffer serious service failures. Various contributory factors thereto have been examined in this short paper such as unsuitable choice of materials, faulty melting and processing history, faulty heat-treatment, poor machining and surface finish, careless handling and last but not the least the damaging effects of stress-raisers, notches etc., in relation to fatigue failure of metals.

The paper is illustrated with brief accounts of some typical service failures investigated in the two year's old National Metallurgical Laboratory.

INTRODUCTION

It has often been stated that great majority of the failures of engineering components encountered in service, are caused by fatigue. Whilst this is generally true, quite a few other important metallurgical factors also exercise considerable influence on the service performance of metallic materials. Good designs are at times totally wrecked by faulty production and processing methods, improper heat-treatments, use of wrong materials without taking into consideration their notch-sensitivity and damping effects, inferior workmanship, poor machining and surface finish, careless handling etc; each of these factors contributes to the potential grief when the inevitable failure has occurred.

The following broad factors are now generally established to affect the serviceability of a metal part singly as well as through their combined incidence under service conditions:—

(a) Choice of the material:

Selection of the materials does not merely imply the chemical composition of the metal or alloy to be employed but its careful scrutiny and choice based on notch-sensitivity data and ability to resist brittle fracture under conditions of service temperature and stresses. Melting history of the metal should be taken into account. In the case of steel, for instance, the mode and extent of its deoxidation during steelmaking will determine a host of its structural and physical properties such as austenitic grain-size, notched-bar impact values at room and sub-normal temperatures, transition temperatures and susceptibility to quench and strain-ageing etc. The practical importance of some of these factors can be illustrated by the developments of ferrous materials with low sensitivity to quench and strain-ageing such as austenitic grain-refined 'Izett' steels developed in Germany and the U.S.A. for applications in boiler steel plates and tubes liable to severe strain-age embrittlement at steam generating temperatures and pressures. Grain-refinement can be conferred on steels through judicious additions of aluminium during their de-oxidation.

A study of melting history of steels will provide clues to the formation of hair-line cracks or flakes which act as potential nuclei for severe stress concentration leading to eventual fatigue failure of the material, forming what is known as 'transverse fissures' in rails, railway tyres and wheels etc. The origin and development of these hair line cracks in the sectional thickness of steel, is believed to be due to intergranular weakness derived from factors associated mainly with steel-making, fabrication and heat-treatment of the product. Data contained in the technical literature are not so far unanimous in attributing this phenomenon to any well-defined set of conditions.

It is however, understood that steel-making conditions involving the solubility of gaseous elements like hydrogen, oxygen and nitrogen in steel, the conditions of deoxidation in final stages of steel-making, teeming conditions and, last but not the least factors associated with heat-treatment and fabrication of the material particularly in its final rate of cooling—all play a part in bringing about a state of inter-granular rupture in the finished product.

(b) Thermal history :

This again does not merely refer to well-known conventional modes of heat-treatment but includes the application of thermal cycles that will develop suitable structures in terms of carbide distribution, lamellar spacing of pearlite, grain size etc., designed to yield superior transition temperature ranges under service stresses, high notch ductility etc. Heat-treatment cycles including finishing temperatures directed to produce fine room temperature grain size are highly beneficial to steel parts operating at low temperatures and to welded or riveted steel structures. Fine ferrite-pearlite grain size confers low transition temperature ranges on the steels where the ductile shear fracture changes into the brittle, cleavage type. Where the metal products require straightening after heat-treatment, a stress relieving cycle after cold straightening will often cause a favourable balance of residual stresses developing high endurance limits and ensuring freedom from fatigue failure. Decarburisation and scaling of the metal surface should not be permitted. In spring steels, a soft decarburized skin gives shockingly low endurance limits and can be prevented by regulating furnace atmospheres to eliminate surface oxidation and scaling.

(c) Mechanical properties of the material :

The requirements in respect of mechanical properties do not again merely signify ability to meet the required service loads based on conventional safety factors. The whole aspect needs careful study in as much as the design should involve the use of lower strength materials as far as permissible that would be less sensitive to notch-effects and surface irregularities, which, however, rigid the inspection may be, can seldom be completely eliminated. The old method of fighting fatigue flaws was to increase the tensile strength and thereby the endurance limit of the material. But in this way the material becomes less ductile, and it can much less readily accommodate and favourably distribute local stress concentrations occasioned by rough-machined surface and other notch effects.

(d) Proper working conditions :

It is highly essential that stipulated service conditions should be strictly adhered to. Although all engineering components are designed to allow occasionally certain overload performance, repeated and unspecified over-stress applications are sure to spell disaster. This applies with equal emphasis to the maintenance of optimum working temperatures, controlled atmospheres during heating etc. In steel rolling mills, persistent over-loading of chilled iron-rolls, giving repeated over drafts without the required cooling down of the rolls, may increase the short-time output but will certainly cause premature breakage of the costly roll and overall loss of production. An occasional over-load or over-stress (stress above the endurance limit of the virgin material) is often imposed on a member say, for instance in automobile leaf-springs without any immediate detrimental results but it is the frequency of such over-load applications which will determine their service life. Endurance limits are very much less for repeated over-stress conditions than the fatigue values used for design purposes, based on laboratory tests.

(e) Strain-ageing and work hardening :

Not only should materials be chosen for optimum strength but due account must also be taken of their ageing characteristics following inevitable strains unavoidably introduced in them during hot and cold forming, fabrication, welding and riveting etc. This applies to materials employed for boiler-tubes and plates, ship-plates, bridge-structures and a host of other engineering products. A material susceptible to strain-age embrittlement can develop subsequent to work-hardening, yield points almost equal to its original ultimate strength accompanied by serious impairment of its ductility, besides acquiring a high degree of notch-sensitivity. The effects of strain-ageing also extend to raising the brittle transition temperature ranges of mild steels. Notch-sensitivity of a material will determine its ability to deform in presence of a notch

or fatigue crack. Soft metals like copper for example exhibit considerable ductility and deform more than relatively harder metals before a major fracture develops.

(f) Damping capacity of materials:

Considerable attention has been directed towards an assessment of damping characteristics of metals i. e. their capacity to damp out vibratory stresses. A metal with high damping capacity can convert the applied energy induced through oscillating stresses, into thermal internal losses and thus damp out the vibrations set up. Cast irons possess high damping capacity and plain carbon steels have fair damping capacity, whilst hardened alloy steels have low damping values.

(g) Fatigue failures involving stress-raisers, notches, sharp corners, abrupt changes of cross sections, small fillet radius, poor surface finish, careless handling during and after fabrication etc.

About 80% of service failures are attributed to fatigue due to one cause or the other. To the designers falls the initial burden of drawing up material specifications, stating finish demanded, designing oil holes, splines, threads, fins, changes in section and the variety of seemingly unimportant details that will ultimately make or mar the design and structure.

It is generally accepted that for a large variety of steels, the limiting fatigue stress on a plain specimen, possesses a fairly definite relationship to tensile strength. The ratio is usually 0.45—0.55, reaching in special cases up to 0.65. Fatigue tests on plain specimens bear no relationship to notch-brittleness or notch-sensitivity. One might consider resistance to fatigue as the resistance to the birth of a crack and notch-bar impact toughness as the resistance to the propagation of that crack. There exists no relationship between static notched-bar toughness and notch sensitivity under fatigue. In general, with a higher tensile strength the greater is the notch sensitivity and the poorer the notch ductility. This may not hold true for specially processed steels possessing inherent fine austenitic grain-size.

If localized stress-concentration takes place at any notch, internal inhomogeneity or external surface, defect, serious havoc may result. The distribution and intensity of stresses at a notch or sharp metal corner is something like the turbulence caused in the flow of a swift-moving water stream around a rock or sharp obstruction. The sharper or deeper the notch the greater its effect. In a fully elastic material, a round notch or hole may multiply the applied stress three-fold. As the sharpness at the root of a notch or at the apex of a discontinuity increases, the stress multiplication correspondingly increases. At the tip of an infinitely sharp crack e.g.—the stress too would approach an infinite value. In practice circumferential tool and machining marks or grinding scratches can give rise to severe stress-concentration which may exceed the endurance limit of the material, with the result that a minute fatigue crack results. In other words, stress-raisers like notches and fillets provide a high intensity of local shear stresses, so that nominally low stresses on repeated application will give rise to a minute crack at the point of greatest shear stress which lies at the root of the notch. The crack once formed further aggravates the stress distribution, since it constitutes an almost infinitely sharp notch, still severer concentration of service stresses thus occur; the process continues with the result that the material is gradually severed into two parts. The process may go on unnoticed until the residual mass of metal, unable to withstand the strain of operational stresses, tears suddenly apart through a shock fracture and the component becomes scrap. It is a remarkable testimony to the strength and ductility of metals, that at times 5—10% of the original sectional thickness holds out to the last before the final failure takes place.

Thus the presence of stress-raisers may convert a ductile material into a brittle material failing at considerably lower loads than it was designed originally to withstand. The nucleus for a fatigue failure can be a tiny surface spot which only rigid and careful inspection can reveal and cause to be removed or a sharp fillet or corner or sudden changes in cross-section, exposed threads etc.

Multitudinous examples of potential sources of stress raisers abound in the technical literature e.g. keyways—a potent source of nuclei for fatigue failure, sharp V—roots at the gear-teeth

and threads, tiny and sharp oil-holes, rough weld surfaces, slag particles in the welds, under-cut-welds, hair-line cracks due to hydrogen-embrittlement-potential nuclei for transverse fissures in rails, tyres etc. Superimposed on these stress-raising factors is the incidence of internal residual stresses within the structure. The above inhomogeneities and crack effects may give rise to severe tri-axial stresses, in the case of welded structures under the constraint effect provided by the rigidity of the structure and cause brittle failure.

The great importance of rounding off sharp corners, grinding and polishing-off rough machining marks, eliminating all notches, scratches, hammer marks or indentations from the surfaces of machined parts, can never be over-emphasized.

The old term 'crystallisation' or re-crystallisation' so often employed in early days of fatigue failures, is a misnomer. The metal does not fatigue, tire out, crystallize or re-crystallize; it is only the crystalline appearance of the last portion of the residual metal to finally tear a part which brought in this inappropriate term into vogue. Fatigue fractured areas on the other hand, present a typical fan-like, radial pattern. A fatigue fracture normally starts at a stress-raiser on the metal surface and progresses gradually by fits and starts with the gradually parting surfaces rubbing against each other thereby developing the typically smooth and fan-like burnished surface appearance. Prevention is always the best cure and there are a host of use ful remedial measures designed to rectify stress-raising influences at the metal surface by subjecting the latter to suitable treatments. These measures depend upon the material being used and the working conditions under which the latter has to give service. Thread rolling, short-peening and slight cold working of surfaces, changes in thermal-treatment to relieve internal residual stresses or favourably limit their intensity and distribution, are some of the measures well known for developing resistance to fatigue failure of service parts. The highly important part which corrosion plays in causing corrosion fatigue, fretting fatigue, stress-corrosion, season-cracking etc are well-known. Technical literature is full of detailed accounts of actual service failures attributed to one factor or the other outlined above or to their combined incidence under operating conditions. The author* has given accounts of investigations relating to service failures such as relating to railway materials like rail and tyres due to 'transverse fissures',¹ caustic embrittlement of boiler and rivet steel², inter-crystalline failure of bullet-proof armour-plate,³ heat-treatment of silico-manganese spring steel⁴ etc.

A short account of some typical service failures investigated in the two years' old National Metallurgical Laboratory should further serve to illustrate some of the factors so far discussed, which contribute to practical failures or erratic service performance.

(a) Failure of a steel driving shaft of a grinding mill through fatigue :

It was reported that a steel shaft of a grinding mill had broken in service after a very short life. The steel conformed to B.S.S. 970-En. 9.

Chemical Analysis :

		Percent
C	..	0.52
Mn	..	0.73
Si	..	0.33
S	..	0.040
P	..	0.035
Ni, Cr, Mo	..	traces
V	..	nil

Macroscopic Examination :

Transverse and longitudinal diagonal slices were taken from near the fracture face for macro-examination including hair-line crack detection. No abnormality was observed.

* References are at the end of the paper.

Microscopic Examination :

Specimens for micro-examination were taken from near the fractured face. Coarse sorbitic grains enveloped in ferrite meshes were observed. The micro-structure showed the steel to have been normalised.

Physical tests :

Longitudinal test specimens machined out of the shaft gave the following results :—

Tensile Test Results

% Elongation on 2" G.L.	..	17.18
% Reduction of area	..	28.15
Tensile strength	..	47.63 tons/sq. in.

Izod Impact Test

Average Izod Impact Value	..	8.3 ft. lb.
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Hardness Test

Hardness values were determined by Brinell Hardness Testing Machine, the average of which was B.H. No. 208.

The steel employed for the broken shaft conformed to B.S. specification No. 970-En. 9 in respect of chemical composition and physical tests in the normalised condition.

Macroscopic and Microscopic examinations did not reveal any abnormality. The structures observed were normal for the steel employed.

An examination of the broken face showed a clear cut fracture as shown by the complementary fracture faces (Figures 1 and 2). It would be observed from Fig. 3 that the surface of the steel shaft adjacent to the fracture was badly machined and poorly finished. The fracture took place along the line AB as shown in the attached drawing Fig. 4 Although a fillet of 1.8" radius was shown in the drawing along AB, this was not actually provided in the shaft. Instead, there was a very sharp corner from which the shoulder part ran sharply out.

A high degree of stress concentration would be caused under service conditions at this sharp corner, from which progressive cracking took place all round the circumference and developed gradually inwards toward the centre of the steel shaft. Rough surface finish of the stressed sharp corner would contribute to such cracking. A generous radius provided at the corner along with proper surface finish would avoid possibilities of such a failure.

Another case related to the failure of bearing bolts of 70 H.P. Diesel Engine. The premature failure of the bolts was due to fatigue crack starting from deep and sharp grooves at the start of the threaded portion of the bolts. Severe stress concentration took place at those sharp edges of the bolt and caused fatigue failure of the material. Suitable rounding off the edges of the groove could have prevented the failure of the bolts.

Another case related to the failure through corrosion-fatigue of over-head copper wire drop-pers of an electric railway.

(b) Illustrating the factor 'choice of material' an example is given of the effect of inappropriate steel-making conditions on the performance of free-cutting steel made to B.S.S.—En. 8-M specification for textile spinning rings. Parts made of this steel were to be forged, machined and carburized to yield a final hardness of R.C. 64 minimum. Products made out of this steel made in open-hearth furnace gave good results whereas those made out of electric furnace steel did not machine freely or give a uniform final hardness following the heat-treatment cycle.

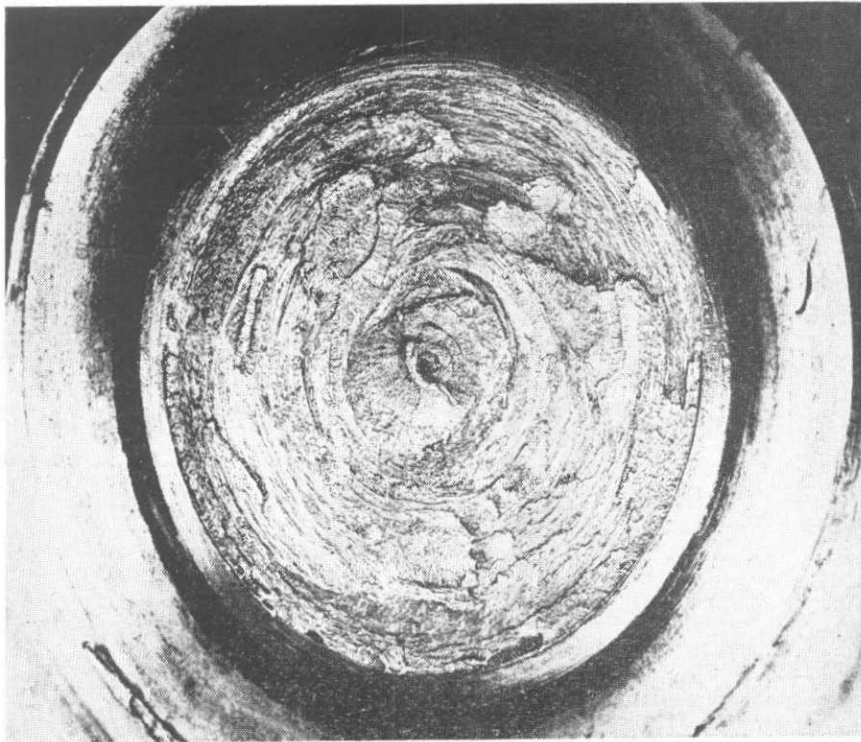


FIG. 1. Photograph of the Fracture in the Shaft. (Reduced to $\frac{1}{2}$ Full size).

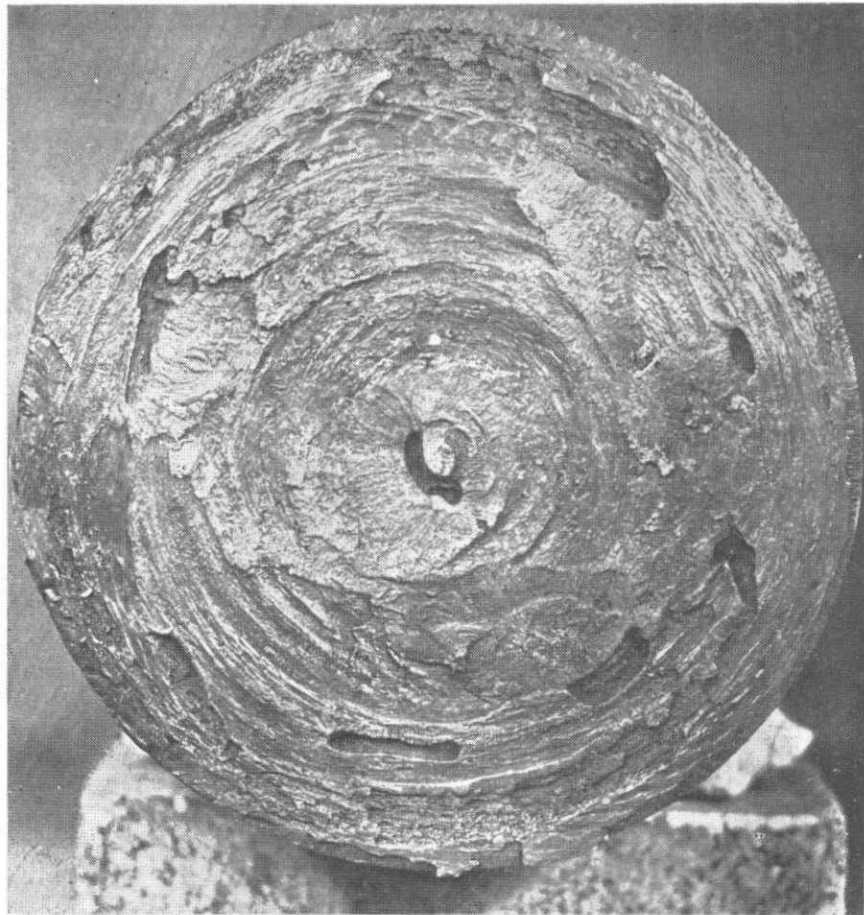


FIG. 2. Photograph of the complimentary Fracture Face (Reduced to $\frac{3}{5}$ Full size).



FIG. 3. Same as Fig. 2 taken from a side, showing Sharp Corner and poor surface finish

ROUGH MACHINE

FINISH MACHINE

GRINDING FINISH

A-B FRACTURE ALONG A-B

X-X' NOT ACTUALLY PROVIDED IN THE SHAFT

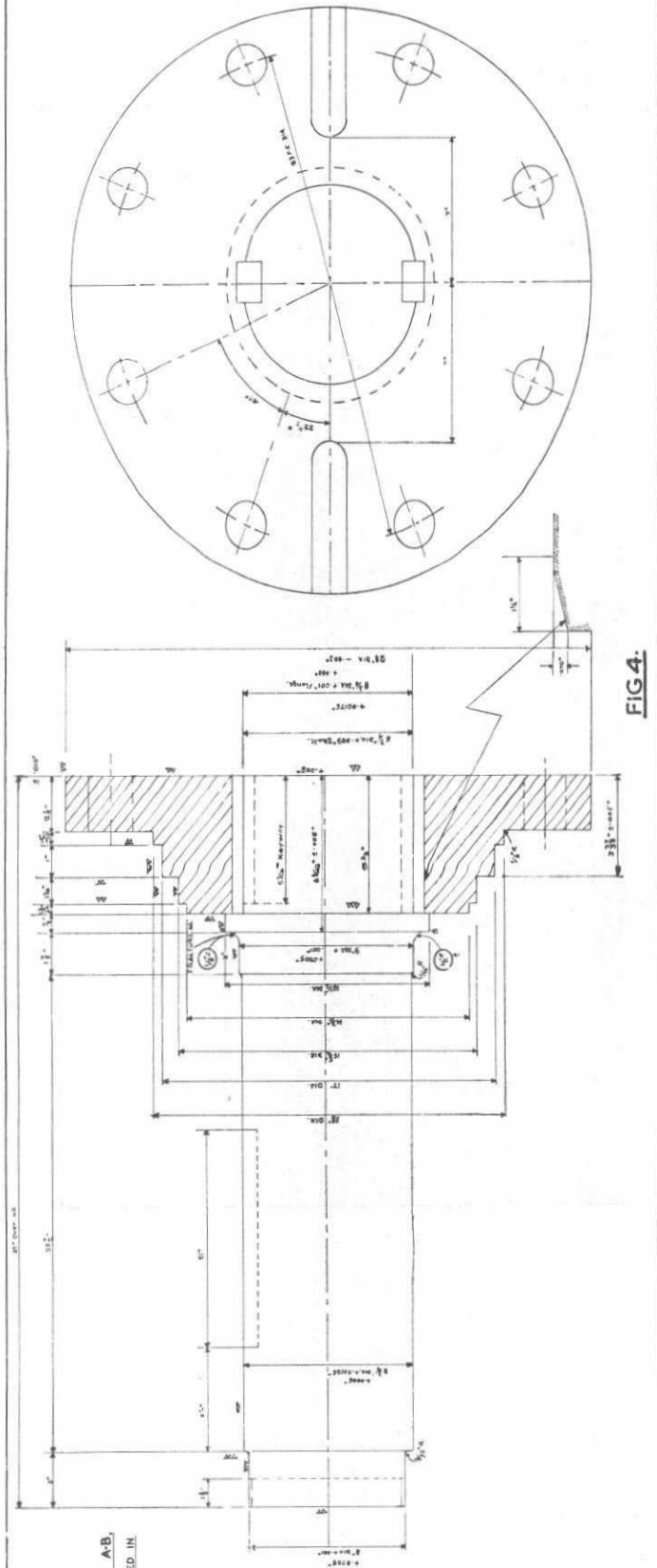


FIG 4

Chemical composition of the steels:

	C%	Mn%	Si%	S%	P%
Steel I Electric	0.41	1.05	0.18	0.202	0.040
Steel II Open-hearth	0.43	1.01	0.015	0.165	0.035

The two steels were further analysed as follows:—

	Aluminium in solution %	Al ₂ O ₃ %
Steel I Electric	0.075	0.044
Steel II Open-hearth	0.006	0.007

Micro-examination:

Micro-examination of the two steels was conducted at length. Steel I showed a highly banded structure as depicted in Fig. 5 whereas Steel II exhibited a very satisfactory micro-structure as shown in Fig. 6. The presence of 'banding' in the structure of Steel No. 1 is a detrimental feature.

Austenitic Grain-Size Test:

The McQuaid-Ehn grain-size test was carried out in accordance with the A.S.T.M. grain-size test No. E-19-46 and showed steel No. 1 and II to be inherently fine and coarse-grained respectively. This is shown in Figs. 7 and 8. Grain-growth characteristics of the two steels were further investigated with increasing temperatures as follows:—

TABLE I
GRAIN GROWTH CHARACTERISTICS WITH TEMPERATURE

Ref. No.	A.S.T.M. Grain Size No. at deg. C.				
	850	900	950	1000	1050
Steel I	8	8	7-8	6-7	4-5 fine grain
Steel II	4-5	3-4	2-3	2-3	1-2 Coarse grain

These tests clearly revealed that steel I was of fine-grained type and resisted grain-coarsening at high temperatures whereas Steel No. II coarsened rapidly at increasing temperatures.

It was further observed that Steel No. 1 developed after pack-carburizing as required in the Grain-size test what is known as an 'Abnormal' structure. Abnormal structure does not lend itself to satisfactory hardening following carburisation. This abnormal structure of steel No. 1 is shown in Fig. 9.

Steel No. II on the other hand, gave a satisfactory pack-carburized structure which is termed



FIG. 5. Pronounced Banded structure of Steel I. Etched in Nital x-250.

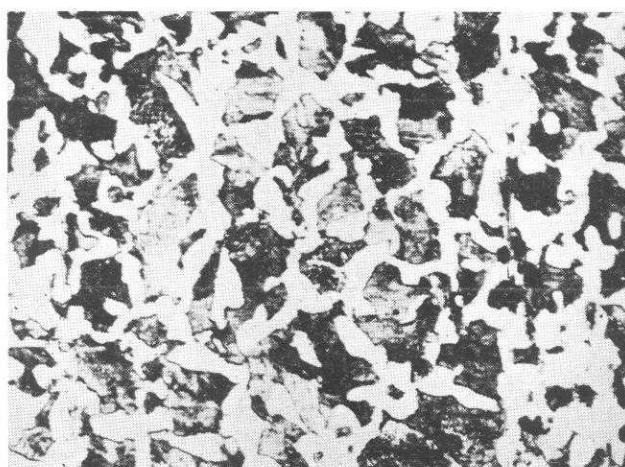


FIG. 6. Structure of Steel II, free from Banding. Etched in Nital x-250.



FIG. 7 McQuaid Ehn Grain-size No. 7-8 of Steel I. Etched in Sodium Picrate x-100.

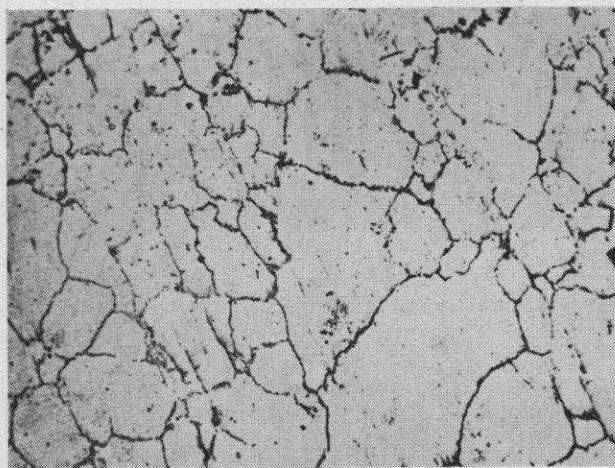


FIG. 8. McQuaid Ehn Grain-size No. 3 of Steel II. Etched in Sodium Picrate x-100.

'Normal' and gives excellent response to post-carburising hardening. This normal structure of Steel II is shown in Fig. 10.

From the chemical composition of the two steels it was clear that steel No. I had been heavily deoxidized as shown by its higher silicon and aluminium (in solution) contents. This steel also depicts a highly banded micro-structure (Fig. 5). Both these features lead to the pointer that excessive oxidation of the steel bath had taken place during steel-making which necessitated an excessive use of deoxidants like silicon and aluminium. In technical language it may be said, that this steel had been doped with aluminium at later stages to rectify an excessively oxidized bath—a condition which should not have been allowed to develop in the first place. Highly banded structure of this steel indicated unsuitable steel-making and teeming conditions and is often attributed to various metallurgical factors such as excessive inter-dendritic segregation of elements like carbon and phosphorus, resisting subsequent homogenisation. Banded structures also cause poor machinability and should be avoided.

The 'Killing' of Steel No. I with silicon and aluminium etc. conferred on it an inherently fine-grained structure as shown in Fig. 7—a highly desirable feature for a set of physical properties and number of applications but least desired for parts such as under investigation, of free-machining high sulphur types requiring high machinability and hardenability.

Coarse-grained structures cause improved machinability. Such grain-coarsening can be developed at normal heat-treating temperatures as shown in the case of Steel No. II in Table I.

Steel No. I which is inherently fine-grained, on carburisation developed an 'Abnormal' structure caused by the divorcement of Pearlite and subsequent coalescence of cementite into white ridges. Such a structure cannot be uniformly or fully hardened following carburisation. Besides, inherently fine-grained steels are shallow hardening and are unsuitable for parts requiring deep hardenability.

The object of high sulphur in free-cutting types of steels is to ensure good machinability through the presence of sulphide inclusions. Heavy additions of de-oxidizers like aluminium necessitated to rectify steel bath conditions may give rise to silicate and alumina inclusions which impair machinability. This factor besides grain-refinement appears to contribute to poor-machinability of Steel No. I.

In view of above considerations, it is recommended that steel-making practice should be so controlled as to avoid excessively oxidized bath conditions. The use of highly oxidized steel scrap should also be avoided. For high sulphur, free-machining types of steels excessive use of deoxidizers like silicon, and aluminium should be restricted so as to ensure an inherently coarse-grained steel. Coarse-grained structures should improve the steel's machinability besides preventing the formation of an 'Abnormal' structure during carburisation, which would on subsequent hardening, cause 'soft spots', shallow and non-uniform hardenability.

Inherently fine-grained steels are not suitable for applications intended herein although these are greatly favoured for multitude other purposes where high sulphur free-cutting types of steels are not required.

It is believed that with the above precautions, satisfactory electric steel can be made which should give good performance for the manufacture of spinning rings.

(c) To illustrate the effect of irregular and over-load working conditions on service failure, an example is given of the failure of a chilled-iron roll in a mill-wright shop engaged in hot rolling of steel sheets.

The roll had broken near the neck on the drag side of the roll. The depth of surface chill specified was 9/16" to 3/4". No surface defects were observed on an at-site inspection of the roll in their hot-mill plant.



FIG. 9. Highly Abnormal Structure of Steel I on pack carburisation. Etched in Nital x-1200.

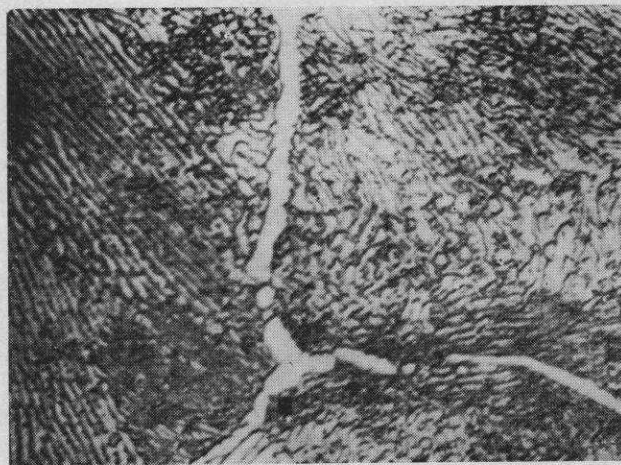


FIG. 10. Perfectly Normal Structure of Steel II on pack carburisation. Etched in Nital x-1200.

Chemical composition :

The chemical composition of the roll is as follows:—

	Percent
Combined Carbon	1.10
Graphitic „	2.01
Silicon	0.63
Phosphorus	0.48
Sulphur	0.09
Manganese	0.40
Molybdenum	0.29
Chromium	0.12
Nickel	0.17

Hardness Test :

Hardness values were determined by means of a Pyramid Hardness testing machine on samples taken from near the fracture area surveying the hardness values from the chill-surface towards the core of the roll. The depth of chill was observed to be about 1-1/4" with an average Pyramid Hardness value of 450. At the roll surface hardness was 475 V.P.H. No., about 5" away from the chill-surface the hardness value dropped to 202 V.P.H.No., with a hardness value of about 300-350 V.P.H.No. in the intermediate mottled zone.

Micro-Examination :

Micro-examination of the samples taken from near the fracture face was conducted. The chilled portion depicted normal pearlite-cementite areas characteristic of a good chill. In the intermediate zone, mottled graphite was distinctly observed changing into small graphitic flakes towards the core. The micro-structure observed was normal in all respects and showed freedom from abnormal sulphide inclusions or phosphide eutectic.

The chemical composition of the roll was satisfactory for all the elements for a chilled iron roll used in hot mill rolling of steel sheets. The micro-structure was completely satisfactory and revealed a normal chill depth. The hardness survey indicated that satisfactory chill-casting had been accomplished. The roll should have given a satisfactory life under normal working conditions.

The failure of the roll appeared to be due to external factors which may include over-heating of the roll, without adequate time given to cool it down during operation or giving a greater reduction than necessary during hot-rolling. Over-heating of the roll will induce internal stresses and strains in the massive roll casting which will in normal or over-load conditions of rolling, cause the failure of the roll.

(d) To illustrate the effects of heat-treatment cycles on the service performance of materials, an example is given of railway coiled buffer steel springs which could not after conventional heat-treatment adequately satisfy the requirements of Specifications in respect of Scragging test; either the springs broke in this test or gave a permanent set more than that specified. Thermal cycle of 'Martempering' was successfully developed and applied to the coiled buffer spring which was made out of a steel containing carbon 0.94%, manganese 0.58%, silicon .3% and sulphur and phosphorus each below 0.03%. Martempering thermal-treatment cycle consisted in austenitizing the spring steel i.e. soaking it at 800-825 deg.C. for 1/2 hour. The material was then readily transferred without loss of time to a molten neutral salt bath held at 200-245°C., and kept there for 1/2 hour followed by air cooling for hardening the spring. Since the temperature of the entire steel section had thus been previously equalised in the salt prior to hardening, complete absence of residual stresses, distortion and quenching cracks resulted. In the old conventional oil hardening of springs, a temperature gradient is set up at the surface and the core of the section—the latter cooling much more rapidly than the former in the oil-quench bath. This causes distortion of the material, internal stresses and propensity to quenching cracks besides yielding un-uniform hardening.

Finally the material is suitably tempered at about 200° C., to adjust its final hardness.

The foregoing data would illustrate the great importance of close co-ordination so necessary between the design engineer, the metallurgist, the workshop or process engineer who machines and fabricates the product and the plant engineer who has to operate and get service from it. Their close co-ordination and an appreciation of mutual requirements should provide adequate safe-guards against service failures of engineering metals and alloys. Here in India, we can greatly profit from a close study of earlier mistakes made elsewhere and evolve suitable machine designs in conformation with the now well-established factors, to which service failures have conclusively been shown to be attributed.

ACKNOWLEDGMENT

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DISCUSSION

Mr. R.A.P. Misra :

Dr. Nijhawan has stated that whenever small cracks are present either as original defects in the steel or initiated in service they will cause high stress concentration. It is wondered if this statement is altogether true, as there have been several cases of fatigue investigations in which small cracks have appeared primarily under fatigue loading conditions, but have not resulted in complete failure of the part because the stress distribution instead of being maximised has actually been relieved by the formation of very small cracks and has gone for a long time even after these small cracks have been formed.

Dr. Nijhawan :

Appreciating Mr. Misra's remarks the author stated that it is quite possible that many cracks may not give rise to complete fatigue failure should their location be not so fortitious in relation to the cyclic stress system encountered in service. Cases have been noted when small incipient crack, have suddenly stopped growing after several million reversing cycles. It is quite a complicated state of affairs to reckon; for example, one would not like to think whilst travelling by the Royal Scot at top speed that on the surface of the Loco wheels must be a multitude of grinding and braking cracks in the martensitic skin. It is not contented that each and every crack must inevitably and surely lead to complete failure but that majority of fatigue failures have been traced to the presence of such flaws giving rise to stress concentration in service, and as such it is most desirable to secure the elimination of such flaws at all possible steps.

Mr. S. Viswanathan :

If a statistical study of all failure in industry were made it may possibly be found that very few were really due to metallurgical causes. The metallurgists blamed the engineers that they were not materially minded. It was desired that as a result of this symposium the engineers should become materially minded and handle the materials properly, as wrong maintenance was really the cause of most failures. It was known that most of the engineers in industry in-charge of maintenance, really cared more for preventive measures.

Dr. A.K. Chatterjee :

Congratulating Dr. Nijhawan for his very excellent practical paper he observed that effect of notches in general, was to alter stress distribution of the system and this had been investigated by various workers including the speaker. Normally speaking, the presence of a crack or notch, in a tensile test piece acted as stress raisers and was therefore detrimental to the structure.

In case of pre-stressed materials the condition might be a little different as the presence of a notch might suitably alter the direction and magnitude of the distributed stress, as a result of which, the total stress action at the root of the notch might be far less than in its immediate neighbourhood. Hence it was thought that the occurrence of a notch may not always be injurious to a structure.

The strength of perfectly polished surfaces had been investigated by various investigators and it had been established that presence of discontinuity would cause the lowering of the strength of a material by even several hundred times. He would like to ask Dr. Nijhawan whether the same effect took place due to the presence of an incoherent precipitate in poly-phase alloy systems and also whether misfits in the mosaic blocks could cause an appreciable alteration of the fatigue strength. It would be interesting to hear the experimental procedures adopted, if any, for investigating the latter effect.

Dr. Nijhawan :

Thanking Dr. A.K. Chatterjee for his complimentary remarks, he observed that Dr. Chatterjee's findings on perfectly polished surfaces were interesting. There was little data available co-relating fatigue properties with phase discontinuities such as misfits in mosaic blocks of poly-phase alloy systems to which Dr. Chatterjee had referred. Author personally did not subscribe to the suggestion that such sub-microscopic misfits in mosaic disjunctions could materially and adversely affect the material's response to fatigue failure under normal alternating loads to which, the latter had earlier been satisfactorily tested for, under the present code of specification testing.

Mr. R.G. Bhatawadekar :

He pointed out the occurrence of failures in railway tyres. These, he pointed out, did not start from the surface, but right from inside the section from hair line cracks.

Dr. Nijhawan :

The author agreed with the remarks of Mr. Bhatawadekar and stated that he had come across several cases of railway tyres* fracturing through 'transverse fissures' arising out of minute hair-line cracks located, within the sectional thickness of the tyres. And yet before final fracturing and severance of the section, the tyres had rendered trouble free and satisfactory service life, almost fifty per cent in excess of that required by the standard railway specifications in force.

* Failures of railway materials: NIJHAWAN. B. R., Iron and Coal Trades Review 158 (7)