Strength and surface finish: influence on fatigue behaviour of steels

E. Gariboldi, W. Nicodemi, P. Pellin, G. Silva, M. Vedani
Politecnico di Milano - Dipartimento di Meccanica
Piazza L. Da Vinci 32, I - 20133 Milano, Italy

Abstract

The paper reviews experimental results published in literature about the influence of material strength and surface finish on fatigue behaviour of steels. The increasing importance of achieving accurate and homogeneous surface finishes as the material strength is increased and/or its toughness is lowered is acknowledged. Further, it is remarked that, when extremely smooth surface conditions can not be reliably obtained, the selection of high strength materials for fatigue loading could become inadequate.
Two case studies are reported in order to show the possible harmful consequences of unsuitable material selection. The first example refers to fatigue failures experienced by springs operating at relatively low temperatures. The springs, quenched and tempered to obtain high strength level, were shot-peened to improve their fatigue behaviour. This latter treatment gave rise to surface defects that acted as nucleation sites for fatigue cracks which rapidly propagated in a material embrittled by a number of factors. The second series of examined ruptures concerns rolls operating in a paper-mill plant. The cracks leading to failures were nucleated at surface pits brought about by environmental corrosive attack and propagated in a steel microstructure unsuitable to sustain the high fatigue loading.

Riassunto

Intendendo considerare l'influenza della resistenza del materiale e della finitura superficiale sul comportamento a fatica degli acciai sono state riesaminate alcune serie di dati riportate in letteratura. È stato messo in evidenza che l'ottenimento di pezzi con finiture accurate assume un'importanza sempre crescente all'aumentare della resistenza e/o al diminuire della tenacita dell'acciaio utilizzato. È stato inoltre sottolineato il fatto che la scelta di acciai ad alta resistenza per condizioni di carico ciclico può rivelarsi inadeguata nei casi in cui non possano venire realizzate superfici estremamente levigate.
Sono stati inoltre riportati due casi per mostrare le possibili conseguenze dannose di una errata scelta del materiale o delle sue condizioni microstrutturali. Un primo esempio si riferisce a rotture per fatica avvenute in molle operanti a temperature relativemente basse. Le molle, temprate e rinvenute per ottenere durezze elevate, erano state successivamente pallinate per migliorare il comportamento a fatica. Difetti e ripiegature superficiali lasciati da quest'ultimo trattamento avevano originato cricche rapidamente propagatesi nel materiale infragilito. Una seconda serie di rotture ha invece riguardato dei rulli operanti in impiamti per la produzione di carta. Le cricche che avevano determinate le rotture avevano in questo caso avuto origine in corrispondenza di vaiolature superficiali causate dall'ambiente corrosivo e si erano propagate per fatica in una microstruttura non adatta a sostenere elevate condizioni di carico ciclico.

Introduction

Fracture by nucleation and growth of fatigue cracks is a topic of great concern for designers. The important role played by fatigue is witnessed by the significant number of the fatigue failure cases, often estimated as about 90% of the mechanical failures. Fatigue has become of increasing importance as the technological development progressively led to a larger amount of equipment subjected to cyclic loads such as transportation vehicles, pumps, turbines and electric household appliances.

Failure analysis handbooks [1,2] report a number of typical fatigue cases often related to unproper design choices concerning stress cycles, overloads, stress concentration effects, corrosion, service temperature, metallurgical structure and inhomogeneities, surface conditions and residual stress distribution. The authors' current practice in failure analysis, focused above all on mechanical steel parts such as shafts, axles, gears, bolts and springs, suggests that when considering the material standpoint, a large number of failures are still due to the wrong selection of the steel grade, of its heat treatment and/or of the surface condition.

The present paper is aimed at remarking some basic aspects about fatigue properties, with special emphasis on the correlation between the fatigue limit and the steel strength level, of particular interest in the design of mechanical components. Two case studies where the wrong choices of material and of surface conditions determined premature failures will be given as examples.

Influence of strength and microstructure on fatigue properties of steel

The basic structural evolution in metal components subjected to cyclic stress was recognised since the beginning of this century. Nowadays it is well established [3-7] that the fatigue process in ductile metals devoid of significant stress raisers and structural imperfections develops through distinct stages. The first stage is crack initiation. In ideally defect-free single crystals, crack nucleation is commonly explained by means of the formation of surface intrusions and extrusions due to bundles of slip bands brought about by the accumulation of microplastic strain. Crack nucleation is promoted by extremely reduced intrusion root radii. This basic theory of crack formation can be replaced by different mechanisms in polycrystalline metals, where the surface contains a number of stress raisers such as grain boundaries, triple points, scratches and machining marks which can initiate a crack even immediately after loading. When the initiated crack length is microstructurally small (shorter than a crystalline grain), the defect grows easily until it reaches a microstructural barrier, such as for instance a grain boundary or an inclusion [8]. It can pass through the barrier and grow only when the resolved shear stress is raised over a threshold level. This mechanism of crack propagation, often referred as stage I or shear crack propagation, is clearly strongly dependant on material microstructure.

Under high stresses the crack is able to propagate through the surrounding grains while reorienting itself along the crystallographic planes nearer to the maximum applied shear stress direction. The subsequent barriers encountered by the crack along its path are gradually easier to pass and the defect progressively tends to realign to a direction roughly perpendicular to the principal maximum tensile stress.

Crack realignment according to the macroscopic stress field corresponds to the onset of the so called stage II, or tensile crack propagation stage. This stage is characterised by the crack growth through two perpendicular shear planes developed at the crack tip, and it seems not to be significantly influenced by the above mentioned microstructural barriers. The development of the crack growth stage brings about a progressive reduction of the cross-sectional resisting area eventually leading to the catastrophic final failure.

The above microstructural behaviour can be easily evaluated and predicted by means of two threshold crack lengths. The first is the maximum distance a crack can growth before a strong barrier is reached (a microstructural parameter). The second parameter, referred as the mechanical threshold lenght, is related to the stress level and to the threshold fracture mechanics parameter characterizing the crack tip [8]. The greater the difference between mechanical and microstructural threshold lengths, the more difficult and time-requiring the early steps of crack growth.

The above basic description of fatigue crack initiation and growth suggests some important features to be kept in mind when designing mechanical components subjected to cyclic loading, particularly when selecting the suitable materials and their thermal and surface treatments. A basic and comprehensive point is that, since cracks grow above all by plastic deformation, any possibility of strain localisation should be avoided [9]. Although this statement contains a number of simplifications, it helps in understanding the effects of material strength, grain size, microstructure and microstructural homogeneity on the fatigue resistance of steel [8, 10]. In fact, it is commonly established that improved material strength develops smaller plastic zones. A reduction in grain size further increases the steel strength and reduces the microstructural threshold crack length. An analogous effect on this latter parameter is obtained by means of an even distribution of microstructural barriers which minimise the mean free path between crack obstacles. Besides, microstructural homogeneity allows to avoid concentrated regions of easily extended slip planes.

On this basis, it is understood that, as a rule, the best steel treatment for optimum fatigue properties is that obtained after quenching and tempering, resulting in a homogeneous tempered martensitic structure. In this condition the fatigue limit is usually considered to be proportional to the steel hardness and to its tensile strength.

Indeed, designers can easily obtain the fatigue limit by means of the fatigue ratio, i.e. fatigue limit/UTS ratio, a characteristic parameter known for several steel families.

However, it must be pointed out that the above mentioned trend will only hold under laboratory test conditions, when perfectly smooth samples free of coarse inclusions and other structural inhomogeneities are used. When considering engineering materials, one has to face with unavoidable material microdefects. Consequently, in practice, fatigue cracks often initiate near or at singularities which may be surface scratches or machining marks, corrosion pits, inclusions, coarse precipitates and embrittled grain boundaries. These act by creating notch effects on a microscale and by introducing new interfaces from which fissures may easily nucleate or find preferential growth paths [9, 11]. Finally, it is to remind that defects may also be initially present in the material as a result of technological processes such as welding, heat treatment or plastic forming. In these cases the high stress concentrations rapidly lead to the mechanical threshold length and eventually to the crack propagation stage.

As shown in Fig. 1, experimental investigations [3] demonstrated that at the highest strength levels and/or for notched specimens the fatigue resistance does not always rise proportionally to the steel strength. It is shown that, beyond a certain limit which depens on steel structure and on its cleanliness (inclusion content) and is related to the steel strength, the fatigue limit will stop to grow and even start to decrease due to the increased material sensitivity to defects and stress raiser effects. In other words, it is suggested that the direct proportionality between hardness (tensile strength) and fatigue limit will only hold until the toughness properties are able to withstand the unavoidable defects in steel structure and on the surface.

Influence of surface finish on fatigue behaviour of steels

As already mentioned, apart from particular cases, all fatigue failures start at the surface of parts. This is true not only under bending or torsion loading conditions, where the maximum stress occurs at the surface, but also in axial fatigue due to the mentioned surface microdefects acting as stress raisers. Therefore, it is well understood that the fatigue behaviour of steels is markedly influenced by the surface conditions. Specifically, significant effects on fatigue are brought about by surface roughness and by changes in material properties at the external layers (decarburized, carburized, nitrided or induction hardened layers) or residual stress gradients below the surface, as found for instance in rolled or shot-peened parts.

A particular feature often disregarded by designers is that all the above defects and irregularities become of increasing importance as the material strength rises. A clear picture of such behaviour is given in Fig. 2 [12] where the surface factor (which reduces the theoretical fatigue limit) is plotted against the steel ultimate tensile strength for various surface conditions. These data demonstrate that the fatigue limit can be as low as 15% the theoretical limit as the steel strength exceeds about 1200 MPa and the surfaces are not properly treated.

Further emphasis on this effect is given in Fig. 3 that depicts the fatigue limit as a function of the steel tensile strength both for mirror polished and for as hot-rolled samples. It is interestingly shown that any increase in the strength level aimed at improving the actual fatigue limit is almost useless for rough surface conditions. In addition, the selection of high grade steels rather than plain carbon steels does not alter significantly the overall behaviour.

Shot peening effects on the fatigue performance of steel

A widespread surface treatment for fatigue loaded mechanical parts is shot peening. It consists in projecting a flow of small hard particles (generally spheres or cylinders made of steel or iron) on the surface to be treated [13,14]. This process can be considered as a good example to show the surface effects on fatigue limit. Indeed, the repeated impingement of shots results in the generation of a compressive stress layer below the surface, in the workhardening of an external material layer and in the impairment of the surface roughness. Although the rise in strength due to workhardening is beneficial and the roughening of the surface constitute a drawback, the remarkable improvement in fatigue limit obtained in shot-peened parts is mainly due to the formation of the compressive stress layer which opposes to the most critical tensile stress during fatigue cycles [15].

It has been recognised [13-16] that the best fatigue performance corresponds to an optimum distribution of residual stresses featuring high compressive layers near the external surface. The achievement of the above condition involves setting several process parameters such as the size and type of shots, their velocity and the duration of the process. The effect of the shot-peening intensity (related to the kinetic energy of the shots and to the process time) varies according to the steel grade and strength [15]. Fig. 4 reports experimental results on the fatigue limit as influenced by the shot-peening intensity (the Almen intensity is measured as the deflection of a standardized thin plate after the treatment) and the tensile strength of two alloy steels [17]. It is shown that, for the steels with higher strength, a maximum value of the fatigue limit was obtained at approximately 0,15 mm Almen intensity. A further increase in intensity led, amongst other effects, to a depletion of the surface conditions that, when associated with the significant notch sensitivity of high strength steel, overbalanced the other beneficial effects and resulted in decreased fatigue properties.

Case studies

Among the various fatigue ruptures examined in our laboratories, a substantial fraction occurred because of the common designers' choice to rise the hardness and the steel strength with the aim of improving the fatigue behaviour of mechanical components. As previously mentioned, this can be deleterious since beyond a certain strength the fatigue limit decreases as the hardness increases, specially when no particular attention is paid to surface finish.

Failures of high-strength springs

This first case history is reported in order to identify the deleterious effects of combining high strength level with inadequate shot peening. A limited number of helical compression springs, installed on components for cable transportation plants had failed in service far before the end of their expected life. The springs, made of UNI 50CrV4 steel, had operated under the designed loading conditions and were in perfect agreement with the production specifications as far as geometry, steel composition and microstructure were concerned. Even if the nominal shot-peening intensity stated by the manufacturer was in agreement with the spring size, a careful analysis of the spring surfaces revealed the presence of microdefects, shown in Fig. 5, associated with laps and ridges of the material produced by the shot-peening process.

The defects appeared very pronounced when the surface was compared to that of other helical springs more conventionally shot-peened at the same nominal intensity. Comparative roughness measurements carried out on the springs quantitatively supported the above observations. The roughness values were systematically higher for the failed components, as can be observed by the roughness profiles depicted in Fig. 6.

Fractographs of the broken springs showed that nucleation of the cracks always occurred in the intrados regions of the helices, which were the most stressed parts when the springs were compressed. The cracks initially developed on flat surfaces oriented along the bar axis. After an initial extension, variable in size depending on the spring examined, the cracks grew along helical surfaces perpendicularly to the normal tensile stress direction as shown in Fig. 7. This behaviour is typical of crack extension in cylindrical bars under torsion with the presence of surface compressive layers [2,18].

Being possible to exclude other particular defects related to the surface condition of the springs, such as the presence of a decarburised layer or of seams, the evidence of fatigue microcracks was accounted for by the surface roughness and microdefects caused by the anomalous shot-peening process. As suggested in Fig. 8, the surface condition and the material properties were such that crack growth started at the surface laps and ridges favourably oriented with respect to the stress direction.
From a microstructural point of view, the fractographic analyses of the springs failed in service, whose temperature at the time of breakage was unknown, always featured an intergranular separation.

In addition to the fractographic exams on the springs, a fatigue test was carried out at room temperature on a part of a spring formerly failed in service. This sample failed after about 10^5 further cycles at a stress comparable to the original design stress. In this case the fracture surface was of different type, mostly of quasi-cleavage mode with some occasional intergranular decohesions. The difference in the fracture mode with respect to that typical of service failures suggests the marked role played by the environmental low temperature on fatigue failures in service.

The mechanical behaviour of the UNI 50CrV4 steel was studied by the authors in the temperature range from -40°C to +20°C and in two different tempers (corresponding to nominal hardness values of 40 HRC and 45 HRC) in a research on the low-temperature properties of spring steels [19]. The data plotted in Fig. 9 show the expected improvements in ultimate tensile strength and 0.2% yield strength at low test temperatures. On the contrary, no remarkable change in tensile ductility was detected in the examined temperature range. Further data on the resistance to dynamic loading and on the effect of the test temperature are obtainable by the transition temperature curves (KV-notch Charpy impact energies vs. temperature) shown in figure 10. These curves illustrate the brittle behaviour of the Cr-V steel tempered at both 465°C and 540°C (corresponding to 45 HRC and 40 HRC, respectively) when tested in the above temperature range, chosen for its particular interest for spring applications. Once more, it is shown that the brittleness becomes more evident as the steel hardness increases.

Tests were performed also in rotating bending fatigue with hourglass-shaped specimens mirror polished up to roughness values lower than R_A= 0.05 μm and not subjected to shot-peening. The fatigue limit at room temperature, determined through the staircase statistical method, slightly improved from 698 MPa to 752 MPa, when increasing the hardness level from 40 HRC to 45 HRC.

From the picture of the properties drawn it was possible to obtain a quantitative assessment of the changes of the material behaviour as a function of the tempering (i.e. of the hardness level) and of test temperature. It was confirmed that modifications of the tempering temperature are effective both on the tensile and fatigue strength while other properties, such as toughness, drop drastically. This trend became more pronounced when considering the data referred to the lower limit of the examined temperature range.

The reported mechanical properties highlight the material brittleness at the highest hardness levels and at the lowest service temperatures, as for the failed springs. In this case the low toughness of the Cr-V steel was connected to a number of use conditions of the material which had to be necessarily satisfied in order to reach high strength levels required by modern spring design. Amongst these factors there can be listed the low tempering temperature chosen to obtain high hardness and YS/UTS ratios, the possibility of falling with this temperature within the embrittling interval, the exercise of the spring in low-temperature environments. Thus, even if the springs in these conditions attained high tensile strength, the steel was not able to counteract the possible flaws either related to the microstructure or coming from the production processes.

Failures in paper-mill roll axles

A second case study is here proposed in order to underline the effect of surface finish, also related to environmental effects altering the initial surface properties.
Some failures occurred after a large number of cycles, of the order of 10^7, in roll axles made of UNI-C45 plain carbon steel and operating in a paper mill plant. A number of breakages occurred in sections close to shoulder fillets in 100 mm diameter axles subjected to moderately low stress levels.

Fig. 11 depicts a macroscopic view of a typical fracture surface. The general morphological features confirmed that the fatigue failure progressed under low stress cycles with an extended crack propagation zone. In the same fillet region, a 40 mm length crack was observed in another axle. Metallographic analyses, showed that the crack was filled with corrosion products and that its flanks were not decarburised, thus excluding any defect brought about by the manufacturing stage.

The examinations of the critical region revealed that the main crack was accompanied by several other microcracks of different lengths which had nucleated from surface pits, as shown in Fig. 12. Such surface pits were also observed in crack-free regions of the axles, far from the shoulder fillets. These were supposed to be brought about by the corrosive environment in which the axles operated.
Fig. 12 also allows to comment on the steel microstructure, which was of pearlitic-ferritic type, as formed by a normalising thermal treatment (the hardness of the steel was about 200 BHN). It is well known [7, 10, 17] that such microstructure does not lead to particularly favourable fatigue properties due to the two inhomogeneous constituents and to the presence of cementite lamellas that favours notch effects on a microscale and the subsequent crack propagation.

From the above observations it was concluded that the failures were due to a sequence of corrosion and fatigue mechanisms. Firstly, environmental corrosive attack caused pits homogeneously distributed on the whole axle surface. In the region near the shoulder fillet, where the material was subjected to notch effects, fatigue microcracks originated from these surface defects and easily propagated through an unsuitable microstructure.

Concluding remarks

By considering data published in literature about the influence of material strength and surface finish on fatigue resistance, it was remarked the increased sensitivity of high strength steel to surface conditions and to microstructural defects. Due to the practical impossibility of avoiding notch effects related to both steel microstructure and to surface condition, the assumption of a direct proportionality between tensile strength and fatigue limit tends to overestimate the actual material performance at the highest strength levels.

This brief overview on fatigue properties as a function of steel strength was aimed at suggesting some metallurgical factors of influence which, although well known for many years, are still responsible for a large number of fatigue failures in engineering parts. In fact, it is still a diffused practice to correct design mistakes leading to fatigue failures by modifying the steel grade or by improving its tensile strength.
Two case histories were reported where the strong effect of surface finish on fatigue properties, particularly deleterious due to either the high brittleness of the steel or to the unsuitable microstructure, was neglected or at least misconsidered at the design stage.
The first examinations, carried out on a series of failed helical springs used in cable transportation plants,

allowed to state that the nucleation of fatigue cracks was brought about by the geometrical irregularities left by the too intensive shot-peening process. Despite its high tensile strength, the steel used, highly stressed in service, was not able to withstand the presence of defects due to poor toughness properties.

The second investigation, concerning roll axles failures in a paper-mill plant, revealed that the environmental corrosive attack had brought about pits. These acted in particularly stressed regions as nucleation sites for fatigue microcracks. Eventually, the cracks were able to grow in a steel not heat treated to the most favourable condition as far as fatigue strength was concerned.

The data and case studies reported emphasise that improvements in steel strength should also involve accurate control of surface condition, of stress raiser geometry and of microstructural irregularities. Whenever such necessities can not be satisfied due to costs, design or reliability factors, the use of high strength steels does not allow to reach effective advantages and could even worsen the fatigue performance of structural parts.

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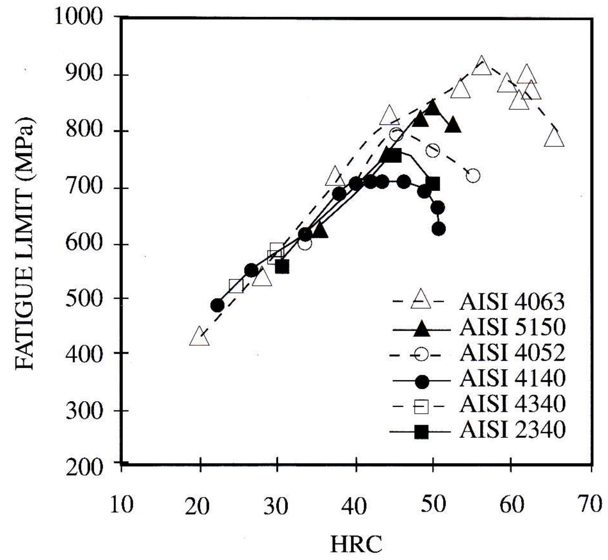

Fig. 1:
Fatigue limit of quenched and tempered steels as a function of hardness. Data from [3]

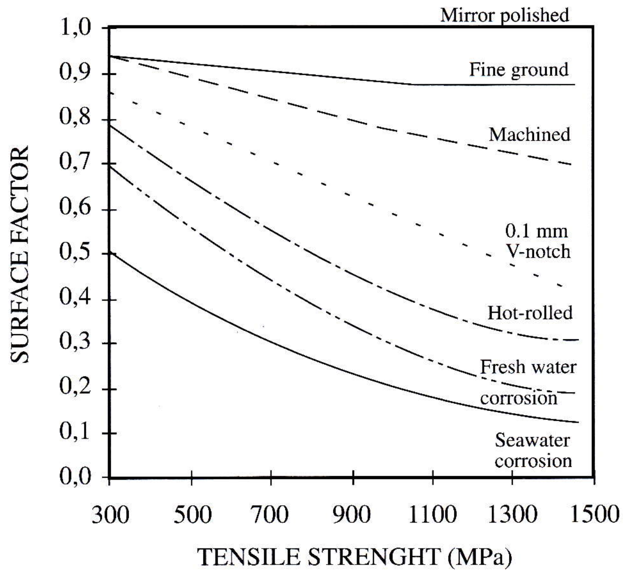

Fig. 2:
Surface factor for fatigue limit as a function of steel tensile strength for different surface conditions. Data from [12]

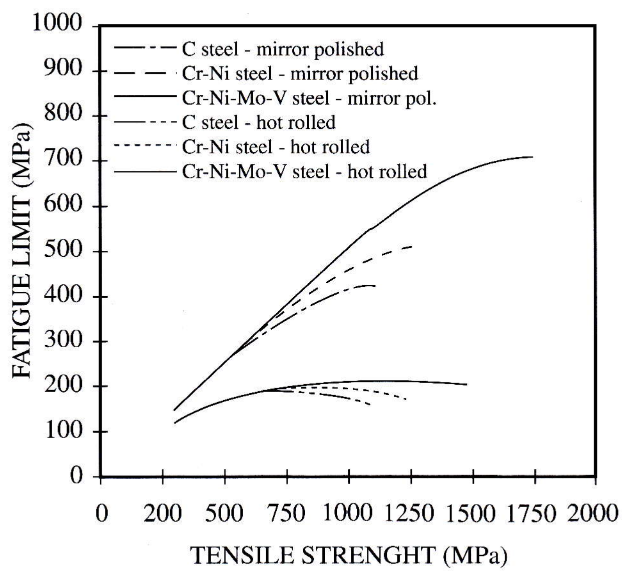

Fig. 3:
Influence of strength on fatigue limit for two different sample surface conditions. Data from [12]

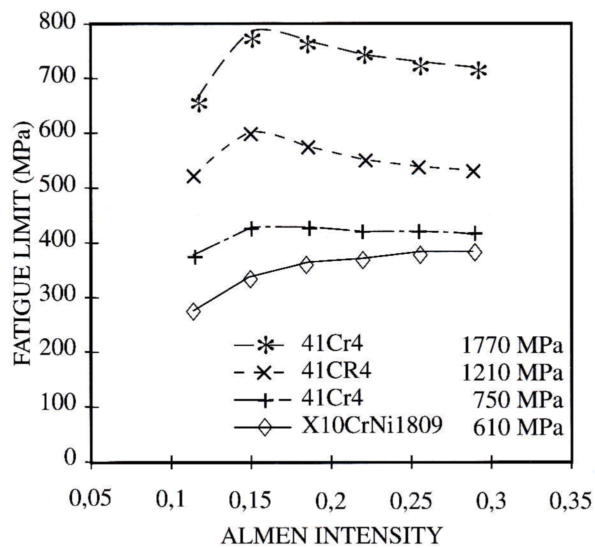

Fig. 4:
Rotating bending fatigue limit vs. shot-peening intensity and influence of tensile stremgth. Data from [17]

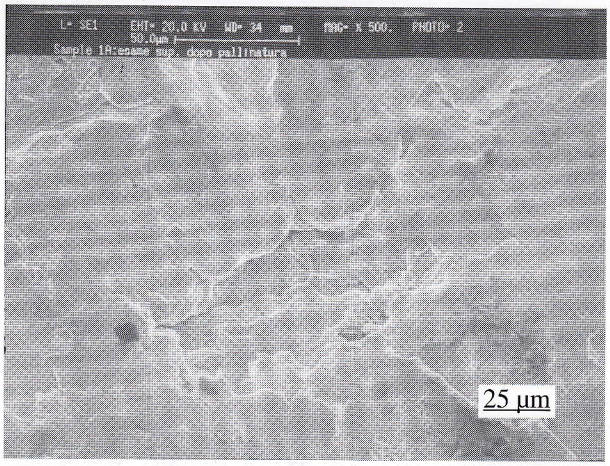

Fig. 5:
Surface defects detected on the shot-peened springs

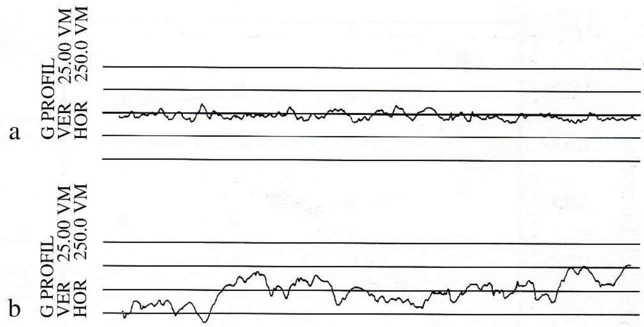

Fig. 6:
Comparison of the surface roughness profiles of two shot peened springs. (a) conventional spring, RA= 1.85 µm; (b) abnormally shot-peened spring, R_A= 5.00 µm

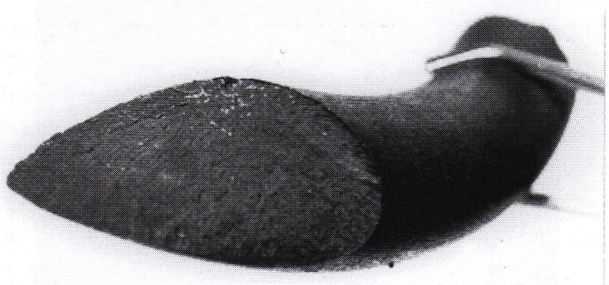

Fig. 7:
Fracture surface of a spring failed in service

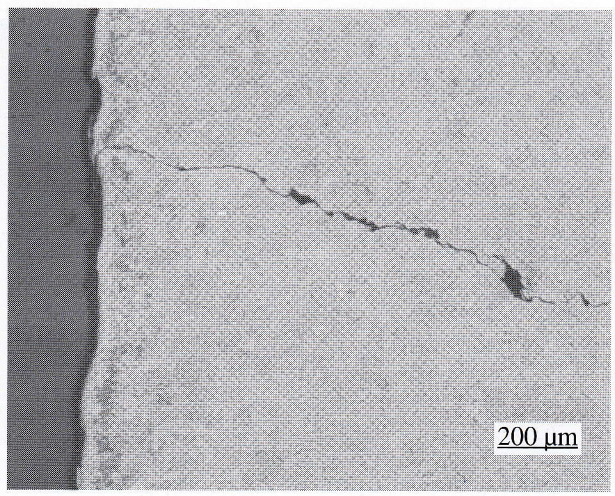

Fig. 8:
Microcrack nucleated from a surface defect

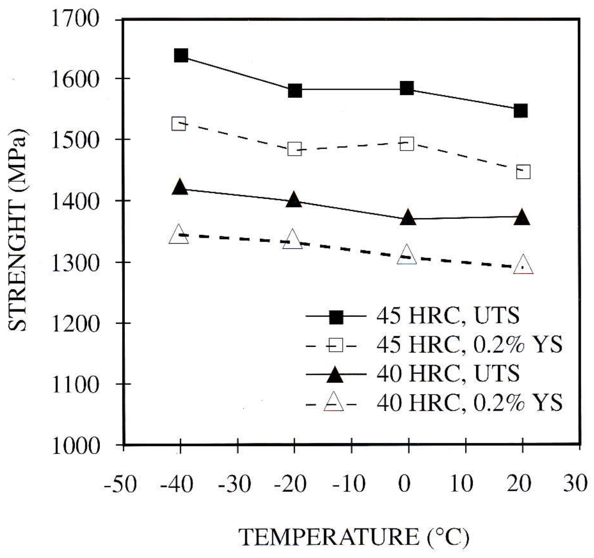

Fig. 9:
Tensile properties of the UNI 50CrV4 steel as a function of temperature

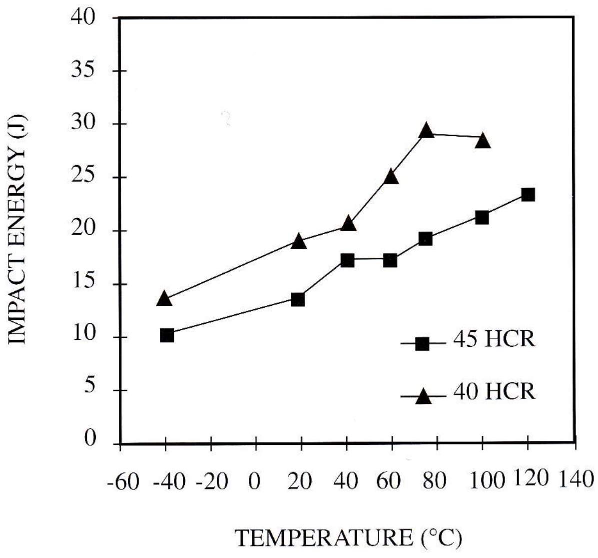

Fig. 10:
Transition curves (KV-notch impact energy vs. temperature) of the UNI 50CrV4 steel

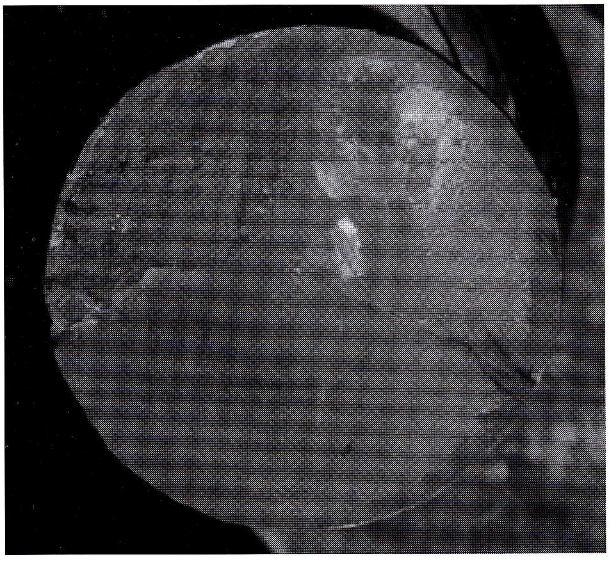

Fig. 11:
Fracture surface of a broken roll axle

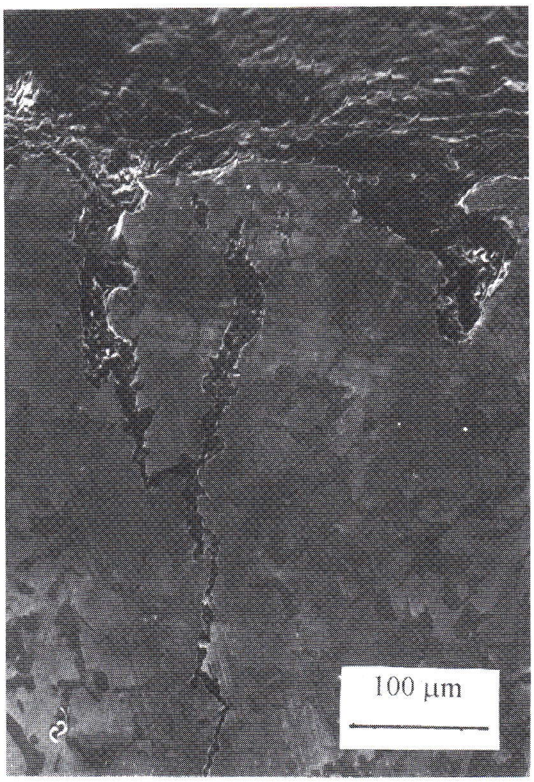

Fig. 12:
Surface region in a longitudinal section of an axle showing microcracks nucleated from corrosion pits (SEM micrograph)