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EFFECTS OF SURFACE TREATMENTS ON THE FATIGUE LIFE OF AN ULTRA HIGH STRENGTH STEEL 300M USED FOR LANDING GEAR COMPONENTS

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EFFECTS OF SURFACE TREATMENTS ON THE FATIGUE LIFE OF AN ULTRA HIGH STRENGTH STEEL 300M USED FOR LANDING GEAR COMPONENTS

Dr S J Trail, Dr J Luo and Prof. P Bowen

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Executive Summary

This report presents the findings of a literature review and an experimental programme conducted on the effects of surface treatments of large commercial aircraft landing gear components on fatigue performance. The review and experimental programme have been carried out in response to the safety recommendations contained within the Air Accident Report No. 1/97 (EW/C95/4/2). This investigated the failure of a MD-83 aircraft's main landing gear outer cylinder. Failure was considered to be due to the presence of small fatigue cracks. The origin of which were associated with features believed to have been produced by a grit blasting operation used to prepare the surface after shot peening for cadmium plating treatment.

The literature review concentrates on the three surface treatments of shot peening, grit blasting and cadmium plating as these are considered to potentially have the greatest influence on fatigue life. The shot peening operation has a number of beneficial effects due to the introduction of a compressive residual stress layer at the component surface. The grit blasting operation is carried out to remove the passive layer found at the surface of ultra high strength steel alloys used in the manufacture of landing gear components. This enhances the adhesion of cadmium during the plating operation. However, the grit blasting process also roughens the surface and leaves embedded grit particles within the surface layer. This may reduce the fatigue resistance of the component. Cadmium plating operations are carried out to give corrosion protection to ultra high strength steel landing gear components. Careful control of the plating process is required in order to reduce the risk of embrittlement caused by hydrogen absorption associated with the cleaning and plating procedure.

It was found that the standards which cover the shot peening process and cadmium plating during manufacture of landing gear components are comprehensive and consistent in their requirements. Furthermore, quantitative quality control methods are specified which ensure the correct levels of peening and cadmium plating have been carried out. However, grit blasting parameters are relatively poorly defined in the standards used in the production of ultra high strength steel components. The levels of blasting achieved are largely left to the discretion of the operator. No quantitative quality control test methods are specified to check the blasting procedure has been performed satisfactorily. Degradation of compressive residual stresses, induced by the shot peening process, may also occur if the grit blasting operation is poorly controlled.

The literature review suggests that the operating parameters for the grit blasting operation are loosely defined and that the levels of blasting are largely at the discretion of the operator. Therefore, it is considered likely that a range of blasting levels will be experienced during the manufacture of ultra high strength steel landing gear components.

The experimental part of this programme considered the effects of variation in grit blasting procedures in terms of surface roughness, residual stress and fatigue life. It was found that the grit blasting procedures performed on the previously shot peened surfaces further roughen the surface, but they do not decrease the magnitude of the compressive residual stress for the material quenched and tempered condition investigated. Specimens which have been shot peened during processing have much longer fatigue lifetimes than those tested in the as-ground condition due to the high residual compressive stress induced at near surface locations by the shot peening process. Any effects of grit blasting procedures on the fatigue life of shot peened specimens are found to be minimal in the present study. In detail, it is of interest to note that the positions of fatigue crack initiation sites move from surface positions (at very high applied stresses) to sub-surface positions (at lower

applied stresses). The sub-surface positions occur at the limits of the compressive residual stresses. These observations are consistent with the assessment that at very high applied stresses the residual stresses can be relieved by local plastic deformation.

Overall in this study no detrimental effects of varying degrees of grit blasting on the fatigue life of shot peened testpieces of UHSS 300M steel were found. Therefore, it is recommended on the basis of this study that there are no additional limits required to be imposed on the grit blasting operational procedures.

Glossary

AAR	Air Accident Report
ACJ	Advisory Circular, Joint (Europe)
AMS	Aerospace Material Specifications
CAA	Civil Aviation Authority (UK)
DERA	Defence Evaluation and Research Agency (UK)
DPS	Douglas Processing Specifications
EDM	Electro Discharge Machining
FAA	Federal Aviation Administration (USA)
Hw	Half Width Diffraction Pattern
IVD	Ion Vapour Deposition
JAR	Joint Aviation Requirements
LG	Landing Gear
MOR	Mandatory Occurrence Report (UK)
N&T	Normalised and Tempered Condition
Q&T	Quenched and Tempered Condition
R_a	Surface roughness parameter: arithmetic mean of the absolute departures of the roughness profile from the mean line in microns
R_q	Surface roughness parameter: geometric mean of the absolute departures of the roughness profile from the mean line in microns. RMS parameter corresponding to R_a
R_t	Surface roughness parameter: the maximum peak to valley height of the profile in the assessment length in microns
R_v	Surface roughness parameter: the maximum depth of the profile below the mean line within the sampling length in microns
RHC	Rockwell Hardness C
SEM	Scanning Electron Microscope
UHSS	Ultra High Strength Steel
UK	United Kingdom
VAR	Vacuum Arc Remelting

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1 INTRODUCTION

This investigation has been carried out in response to the safety recommendations contained within the Air Accident Report (AAR) No. 1/97 (EW/C95/4/2) [1]. This AAR was produced by the Air Accidents Investigation Branch following the catastrophic failure of a MD-83 aircraft's main landing gear (LG) outer cylinder during a landing roll on the application of bending loads resulting from normal braking. This was due to the presence of a small fatigue crack. The origin of the fatigue crack was associated with features which are believed to have been produced by a grit blasting treatment used to prepare the surface after shot peening for cadmium plating treatment. The failed component was manufactured from an ultra high strength steel (UHSS) 300M alloy.

2 LITERATURE REVIEW

This section presents the findings of a literature review conducted on the surface treatment processes performed in the production of steel LG used on large commercial aircraft and their influence on fatigue performance. The overall objective of this project was to ascertain the necessity for the industry to develop improved surface treatments for highly loaded UHSS components. The industry standards relating to the processing parameters of surface treatments are reviewed and their effects on fatigue life are considered. Past incidence of fatigue related failures of LG have been investigated and a brief review of the lifing of LGs and alternatives to cadmium plating are presented. Finally, the conclusions of this work are given.

2.1 Range of Ultra High Strength Steels Used in Landing Gear

The UHSS used in civil aircraft LG are primarily alloys developed twenty-five or more years ago [2]. They remain the preferred materials choice due to their combination of high strength and stiffness, together with low volume and hence overall weight [3]. Low-alloy steels predominate such as 4340, 300M, HY-TUF and D6AC which have tensile strengths in excess of 1500 MPa. These steels are normally produced for aerospace applications by vacuum arc remelting of electrodes prepared via induction melting. The steels are used in their tempered martensitic form after heat treatment by austenitising, a subsequent cooling to room temperature during which most of the austenite is transformed to martensite and finally, a tempering treatment during which carbides are precipitated [2].

Typical compositions and mechanical properties for these steels are presented in Table 1 and Table 2 [2-6]. 300M was introduced as a higher strength replacement for 4340. This material has slightly higher carbon than 4340 and has silicon added to allow it to be hardened to 1860-2070 MPa tensile strength with a higher tempering temperature well outside the temper embrittlement region. The silicon addition retards carbide tempering during heat treatment and shifts the '350°C Embrittlement' through to higher temperatures (of approximately 450°C) [5-7]. HY-TUF is a lower strength material but has a higher level of defect tolerance. However, its resistances to hydrogen embrittlement and stress corrosion cracking are reported to be comparable to those of the other UHSS used in the manufacture of LG components [4]. D6AC has the advantage of being deeply hardenable and suitable for heavy sections. It is also heat resistant, which is an advantage for components such as axles [5].

2.1.1 *Fatigue Properties*

Typical fatigue crack growth rate data and fatigue threshold value data for these steels are presented in Table 2 [5-11]. Under strain controlled conditions these steels are reported to cyclically soften, potentially leading to earlier crack initiation in the material [6]. A consequence of the high operating stresses imposed on LG and the modest fracture toughness of the steels (see Section 2.1.2) is that only very limited fatigue crack growth will occur before the critical defect size is reached and catastrophic failure occurs. For these reasons, it is essential that conditions exist which preclude fatigue cracks from initiating. Intrinsic factors of LG components which influence crack initiation include residual stress, surface roughness and corrosion resistance. These factors are discussed in detail later.

2.1.2 *Fracture Toughness*

Typical fracture toughness data for LG steels are presented in Table 2 [2-4]. It can be seen that they have a relatively low defect tolerance with typical fracture toughness values of $70 MPam^{1/2}$. It has been shown that critical flaw sizes of approximately 0.25 to 0.50 mm can be expected [2] (where the critical flaw size is defined as the depth of the smallest long, slender surface flaw that will cause catastrophic failure under stress. Stresses of yield strength magnitude are assumed). It is of interest to note that the 300M alloy has higher strength than 4340 but with only an equivalent fracture toughness (see Table 2). The combination of a higher strength without a corresponding increase in fracture toughness results in a smaller critical flaw size (if the increased strength level is utilised) and, is thus, even less damage tolerant. Such relatively small critical flaw sizes makes meaningful non-destructive examination difficult during service. For this reason LG^2P are designed using the safe life approach [12].

2.1.3 *Stress Corrosion Cracking*

The stress corrosion cracking resistance of some LG steels are presented in Table 2 [2, 13, 14]. Stress corrosion cracking involves failure by cracking in the presence of both a stress and a corrosive medium. It can be seen that UHSS are particularly vulnerable to this type of failure with K_{ISCC} values as low as 11 $MPam^{1/2}$ reported [2]. The need for comprehensive corrosion protection is clear and it is for this reason that cadmium plating is applied to the surface of UHSS parts.

2.1.4 *Hydrogen Embrittlement*

Failure of UHSS may also be influenced by the absorption of hydrogen, leading to embrittlement. There have been many reported failures of UHSS into which hydrogen was introduced during electroplating of protective surface layers [14]. Concentrations of a few parts per million are often sufficient to cause failure [15]. While much hydrogen escapes from steel in the molecular form during treatment, some can remain and precipitate at internal surfaces such as inclusion/matrix and carbide/matrix interfaces, where it may form voids or cracks. Crack growth may then occur slowly under internal hydrogen pressure, until the critical length for instability is reached and failure occurs rapidly. Hydrogen embrittlement is most sensitive to strength level and relatively insensitive to composition [16]. It is also clearly possible that a sub-critical crack may form due to hydrogen absorption which may then further propagate by a fatigue mechanism until catastrophic failure occurs.

2.2 Surface Treatments Used in the Production of Landing Gear Components

Practically all fatigue failures initiate at near surface locations under conditions of plane stress and whose localised yielding is promoted [17]. This is also due to the fact that for many common types of loading such as bending and torsion, the maximum stress occurs at the surface. In addition, the surface is subjected to possible corrosion. There is a large body of evidence that suggests that fatigue properties are very sensitive to surface condition [18]. The factors which affect the surface of a component subject to fatigue loading can be divided approximately into three categories:

(i) surface roughness or stress raisers at the surface;

(ii) changes in the strength of the surface metal and

(iii) changes in the residual stress conditions of the surface [18].

Consequently, any processing stage in the manufacture of LGs that affects the condition of the surface will potentially have an influence on the fatigue performance of the component. The processing operations which are considered to have the greatest effect on fatigue life of LG components are discussed below.

2.2.1 *Shot Peening*

Shot peening is a method of cold working in which compressive stresses are induced in the exposed surface layers of metallic components by the impingement of a stream of shot, directed at the metal surface at high velocity and under controlled conditions. The major purpose of shot peening is to increase fatigue strength [19]. In many cases residual stresses can be considered identical to the stresses produced by an external force with the exception that they are in self equilibrium (i.e. the resultant sum of forces and bending moments at any point in the body must be zero) [18]. Although the addition of a compressive residual stress, which exists at a point on the surface, to an externally applied tensile stress on that surface decreases the likelihood of fatigue failure at that point, tensile residual stresses will be produced sub-surface. These could have a deleterious effect, but the importance of near surface regions in promoting crack initiation under fatigue loading tends to dominate. The principal variables in the process are the shot velocity and the size, shape and hardness of the shot. Care must also be taken to ensure uniform coverage over the area to be treated [19], otherwise localised regions of tensile residual stress could be produced at surface positions.

Cold working can also have beneficial effects due to work hardening, improving grain structure, improving surface texture and closing porosity. Hence the benefits obtained from the process, in addition to improved resistance to mechanical fatigue, can include resistance to stress corrosion cracking, intergranular corrosion and hydrogen embrittlement [20].

It should be recognised that improvements in fatigue properties do not automatically result from the use of shot peening. It is possible to damage the surface by excessive shot peening and in certain cases increase the surface roughness. It has also been demonstrated that these residual stresses are not always permanent, but can tend to diminish as a function of time, temperature, load history and metal removal in the form of either wear or corrosion [21].

2.2.2 *Grit Blasting*

Abrasive blast cleaning entails the forced direction of abrasive particles against the surface of metal components, to remove contaminants and/or to condition the surface for subsequent finishing [19]. Grit blasting is required in the manufacture of LG components so as to remove the passive layer associated with the presence of certain alloying elements such as chromium, vanadium and silicon. If the passive layer is left untreated the plating cycle will have to be lengthened and increasing the risk of hydrogen absorption and subsequent embrittlement [22]. Additionally, the cadmium may not adhere to the substrate satisfactorily [19]. Pickling is not used to remove the passive layer due to the risk of hydrogen absorption [22]. The grit blasting operation is thus carried out immediately before the cadmium plating cycle.

Although grit blasting is considered necessary by the industry to ensure successful cadmium plating it may introduce potentially deleterious effects in terms of fatigue resistance. It has been shown that grit blasting may roughen the surface and leave embedded grit particles in the surface [1]. It may also reduce the level of beneficial compressive residual stress at the surface formed through shot peening, although such effects are expected to be relatively modest because of the limited depth of material removed by grit blasting. Typically, this might be expected to be of the order of $10\mu m$. It is well established that an increase in surface roughness will generally lead to a decrease in fatigue life [18]. Furthermore, the effect of surface roughening on the surface life of a coating is not well understood. For example, a rough surface may actually improve the service life of the cadmium plating by increasing the surface area for adhesion. Alternatively, a rough surface may be detrimental in that it may affect the electrochemical behaviour of the surface and make it more difficult to protect the steel from corrosion, since a very rough surface requires special care to insure that the peaks of abraded surface are covered by an adequate coating thickness [23].

2.2.3 *Cadmium Plating*

UHSS landing gear components are protected from corrosion by electroplating a thin coating (<1mm thick) of cadmium on the surface. Cadmium plating functions as a very effective barrier coating, particularly in the environments frequently experienced by aircraft [24]. Furthermore, cadmium is anodic to iron and therefore, the underlying ferrous metal is protected at the expense of the cadmium, even if the cadmium becomes scratched to expose the substrate. Additionally, the potentials of aluminium alloys are similar to that of cadmium so that the risk of damaging galvanic interactions occurring between them is small [25].

Cadmium is usually deposited from an alkaline cyanide solution; alternatively, a cadmium fluoborate solution may be used. After careful surface preparation by degreasing and grit blasting the components will be thoroughly washed in cold water to remove particles of abrasive. Plating will then occur followed by a water rinse, acid rinse, water rinse, de-embrittlement heat treatment and finally passivation [22].

Cadmium has the disadvantage of being highly toxic [26]. Moreover, it may embrittle steel at elevated temperatures (above 200°C) [27] and there is also hydrogen absorption associated with the plating process [28]. It has been reported that electrodeposits can reduce the fatigue strength of plated parts [29]. The reasons for this include:

(i) hydrogen pick up resulting from the cleaning and plating process;

(ii) surface tensile stresses in the deposits; and

(iii) lower strength of the deposits compared to the base metal leading to cracks in the deposit which subsequently may propagate through to the base metal [16].

2.3 Residual Stress Resulting From Surface Treatments and its Effect on Fatigue Life

Residual stresses arising from fabrication or surface and heat treatments, when superimposed with the applied fatigue loads, alter the mean level of the fatigue cycle and the fatigue life for crack initiation. This is particularly important for steel LG components which have been shown to have relatively small critical defect sizes [4]. Consequently, during design, the fatigue life of LG components is based on the initiation stage of crack development. In general, residual stresses may affect the fatigue behaviour of materials in the same way as the static mechanical stresses superimposed on a cyclic stress amplitude. Therefore, residual stresses are favourable if compressive and detrimental if tensile; this is particularly true for high strength materials [18]. Any fabrication process which introduces a more compressive residual will have a beneficial effect on fatigue life. Likewise, any process which introduces a more tensile residual stress will reduce the fatigue life of a component.

2.3.1 *Shot Peening*

The magnitude of compressive stress produced by a shot peening process can be as high as 60% of the tensile strength of the material being treated [20]. A number of shot peening stress profiles are presented in the literature [30, 31] a selection for UHSS used in LG components are reproduced in Figure 1. The magnitude of compressive stress reaches a maximum at approximately 0.1mm from the surface, before changing to slight tensile stress beyond 0.5mm. Peak compressive residual stresses ranging from 1600 MPa to 700 MPa have been reported for UHSS. Since most fatigue failures initiate from some feature at the surface, the high degree of pre-stress afforded by shot peening can have a profound improvement on the fatigue life of a component (see Figure 2) [17, 31].

2.3.1.1 Control of Process Variables

Major variables in the shot peening process are shot size and hardness, shot velocity, peening intensity, surface coverage, angle of impingement and shot breakdown. These are now briefly discussed [19]:

(i) Figure 3 shows the relationship between depth of compressive layer and shot peening intensity [31]. A higher peening intensity will result in a greater depth of compressively stressed layer.

(ii) Size of shot. When other factors are kept constant an increase in shot size will result in an increase in peening intensity and a decrease in coverage.

(iii) Hardness of shot. Variations in the hardness of the shot do not affect peening intensity, provided the shot is harder than the workpiece. If the shot is softer than the work piece, a decrease in shot hardness will result in a decrease in intensity [19, 31]. This is shown in Figure 1b. Special hardness shot should be used for high strength, high hardness steels.

(iv) Velocity of shot. Peening intensity increases with velocity. However, adverse effects due to shot breakdown may occur.

(v) Surface coverage. This is the measure of how completely an area has been hit by the impinging shot particles. With less than full coverage, the improvement in fatigue characteristics normally produced by shot peening will not be obtained. The results of a recent study into the effects of partial coverage on fatigue life are presented in Figure 4. It can be seen that fatigue lives may be 200% greater for specimens receiving full coverage compared with 35% coverage. However, it is of interest to note that even at only 35% coverage the fatigue life may be improved by up to 50% compared with unpeened specimens [32].

(vi) Angle of impingement. By definition, the angle of impingement is the angle between the surface of the workpiece and the direction of the blast. As this angle is decreased from 90°, peening intensity is reduced. Peening intensity varies directly as the sine of the angle of impingement [19].

(vii) Breakdown of shot. Broken or sharp edged particles may be damaging to the surface. It is therefore essential to ensure that the shot used is always in good condition and conforms to size restrictions.

2.3.1.2 Intensity Measurement

Calibration of the impact energy or peening intensity of the shot stream is essential to produce controlled shot peening. In order to specify, measure and calibrate peening impact energy the Almen strip method is generally used [32]; this method is detailed in Appendix A. This allows the peening process to be accurately controlled and acts as an effective quality control check to ensure satisfactory peening has taken place.

2.3.2 *Grit Blasting*

The grit blasting operation is performed after shot peening to prepare the surface for cadmium plating. It may also, unintentionally, affect the residual stress profile at near surface locations. It should be noted that the surface will be in the fully hardened, pre-stressed condition prior to grit blasting taking place.

No data in the literature has been found as to the effects on residual stress of grit blasting a previously shot peened surface. However, it has been shown that grit blasting on an as ground surface will introduce compressive residual stress, much in the same way as shot peening does. Interestingly, there was a slight reduction in the compressive residual stress (by up to 30MPa) as the time of grit blasting increased from 30 to 90 seconds [33]. Similar results are presented in another study [34]; the reasons for this decrease in residual stress are not given. It is not clear from the literature what the overall effect of the grit blasting process has on the residual stress present at the surface. The extent of any change in the residual stress state through grit blasting will presumably depend upon the grit blasting procedure [19].

2.3.3 *Cadmium Plating*

It has been shown that in the cases of 'hard' plating materials such as chromium and nickel, high residual tensile stresses can be induced in the plated metal by the electrodeposition process [35]. Tensile residual stress levels as high as 413 MPa have been reported for chromium deposits on hardened steels [25]. However, electrodeposits of relatively soft cadmium exhibited stresses which are generally low in magnitude and compressive. It is reported that the stress produced for cadmium deposits produced by cyanide baths without brighteners or alloying additions is usually within the range -3.5 MPa to -21 MPa. The internal stress in cadmium deposits (8 and 14μm thick) from sulphate solutions with additions of naphthalene disulfonic acid and gelation was relatively low (5 to 15 MPa) in tension [25]. A number of theories have been proposed to account for the induced stress and are summarised elsewhere [36, 37]. Therefore, it is considered that the electroplating process will have an insignificant affect on the overall residual stress profile of the LG components. It is standard practice to perform a post plating 'bake out' heat treatment after plating to reduce the risk of hydrogen embrittlement. It is important that the temperatures are controlled to ensure that thermal induced relaxation of the residual stresses does not occur. The standards for cadmium plating generally specify a bake out temperature of 190°C.

2.3.4 *Residual Stress Relaxation*

The shot peening operation performed during the manufacture of LG components is primarily carried out in order to introduce a beneficial residual compressive stress state to the surface layer of material and consequently increase its fatigue life. However, the residual stress distribution may be modified by plastic deformation, thermal activation and metal removal through wear or corrosion [18]. Any reduction in the magnitude of the compressive residual stress will be expected to reduce the fatigue life of the component (see Figure 2 [31].

Residual stresses would be expected to relax whenever the applied loading resulted in reversed plastic straining in the steel (possibly as a result of heavy landings or severe gear walk). Many steels, including UHSS used in LG components, exhibit cycle-dependent softening which may occur at lower stresses than would be anticipated based upon monotonic yield strengths [38]. Furthermore, the residual stress may relax on the application of a fatigue stress which is less than that of the pre-straining stress [39]. The relaxation of the residual stress can follow an exponential function with the number of fatigue cycles (see Figure 5). Residual stresses have their greatest influence near the fatigue limit, where little fading occurs. Conversely, the fatigue life at high applied stresses depends little on residual stress [40]. The relaxation behaviour is little affected by the magnitude of the residual stress, but depends primarily on material strength and applied strain amplitude. The highest strength materials will tend to have the greatest resistance to stress relaxation [38].

Evidence of cyclic relaxation occurring in LG components is given in Reference [41]. Here it was found that cracking occurred in two locations of a LG during full scale fatigue testing. The two locations where cracking occurred experienced compression dominated loading during the test and there was sufficient plasticity at these locations to allow the stress to relax under cyclic loading. Introducing cyclic relaxation of the mean stress into the analysis gave life estimates that correlated well with the full-scale fatigue test results. The significantly shorter than predicted fatigue lifetimes (by a factor of 3.5 and 10 on life) of the LG components were considered a result of stress relaxation.

Exposure of a peened component to elevated temperatures will relieve induced stresses. In the case of UHSS used in LG, post peening heat treatments and in-service operating temperatures should be kept below 250°C in order to avoid stress relaxation [31]. Removal of material from the surface after peening will diminish the depth and magnitude of the induced compressive residual stress. Care must be taken to avoid material removal through excessive grit blasting, wear or re-work.

2.4 Surface Roughness Resulting From Surface Treatments and its Effect on Fatigue Life

The surface roughness of a component can significantly affect its fatigue life [18]. Scratches and machining marks which exist in engineering components can be considered as stress concentration features. As the roughness of a component's surface increases, an increase in the local levels of stress can be expected for a given applied load. This will lead to a corresponding reduction in the fatigue life of that component (see Figure 6) [18]. It is of interest to note that the fatigue life becomes more sensitive to surface roughness as the tensile strength of the material increases. Therefore, it is expected that the fatigue lives of UHSS used in landing gear will be strongly influenced by surface roughness. As discussed previously, the surface is of particular importance because this is where the highest stresses are generally found.

It is reported that if the surface damage, such as increased roughness, is contained within the compressive residual stress layer formed by shot peening it will not significantly affect the fatigue life of a component [42]. However, if the compressive stress state should reduce in magnitude through thermal or cyclic stress relaxation then a pronounced effect on fatigue life may result.

2.4.1 *Shot Peening*

There is little data in the literature which reports the effect of shot peening on surface roughness. This may be because the benefits derived from the compressive residual stress induced at the surface through shot peening on fatigue life are generally considered to override the possible deleterious effects of increased surface roughness [31]. Results presented in Reference [43] suggest that a greater shot peening pressure (presumably leading to an increase in shot velocity and peening intensity) will create a rougher surface for a given shot size. Air pressures of 0.2, 0.4 and 0.6 MPa produced surface finishes of 7.8, 10 and 14.4 R_a (μm) respectively on a UHSS (σ_y=1420 MPa, σ_{TS}=1919 MPa). A corresponding decrease in high cycle fatigue strength resulted with fatigue strengths of 1330, 1280 and 1210 MPa reported at 5 million cycles for the three conditions previously detailed respectively. The shot size was 1.1mm in diameter and the fatigue loading ratio employed was R=0.05. However, in all the cases above it is likely that the fatigue strengths recorded are higher than would be obtained on the material in the non-shot peened condition (see Figure 4).

Work presented in Reference [44] shows that an increase in shot velocity and intensity will have the effect of increasing the size of the impressions left by the shot after it has impacted at the surface of the material. This will result in an increase in the surface roughness values of R_a and R_t (where R_a and R_t are defined as the mean and maximum amplitude of the surface in microns respectively). It was found that for a hard material (620Hv) surface roughness values of R_a =1 and 2.5μm were recorded for Almen intensities of 30A2 and 60A2 respectively. The size of shot was also shown to affect the surface finish. The diameter of the impression made at the surface by the shot will be proportional to the diameter of shot used. Generally, for a given peening intensity a larger shot size will produce a finer surface finish [45]. The level of surface roughness found after peening will be dependent upon the initial surface finish, peening intensity and shot size, assuming full coverage has been achieved.

2.4.2 *Grit Blasting*

Work performed on a 080 M80 grade steel in the as ground condition showed that grit blasting with alumina grit with a mean diameter of 1.1mm significantly increased the surface roughness [46] R_a values were increased from 1 to 13μm for the as ground and blasted conditions respectively. Grit blasting is reported to produce a random and isotropic surface topography [47]. The number of passes of the grit blasting gun over the surface necessary to fully transform the surface will vary depending on the stand-off distance, the grit used, the intensity of erosion and the speed of traverse. Normally, some five or six passes are needed. How many passes are required is normally determined by the operator by simple observation. Figure 7 shows the relationship found between the number of passes and R_a. As can be seen, a maximum roughness is achieved at 4 passes, after which the surface becomes less rough. Another study reports similar findings [34]. Here it was shown that the surface roughness reaches a maximum after a relatively short blasting time (2.5 seconds); after this nothing but an increase in grit residue took place. Further studies [48] have shown that for a given blasting time a 45° angle led to significantly less residues in the surface than if the angle of blasting was perpendicular to the surface. Also, the distance between the grit blasting equipment and the specimen plays a minor role for surface properties, within 0–250mm, for pressures at 3 or 4 bar. It has also been reported that a larger grit size and a higher pressure will result in a rougher surface [34].

The effect grit blasting has on the surface of LG components is shown in Reference [1]. The surface layer of the failed LG can be seen to be rough with evidence of embedded grit particles (see Figure 8). No data in the literature was found as to the effects on surface roughness of grit blasting a previously shot peened surface.

2.4.3 *Cadmium Plating*

The cadmium plate layer will tend to have a smoother finish than the underlying base metal [49]. However, the roughness of the base material at the steel / cadmium plate interface will be unaffected by the plating process. The relatively thin cadmium plate layer is significantly weaker than the steel substrate. Therefore, it may be considered that it is the surface properties, including the roughness, of the underlying base metal which will determine the fatigue life of LG components.

2.5 **Cadmium Plating and its Effect on Fatigue Life and Steel Embrittlement**

Little data exists in the literature pertaining to the effect of cadmium plating on fatigue life. A limited study compared bare and plated UHSS fasteners subjected to high cycle fatigue [29]. Testing using the same cyclic loading on five specimens gave average fatigue lifetimes of 114 600 and 121 500 cycles for the plated and unplated conditions. This modest decrease in fatigue life for the plated fasteners is within normal experimental variation for this type of test.

The low levels of stress associated with cadmium deposition are unlikely to influence fatigue resistance greatly [25]. Also, the cadmium plate is significantly weaker than the UHSS used in the manufacture of LGs with approximate tensile strengths of 70 and 1800 MPa respectively. It is also of lower modulus (approximately 55 GPa compared with a value of 210 GPa for steel [25]) and has a good ductility. Furthermore, it is reported that the pre-stressed layer formed during the shot peening process will inhibit crack propagation through the relatively weak plated layer into the base metal [31]. The limited research in this area suggests that the cadmium plate layer in itself will have only a modest affect on fatigue life. This may be contrasted, for example, with the effect of depositing a relatively hard material such as chromium on steel. It has been reported that tensile residual stresses of up to 413 MPa may form in the chromium plate layer during deposition and fatigue strengths may be reduced by up to 73% compared with unplated components [25]. However, hydrogen embrittlement resulting from the cleaning and cadmium plating process may significantly influence the service life of LG components.

2.5.1 *Hydrogen Embrittlement*

For hydrogen embrittlement to occur, hydrogen must be absorbed into the steel; this is not an issue during the shot peening and grit blasting operations. However, the cadmium plating process can be a potent source of absorbable hydrogen [28]. This includes cathodic cleaning, pickling and electroplating. Hydrogen in the atomic form is produced during plating at the cathode surface. This is due to the cathode over voltage which inhibits its association to form molecular hydrogen [25]. This atomic hydrogen may then enter the surface of the steel at dislocations and grain boundaries and precipitate at internal surfaces such as inclusion/matrix and carbide/matrix interfaces. Concentrations of only a few parts per million are often sufficient to cause failure in UHSS components [15, 50].

Post plating 'bake out' heat treatment at 190°C for up to 24 hours is a common practice for reducing hydrogen embrittlement [22]. It had also been shown that shot peening before plating, avoidance of cathodic cleaning or pickling, the use of grit blasting for oxide and scale removal rather than pickling and the use of solvent cleaning before cleaning in aqueous solutions reduce the hydrogen absorption [16]. It is better to minimise hydrogen absorption during processing than rely on the bake out procedure. It has also been reported that the use of fluoborate or cadmium-titanium instead of cyanide cadmium plating process will result in reduced hydrogen pick up [28].

2.5.2 *Cadmium Embrittlement*

It has been shown that molten cadmium embrittles UHSS 4340 in a high strength condition by a grain boundary penetration mechanism [14]. However, it was also reported that embrittlement can also take place at temperatures below that of the melting point of electrodeposited cadmium (322°C). Embrittlement of D6AC, 4340 and maraging 200 steels was shown to occur at temperatures as low as 204°C [27]. Therefore, it is important that cadmium plated components do not experience temperatures above 200°C to ensure freedom from embrittlement. This requires control of the bake out heat treatment after plating. It may also be possible for localised areas experiencing plastic strains during service to experience elevated temperatures. No reports of cadmium embrittlement being associated with the failure of LG components have been found.

2.6 Review of Surface Treatment Processing Standards Employed Currently

The three manufacturing processes of shot peening, grit blasting and cadmium plating are covered in a number of standards; many of which are specifically written or make special mention of processing using UHSS which are used in aerospace applications. A list of Boeings' approved process specifications and contractors, including those connected with the manufacture of LG, can be found on their web site [51]. The major LG manufacturers include Messier-Dowty (UK), Messier-Bugatti (France), Menasco Aerospace Group (Canada) and B F Goodrich (US). In the UK there are two CAA approved manufacturers of LG: Messier-Dowty and APPH Ltd. The various standards employed currently for these manufacturing processes are compared and discussed below. They include Douglas Processing Specifications (DPS), Aerospace Material Specifications (AMS), US Military Standards, Defence Standards and individual company specifications.

2.6.1 *Shot Peening*

The principal operating parameters which affect the results of the shot peening process and the various process specification requirements for these parameters are presented in Table 3 [45, 52-57]. Possibly the most important parameter in the process is the shot peening intensity. In all cases this is determined by the engineering drawing requirements and section thickness to be peened. Almen strips are used to ensure the correct intensity is achieved. The level of peening intensity is normally specified in the engineering drawing requirements. However, the standards give guidance on suitable peening intensities depending on material type and thickness. These are reviewed and presented in Table 4 [45, 52-57].

In all cases it is required that at least 100% coverage of the surface is achieved. Post peening checks are specified to ensure this has occurred and take one or more of the following forms:

(i) visual examination using a x10 magnifying glass;

(ii) visual examination using an approved liquid tracer system whereby a control specimen is completely coated and then shot peened using the correct intensity and parameters specified for complete coverage. On re-examination the tracer residue should have been completely removed.

(iii) The length of time to achieve complete visual coverage shall be measured. The final operation shall last twice that time for steel shot, i.e. 200% coverage.

Shot size, hardness and type are specified according to the strength level of material to be peened. In the case of UHSS used in the production of LG all the specifications require cast steel shot within the size range of 170 to 230 mesh and with a hardness of between 52 and 65 Rockwell Hardness C (RHC). It is important that the shot is at least as hard as the material to be peened. Also, in certain standards it is recommended that the angle of impingement is kept at 45° or higher (see Table 3). In all cases, it is required that broken shot be continuously removed from the system to ensure that the correct size and shape of shot is maintained. Acceptable levels of deformed or broken shot are specified.

Post process requirements are specified to ensure the induced compressive residual stresses are not subsequently degraded. These include that excess removal of material does not occur (10% of hardened layer) and subsequent heat treatments or operating temperatures do not exceed 250°C. This is in order to preserve the protective residual compressive layer formed at the surface.

It is considered that the standards reviewed give comprehensive and specific guidance on the shot peening variables to be used during the manufacture of LG. Moreover, it can be seen, Table 3 and Table 4, that the standards are consistent with each other. A system using Almen strips is employed to ensure the correct intensity of peening is achieved and thorough visual inspection ensures full coverage.

2.6.2 *Surface Preparation prior to Cadmium Plating*

The primary cause of premature coating systems failure is thought to be poor surface preparation [23]. The principal process operation carried out to prepare the surface prior to cadmium plating of LG components is grit blasting. The various process specification requirements for the preparation of LG components are presented in Table 5 [58-61].

The standards reviewed generally specify that a stress relief heat treatment and shot peening operation are carried out prior to grit blasting. In all cases, following the grit blasting operation, the component should be rinsed clean and transferred to the plating baths. The stress relief and shot peening process have been shown to inhibit the absorption of hydrogen associated with the plating procedure [25]. The operations of shot peening and heat treatment are well defined and consistent between the specifications reviewed (see Table 3 and section 2.6.1).

The grit blasting requirements outlined in the specifications are relatively poorly defined and can vary markedly between the standards (see Table 5). Generally alumina grit is specified, but the size required varies between 90 and 180 mesh between different standards. Blasting pressures, when specified, range from below 25 psi to a maximum of 100 psi (see Table 5). Requirements for coverage, blasting angle, blasting distance and blasting time (which will affect the depth of material removed) are in the majority of cases ambiguous where given, and are largely left to the discretion of the operator. For example, it is stated that blasting should take place '... until a uniform matt finish is obtained'. In certain cases, it recommends the continuous movement of the grit blast nozzle across the surface to prevent localised heating and excessive removal of material. There are no methods of testing in the specifications which check the quality of grit blasting and hence no way to quantify the condition of the surface after the blasting procedure. The level and quality of blasting is largely at the discretion of the operator and is, therefore, likely to vary accordingly.

2.6.3 *Cadmium Plating*

The cadmium plating specifications reviewed are outlined in Table 6 [61-69] and the main processing steps and requirements are summarised. Generally, although different plating solutions may be specified, the standards are consistent with their approach and requirements. Specific guidance is given as to plating solution maintenance and the plating cycle. In all cases a post plating 'bake out' heat treatment is required in order to minimise the risk of hydrogen embrittlement. The plating procedures are monitored to ensure effective treatment with tests required for plate thickness, adhesion strength, embrittlement and corrosion resistance. In this way it can be confirmed that the plating process has been carried out within specification requirements.

2.6.4 *Discussion*

The standards which cover the process procedures of shot peening and cadmium plating carried out during the manufacture of UHSS LG components are generally comprehensive and are consistent in their approach and process parameter requirements (see Table 3 and Table 6). Methods are specified and required which check the coverage and intensity of the shot peening process and the corrosion resistance, hydrogen embrittlement and plate adhesion properties of the plating process. Therefore, it is possible to quantify and check that the processes have been performed within specification in both cases.

The grit blasting operation is relatively poorly defined in many cases and specified process parameters vary significantly between the different standards reviewed. Compared with the shot peening and cadmium plating specifications, procedure parameters are largely at the discretion of the operator. Additionally, there are no methods specified in the standards which quantify the process or can be used to check that blasting was performed satisfactorily. Consequently, variations in the levels of blasting are likely to occur both between components and for different areas of the same component.

2.7 Alternatives to Cadmium Plating

Cadmium plating is widely used on aircraft for the protection of steel components. The advantages of cadmium plating have been outlined earlier, see Section 2.2.3. The main disadvantage associated with the use of cadmium is the high toxicity of the metal and its compounds [26]. This has resulted in restrictions in the use and exposure to cadmium [26]. At present, only aerospace, mining, nuclear and marine industries, are exempt, but only until a substitute material can be identified. The use of an alternative offers the potential for eliminating two environmental hazards – cadmium and cyanide [24].

As a result of these health and safety issues a number of alternatives to cadmium have been proposed. Boeing has developed a zinc-nickel coating under the name CorroBan [70]. It is an acid zinc-nickel process producing a deposit containing 8-12% nickel. It is reported that the coating is a viable alternative to cadmium, exhibiting superior corrosion protection in certain cases and greatly reduced effluent problems. Further research has shown that zinc, IVD aluminium and zinc-nickel coatings have comparable substrate corrosion resistance as cadmium [71]. Work performed by the Defence Evaluation and Research Agency (DERA) also shows that zinc-nickel coatings were comparable to cadmium in terms of corrosion resistance [24].

These studies have shown that the corrosion resistance of cadmium plating can be matched or exceeded by several different alternative coating types. However, no one coating would appear to offer the same broad range of properties as cadmium plating. These include galvanic compatibility with aluminium alloys, good surface lubricity and the possibility of in-situ repair by brush-plating. Therefore, there is unlikely to be, as yet, a single direct substitute for cadmium plating [24].

2.8 Lifing of Landing Gear Components

The code JAR (Joint Aviation Requirements) 25.571 [12] prescribes airworthiness standards for the damage tolerance and fatigue evaluation of LG used on 'large aircraft' of more than 5700Kg maximum certified take-off weight. It is stated that 'an evaluation of the strength, detail design and fabrication must show that catastrophic failure due to fatigue, corrosion and accidental damage, will be avoided throughout the operational life of the aircraft'. For structures, such as LGs, which could contribute to a catastrophic failure, a safe-life fatigue evaluation is specified. LG must be shown by analysis, supported by test evidence, to be able to withstand the repeated loads of variable magnitude expected during its service life without detectable cracks. Appropriate safe-life scatter factors are applied. In the case of nose and main LG a factor of at least 5 on life is required, whilst a factor of 3 has been used for LG not essential for landing of the aircraft such as body LG on certain aircraft. It should be noted that the Federal Aviation Administration (FAA) and other bodies may use different safety factors from those detailed above.

The ACJ (Advisory Circular, Joint) [72] contains guidance on compliance with JAR 25.571. These are not necessarily the only means of compliance.

During the design stage of LG, the potential benefits of shot peening on increasing the fatigue life are not generally taken into account, but rather considered an additional bonus. However, account is not taken of the increased surface roughness associated with the grit blasting and shot peening processes which may reduce the fatigue resistance of the component. The effect of surface roughness will become more pronounced if some relaxation of the compressively stressed surface layer occurs.

2.9 Fatigue Failures of Landing Gears

In addition to defects introduced during the manufacture of LGs, service operation can result in mechanical and environmentally induced damage. Fatigue cracks may initiate from these various kinds of damage. Once initiated the fatigue cracks usually propagate to cause component failure, since stresses are high and there is little or no redundancy. In turn component failure may lead to operational failure of the entire LG [5].

The MORs submitted to CAA and connected with LG for large commercial aircraft over the past ten years were reviewed. The only incident where fatigue cracking, which led to catastrophic failure, was thought to initiate from surface features associated with the processes of shot peening and grit blasting during manufacture of LG components was the one in which an MD-83 aircraft's main landing gear outer cylinder cracked at Manchester airport [1]. All other catastrophic failures were considered primarily as a result of one or more of the following: heavy landings; corrosion and incorrect maintenance procedures.

A search of the literature revealed only one other fatigue failure attributed to the shot peening process in an aerospace component [73]. It was considered that the failure of a helicopter tail rotor spindle resulted from a fatigue crack and that primary initiation had resulted from stress raisers in the form of surface discontinuities in its as forged and de-scaled surface and/or flaking caused by shot peening at an oblique angle.

Based on the past operational record of LG it would appear that the surface treatments carried out during manufacture do not have a significantly deleterious effect on the fatigue resistance of UHSS components under the present conditions of use. Only one recorded incident of fatigue failure has been reported to the CAA in the last ten years where failure has initiated from the surface condition induced through abrasive blast cleaning and/or shot peening. However, features such as surface roughening and embedded abrasive particles, which are present after manufacture, may have a greater influence on the fatigue lifetimes as higher performance, more highly stressed LG are developed.

2.10 Conclusions

The finishing surface treatments of shot peening, grit blasting and cadmium plating, which are carried out during the production of large civil aircraft LG, have been reviewed and assessed in terms of their affect on the fatigue life of ultra high strength steel landing gear components. The following conclusions have been made from this review of the available literature.

(1) A review of the MORs, covering the UK fleet only, revealed that only one fatigue failure has been reported in large civil aircraft LG in the past ten years where crack initiation has thought to have occurred as a consequence of the surface condition produced through the shot peening and/or grit blasting operations.

(2) The shot peening operation has a number of beneficial effects due to the introduction of a compressive residual stress layer at the components surface. This primarily results in an increase in fatigue lifetimes, but may also inhibit hydrogen embrittlement and stress corrosion cracking. The standards which cover the shot peening process during manufacture of landing gear components are comprehensive in their requirements and consistent with each other. Furthermore, quantitative quality control methods are specified which ensure the correct levels of peening have been carried out.

(3) The grit blasting operation is carried out to remove the passive layer found at the surface of ultra high strength steel alloys used in the manufacture of landing gear components. This enhances the adhesion of cadmium during the plating operation. However, the grit blasting process also roughens the surface and leaves embedded grit particles at the surface. Grit blasting parameters are relatively poorly defined in the standards used in the production of ultra high strength steel components and the levels of blasting achieved are largely left to the discretion of the operator. Therefore, it is considered likely that a range of blasting levels will be experienced during the manufacture of ultra high strength steel landing gear components. No quantitative quality control test methods are specified to check the blasting procedure has been performed satisfactorily. Some degradation of the compressive residual stresses, induced by the shot peening process, may also be possible if the grit blasting operation is very poorly controlled.

(4) The cadmium plating operations are carried out to give corrosion protection to UHSS LG components. Careful control of the plating process is required in order to reduce the risk of embrittlement caused by hydrogen absorption associated with the cleaning and plating procedure and this is reflected in the associated standards. Post plating test methods are specified in the standards to ensure satisfactory levels of plate adhesion, corrosion protection and resistance to hydrogen embrittlement are met. A number of alternatives to cadmium have been proposed in the literature; the most promising appears to be a Zn-Ni coating. However, no one coating would appear to offer the same broad range of properties as cadmium plating and hence there is, as yet, no single direct substitute available.

(5) The increased levels of roughness at the surface and embedded grit particles associated with the shot peening and grit blasting operations may reduce the fatigue lifetimes of landing gear components. However, any deleterious effect of the rougher surface on fatigue life is normally overshadowed by the beneficial compressive stress state at the surface produced by the prior shot peening operation. Fatigue lifetimes for rougher shot peened components are actualy reported to be greater than for smoother unpeened ones. However, residual stress relaxation may occur as a result of subsequent processing and / or during service life.

3 EXPERIMENTAL PROGRAMME

A short term experimental programme was undertaken after consideration of findings of the literature review. In particular, the review suggested that the standards which govern the grit blasting operation performed during the manufacture of UHSS LG components, were loosely defined and that the levels of blasting were largely at the discretion of the operator. Therefore, it was considered likely that a range of blasting levels could be experienced during the manufacture of UHSS LG components.

This experimental programme has examined the possible effects associated with different grit blasting procedures in terms of surface topography, residual stress profile and fatigue life. Work has been conducted on a 300M alloy steel in a quenched and tempered (Q&T) condition appropriate to its in-service application as landing gear. Specimens were ground initially prior to shot peening and grit blasting.

3.1 Experimental Procedure

3.1.1 *Material*

The material investigated was a 300M grade UHSS manufactured by British Steel Engineering Steel, Stocksbridge; a CAA approved source and under cover of a CAA approved certificate. The steel was electrically (air) melted and vacuum arc remelted (VAR). It was supplied as three inch diameter round bar in the normalised and tempered (N&T) condition. The certified chemical analysis is detailed in Table 7 [74]:

Testing was performed on the material in the Q&T condition. The heat treatment hardened the steel and produced a condition representative of that found in UHSS LG components prior to the shot peening, grit blasting and cadmium plating manufacturing processes.

3.1.2 *Heat Treatment*

Heat treatments were carried out in air using a muffle furnace. The specimens were initially heated to a temperature of 870°C and were held there for 1 hour. An external thermocouple was employed to measure the temperature of the specimens and it was possible to control the hold temperature to within the range 865-875°C. After an hour at temperature the specimens were quenched into oil. The oil had an initial temperature of 26°C and was agitated to ensure hot spots did not form during quenching. After cooling completely to room temperature, the specimens were degreased using solvent. A double tempering treatment was then conducted, i.e. the specimens were heated to 300°C and held at temperature for 2 hours. They were then removed from the furnace and allowed to air cool to room temperature. This tempering treatment was then repeated. A Hardness value of 600 Hv30 was measured using a 30 Kg load after these heat treatments.

3.1.3 *Specimen Preparation*

All specimens were initially machined from the bar in the as-supplied, N&T condition by using Electro Discharge Machining (EDM). Specimens were machined to dimensions of 14×12×70mm. Heat treatment was then undertaken as described in section 3.1.2. The surfaces of all specimens were subsequently ground using a flat bed grinder. Care was taken during grinding to avoid cracking of the surface. The specimens which had been heat treated were ground back by at least 700μm on the 3 faces which would experience the highest tensile stresses during subsequent fatigue testing. This was sufficient to remove the layer affected by the EDM process and to remove the surface layer affected by de-carburisation as assessed by performing microhardness traces on sectioned specimens and to eliminate any cracks which may have formed during heat treatment [75]. Full hardness was measured 400μm from the surface. After grinding, the specimen surfaces were protected from the environment by coating them in oil. In all cases the corners bordering the face of the specimen which would experience the highest tensile stresses during fatigue loading were then rounded off by hand using silicon carbide papers down to 800 grit. This was performed in order to reduce any effect of stress concentration caused by the sharp corners formed by EDM.

Prior to fatigue tests, surface topography and residual stress analyses, specimens were processed as detailed in Table 8. Sets of 9 or 10 specimens were processed for each condition. All specimens were initially ground and the as ground condition is designated as surface condition 0. Selected sets were then shot peened and, in the majority of cases, subsequently grit blasted to various levels. All shot peening and grit blasting operations were performed by the Metal Improvements Company, Derby.

Shot peening was carried out in accordance U S Military specification MIL-S-13165C [45]. Cast steel shot of size 230 and hardness 55-62 HRC was employed. Peening was carried out on all four of the major faces of the specimen surface and at an angle of 90°. The shot velocity was calculated at 23m/s using PEENSTRESS software. This gave a measured intensity of 0.07 inch on Almen strip A. Specimens whose surfaces were ground, shot peened, but not grit blasted are designated here as having surface condition 1.

Grit blasting of the ground and shot peened specimen surfaces was performed at two different levels: surface conditions 2 and 3. Sets of specimens for surface conditions 2 and 3 were blasted using aluminium oxide grit of sizes 120/220 and 40/60 mesh (over grit blasted) respectively. The severity of the blast was controlled by the coarseness of grit. In each case the pressure used was 60 psi, with a nozzle stand-off distance of 150mm and at an angle of 90° to the surface. 5 passes of the nozzle were made across each specimen face.

3.1.4 *Metallography*

Specimens for optical examination were first mounted in bakelite and then ground down through 150 to 1200 grades of SiC paper and then polished down to 3μm using diamond polishing wheels. Specimens were etched using 2% Nital reagent

($2\%HNO_3$, 98% Ethanol) prior to optical examination. Microstructures of the material were then observed using a Leica optical microscope.

3.1.5 *Hardness and Compression Testing*

Vickers hardness testing was carried out using an Indentec 5030 SKV machine. Ground specimens were tested using a 30kg load and pyramidal diamond indentor. Micro hardness testing of the heat treated samples was performed on a Mitutoyo MVK-H1 machine using a load of 500 grammes and a pydramidal diamond indentor. Measurements were made on sectioned, heat treated specimens, which had been ground and polished. Hardness traces were made at measured distances from the specimen surface by the use of a stage with digital micrometer. Several traces were made in each case at staggered distances in order to ensure results were not affected by previous indentations.

Compression testing was carried out using a 50kN ESH servo hydraulic test machine. Test cylinders were 12 mm in length and 5 mm in diameter.

3.1.6 *Surface Roughness Analysis*

The fatigue life of a material can be highly sensitive to the surface roughness [6]. Therefore, the relative magnitudes of roughness (stress raisers) of the four different surface conditions of specimens tested under cyclic loading, i.e. as-ground, shot peened and shot peened and grit blasted to two different levels, have been measured. The surface roughness of all surface conditions were assessed using a Form Talysurf 120L machine. The stylus tip is a conical diamond of tip radius 1.5 – 2.5μm and the vertical deflection is measured by a laser with 10nm vertical resolution. A stylus force of 70-100 mgf was used over the full range. The surface roughness was measured over a distance of at least 4mm in all cases. Measurements were made both along the length and across the width of specimens. R_a, R_q, R_t and R_v values were measured in microns where R_a, R_q, R_t and R_v are defined as: the arithmetic mean of the absolute departures of the roughness profile from the mean line; the geometric mean of the absolute departures of the roughness profile from the mean line; the maximum peak to valley height of the profile in the assessment length and the maximum depth of the profile below the mean line within the sampling length of the surface respectively. A hard copy trace of each surface was also produced. Additionally, the surface roughness was measured over an area of 2×2mm in each case and three dimensional images were generated with the results using Surfascan Toposurf imaging software.

3.1.7 *Residual Stress Analysis*

The residual stress profiles of the various specimen surface conditions were determined by employing a X-ray diffraction technique. A Rigaku Strainflex PSF-2M stress analyser machine was used in all cases operating at 30kV and 10mA. Cr K_α radiation (l=2.291Å) was used in conjunction with a 1° receiving slit, 1° primary beam slit and a vanadium filter. The (211) plane of α-Fe was chosen for the diffracting plane: this has a peak at approximately $2\theta=156°$. Sample rotating angles (ψ_O) of 0°, 15°, 30° and 45° were chosen and the residual stress was determined by the $2\theta\text{-}\sin^2\psi$ method (see Figure 9), where:

$$\psi = \psi_0 + \eta \qquad \text{and} \qquad \eta = \frac{180 - 2\theta_o}{2}$$

The stress profile through the depth of the specimens was determined by repeatedly etching away the surface layer to measured depths of typically 20 μm increments and taking further X-ray measurements. The etchant used was dilute nitric acid (15% HNO_3 and 85% distilled water) and the depth of etching was measured using a micrometer.

3.1.8 *Fatigue Testing*

S-N curves were generated using a 250kN ESH servo hydraulic test machine. Tests were performed at frequencies of 8 Hz and under constant amplitude loading. A nominal R-ratio (where R is the ratio of minimum stress to maximum stress applied over the fatigue cycle) of 0.1 was used. Tests were performed at ambient temperature, in air and the number of cycles to cause failure were recorded. Testing was conducted in order to achieve failure in 10^4-10^5 number of cycles. This is considered representative of the number of significant loading cycles encountered during service on commercial aircraft landing gear. In all cases four point bend loading was used with major and minor spans of 60 and 15mm respectively. A hemi-spherical thrust bearing was employed to ensure even loading at each contact point. Test piece dimensions were approximately 12.5×11×70mm. Tests which endure a cyclic loading cycles of 10^6 are counted as run-outs in this present study.

3.1.9 *Fractography*

Fracture surfaces were examined on a Jeol JSM 5410 Scanning Electron Microscopy (SEM) operating at an accelerating voltage of 20kV and 0° tilt. The SEM was used to assess the fracture surfaces produced under fatigue loading in order to characterise failure mechanisms and sites of crack initiation. Energy-dispersive spectrometric (EDS) analysis, using an electron probe analyser, was performed in order to identify qualitatively the chemistry of particles found at positions local to crack initiation sites.

3.2 **Results and Discussion**

3.2.1 *Metallography*

The microstructure of the material after the Q&T heat treatment is shown in Figure 10. It can be seen that the material comprises a uniform tempered martensitic structure.

3.2.2 *Hardness and Compression Tests*

The average hardness values measured for the Q&T material conditions was 600 Hv30. The hardness level of 600 Hv30 is typical of that used for UHSS LG. Compression testing conducted on four specimens gave 0.2% proof stresses of 1793, 1817, 1852 and 1902 MPa with an average of 1841 MPa.

3.2.3 *Surface Roughness*

Surfaces have been characterised in terms of R_a, R_q, R_t and R_v for measurements determined both along lines of at least 4mm length and over a 2×2mm square sectional area. R_a is the most commonly quoted surface roughness parameter and represents the average departure from the mean line. However, in terms of fatigue crack initiation resistance it is perhaps the value of R_V, the deepest valley recorded over the assessment area, is most important. This is because fatigue cracks will generally initiate at the sites of greatest stress concentration whereby one deeper scratch on the surface may be more damaging than many shallower ones. The results of the surface topography analysis in terms of both R_a and R_v are presented in Figure 11 and Figure 12 respectively. It can be seen that the ground surface has the smoothest topography with R_a and R_v values of 0.5 and 3.61μm (over the square section) respectively. The shot peened and shot peened and grit blasted surfaces (surface conditions 1 and 2) have similar surface roughness values with only a relatively small further increase in roughness occurring during grit blasting. They are both approximately twice the roughness of the as-ground condition. The surface roughness of the over grit blasted samples (surface conditions 3) is approximately twice as rough as conditions 1 and 2. R_a and R_v values for surface condition 3 of 1.66 and 19.85 μm were recorded respectively.

It can be seen that shot peening process roughens the surface when compared with the as-ground finish, with R_v values increasing from 3.61 to 5.7 μm. There appears to be further degradation of the surface when grit blasting to condition 2, which was considered, before testing, to be the ideal grit blasting procedure, is subsequently carried out. When the aluminium oxide grit particle size was increased from 120/220 to 40/60 mesh (surface condition 3, over blasted) a more significant increase in surface roughness was measured. R_v values of 7.39 and 19.85 μm were recorded for surface conditions 2 and 3 respectively.

The results obtained from the line measurements, both along the specimens length and across the width, show that the as-ground surface exhibits a strong directionality in surface profile with peaks and valleys running parallel to the direction of grinding (see Figure 13). This directionality can even be discerned after shot peening and grit blasting, as shown by Figure 14 and Figure 15. This demonstrates the general resistance to deformation exhibited by the Q&T material.

An example of the variation in blasting level which may occur during the grit blasting process, even on small simple components such as the testpieces used in these experiments, is shown in Figure 16. A region on a specimen prepared in accordance with surface condition 3 was observed by eye to be shaded differently to the rest of the specimen and other specimen surfaces of the same set. Subsequent surface roughness measurements, Figure 11 and Figure 12, revealed that R_a and R_v values were approximately half those measured on other specimens. The 3D image of the surface also revealed that the underlying as-ground topography could still be observed (see Figure 16), suggesting that this area had been significantly under blasted when compared with other regions.

3.2.4 *Residual Stress*

The results of the residual stress analysis performed in various surface conditions are presented in Figure 17. There are clear differences between specimens which were analysed in the as-ground surface condition when compared with those which had undergone shot peening during processing. The shot peening procedure has produced a compressive residual stress layer of significant magnitude at the surface. From the stress profiles shown in Figure 17 it can be seen that the highest compressive stresses, for those specimens which were shot peened during processing, are found at the surface or within approximately 40μm of the surface. The magnitude of the residual stress steadily reduces through the depth of the specimen until it stabilises at a level of near zero residual tensile stress. In comparison the as-ground samples have a significantly different residual stress profile with small residual tensile stress found at surface.

It can be seen that the compressive residual stress layer extends approximately 150 μm in from the surface (see Figure 17). The highest compressive residual stresses were recorded at about 40 μm from the surface for all the shot peened conditions. The peak compressive stress of -843 MPa was measured at about 35 μm depth from the surface for the as ground and shot peened condition 1. This represents approximately 45% of the 0.2% proof stress of the material (σ_y=1841 MPa). It can be seen that subsequent grit blasting of the ground and shot peened samples, surface conditions 2, 3, slightly increases the magnitude of the peak compressive residual stress and the compressive residual stress depth. It is interesting to note that this result is opposed to the expectation in literature review, see section 2.2.2 and 2.3.4, where the compressive residual stress value and the depth were suggested to be lowered by grit blasting due to the material removal by grit blasting and the likely elevated temperature caused by this material removal and plastic deformation. The results in this present work suggest that the grit blasting process imposed on a shot peened surface can further increase slightly the effect of shot peening in creating compressive residual stress layer for the high strength material such as Q&T 300M steel used in LG components. It can be argued that the impingement of the grit particles on component surface during grit blasting procedure is, at least theoretically, similar to the impingement of shot on component surface during shot peening procedure. Whether the grit blasting strengthens or lessens the effect of the previous shot peening procedure depends on the combination of the blasted material and the blasting parameters. Any assumed erosion of the surface during grit blasting and any assumed localised heating of the surface do not affect the residual stress profile presumably because of the high strength of the material used in this present investigation.

However, it should be pointed out that in the present study it was necessary to perform the residual stress analysis in a very short period. One compromise was not to compensate for the removal of surface layers in recalculating the effective residual stress shown in Figure 17 (This can be achieved by measuring the back face strain on the testpiece as a function of surface removal, to allow a force and moment balance to be established). Therefore, the profile shown in Figure 17 should be regarded as approximate only (although the near surface stresses and the point of zero stress with depth can be considered to be accurate). Clearly as shown in Figure 17, there is no tensile stress sub-surface to balance out the high compressive near surface stress, but the analysis is considered sufficient for the present investigation.

3.2.5 *Fatigue Results*

The results of the S-N fatigue tests are presented as S-N curves in Figure 18. Individual data are presented in Table 9. It can be seen that all the specimens which have undergone shot peening during their processing have markedly superior lifetimes to specimens with the as-ground surface condition. When comparing the fatigue lifetimes for all the shot peened surface conditions (conditions 1 to 3), it can be seen that the two grit blasting conditions employed are not detrimental to fatigue life.

3.2.5.1 Fractography

Fractography shows that fatigue cracks can initiate from both surface and sub-surface positions for all the shot peened surface conditions 1 to 3. When cracks were initiated from the surface the positions of crack initiation sites can be either at the corner, or at the centre of the surface having the highest stress (see Figure 19 and Figure 20). Crack initiation from a sub-surface position is shown in Figure 21. It was found that the tendency of sub-surface crack initiation is promoted at lower applied stresses. It seems that a transition stress exists above which cracks initiate from surface positions and below which cracks initiate from sub-surface positions. The transition stresses for conditions 1, 2 and 3 are approximately 1400, 1700 and 1500 MPa respectively. Evidence of grit particle related crack initiation, which was suggested to be the cause for the failure of a MD-83 aircraft's main landing gear outer cylinder [1], was not found. Instead, cracks were found to initiate from damaged surface features such as shot indentions or scratches left by shot peening and grit blasting in the case of surface crack initiation (see Figure 22 In the case of sub-surface crack initiation, cracks were initiated from Ti-containing inclusions (see Figure 23). An EDX profile shown in Figure 24 clearly indicates that the inclusion in Figure 23 is a Ti-containing inclusion. The existence of large Ti-containing inclusions in the material is also confirmed by the optical microscopy (see Figure 25). The locations of the sub-surface crack initiation sites were found to be just beyond the predicted compressive residual stress depth. In many cases, particularly at higher stress levels, a number of initiation sites were present on each specimen (see Figure 26).

3.2.5.2 Effects of Residual Stress and Surface Roughness on Fatigue life

Specimens which had been shot peened prior to fatigue testing recorded superior fatigue lifetimes when compared with the as-ground specimens. This improvement in fatigue resistance has been measured even though the as-ground specimens have the least rough surface topography. In this case it would appear that any detrimental effect of a rougher surface on fatigue performance has been negated by the effects of a compressive residual stress layer at the surface, resulting from the shot peening process. It may be considered that the effective stress acting on the specimen is a combination of both the applied and residual stress. Because of high compressive residual stresses at surface positions, the maximum combined tensile stresses are transferred to sub-surface locations. Consquently the crack initiation sites can be found at sub-surface locations. Indeed, sub-surface crack initiation is found in all shot peened conditions. However, the stress concentration effects of a rough surface may magnify the stresses at localised areas, increasing the near surface stresses. In this manner the surface roughness may still affect the fatigue life if cracks initiate at surface positions. In this study surface crack initiation can occur at high applied stress levels where these applied stresses are greater than the yield strength of the material, and where residual stresses are presumably relieved by local plastic deformation.

3.2.6 *Engineering Implications*

The fatigue design of UHSS LG components is based on a safe-life approach with a safety factor of at least 5 on life required [12]. During the design of UHSS LG components, fatigue life is calculated assuming an as-ground surface finish and with no account taken of the effects of the manufacturing processes of shot peening, grit blasting and cadmium plating. It is well established that the shot peening process imparts a compressive residual stress at the surface of a component that may significantly increase the fatigue life of components. It has been demonstrated in this investigation that an improvement in fatigue life may be expected after shot peening even when the surface has been roughened by the shot peening and grit blasting processes, when compared with the as-ground condition. Therefore, any assessment that used the as-ground surface condition during the design stage would be overly conservative in terms of fatigue life. However, the improvement in fatigue life will only occur if the induced compressive residual stress state at the surface is maintained through the life of the UHSS LG component. It has been reported elsewhere that the beneficial compressive residual stresses are not always permanent, but tend to diminish as a function of time, temperature and load history [76]. If the magnitude of compressive residual stress at the surface is reduced, then the effects of increased surface roughness will become more pronounced with respect to fatigue life. It may be expected that in the case of no residual stress or a tensile residual stress being present at the surface, that the increase in surface roughness associated with the shot peening and grit blasting processes could conceivably reduce fatigue lifetimes below those of the smoother, as-ground surface condition. Therefore, if residual stress relaxation should occur during the manufacture or during the service life of UHSS LG components it may result in shorter than expected for fatigue lifetimes. This is perhaps most likely in localised areas of high stress concentration. If plastic deformation should occur during overloading, as may be experienced during a heavy landing or as a result of severe gear walk, then the compressive residual stress state in these localised areas may be reduced in magnitude or transformed to a residual tensile stress. In such cases, it is conceivable that a rougher surface related to grit blasting may then reduce the fatigue life compared with as-shot peened conditions

3.3 Conclusions

The finishing surface treatments of shot peening and grit blasting, which are carried out during the production of large civil aircraft LG, have been examined and assessed in terms of their affect on the fatigue life of ultra high strength steel landing gear components. The following conclusions have been made from this experimental programme.

(1) Specimens which have been shot peened during processing have markedly superior fatigue lifetimes to those tested in the as-ground condition. The improvement in fatigue lifetimes is considered to be due to the high residual compressive stress state induced at near surface locations by the shot peening process. The beneficial effect of the compressive residual stresses have more than compensated for any reduction in fatigue life which may have been caused by an increase in surface roughness associated with the shot peening and grit blasting procedures.

(2) The grit blasting procedures performed on the previously shot peened surfaces have been shown to further roughen the surface, but for the range of parameters studied they can actually increase slightly the magnitude of the compressive residual stresses.

(3) At lower stress levels compressive residual stresses were found to transfer the crack initiation sites to sub-surface locations roughly corresponding to the compressive residual stress depth. However, at higher stress levels, cracks were initiated from surface positions and in such cases, it is considered that compressive residual stresses at the surface layer have been relieved by plastic deformation.

4 OVERALL SUMMARY

This short-term literature review and experimental programme on UHSS 300M LG steels has confirmed:

(1) The beneficial effect of shot-peening in enhancing fatigue life compared with as-ground conditions, and that the standards covering the shot-peening process during manufacturing landing gear components are comprehensive and consistent. Quantitative quality control methods are specified to assure that the correct levels of peening have been attained.

(2) No detrimental effects of "optimised" and "over-blasted" grit blasting procedures on the fatigue life of prior shot-peened testpieces have been obtained in this experimental programme. Therefore, although the standards and quality control procedures for grit blasting are not as well established as those for shot peening, this study has found no reason to recommend any tightening of the procedures.

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Table 1 Typical Compositions of Ultra High Strength Steels Used In Civil Aircraft [2–6]

Alloy	C	Mn	Si	Ni	Cr	Mo	V	Fe
4340	0.40	0.75	0.25	1.8	0.80	0.25	-	Remainder
HY-TUF	0.25	1.3	1.5	1.8	0.30	0.40	-	Remainder
300M	0.43	0.75	1.6	1.8	0.80	0.40	0.07	Remainder
D6AC	0.45	0.7	0.2	0.5	1.0	1.0	0.1	Remainder

Composition (wt.%)

Table 2 Typical Mechanical Properties of Ultra High Strength Steels Used In Civil Aircraft [2–6]

	Tensile Properties		Fracture Toughness	Stress Corrosion Cracking	Fatigue Crack Growth Rates		Fatigue Threshold Values
Alloys	σ_y (MPa)	σ_{TS} (MPa)	K_{IC} (MPam$^{1/2}$)	K_{ISCC} (MPam$^{1/2}$)	C (m/cycle)	m	ΔK_{th} (MPam$^{1/2}$)
4340	1 480	1 965	70	11-16	5×10^{-10}	2.5	7.6
300M	1 690	1 965	70	11-16	2.5×10^{-11}	2.6	3
HY-TUF	1 350	1 600					
D6AC	1 400	1600	70	11-16	7.2×10^{-12}	2.9	6

Fatigue properties at R=0.1

Table 3 Summary of the Shot Peening Standards Used in the Manufacture of Steel Landing Gear Components [45, 52-57]

Shot Size and Type	Cast Steel Specified on engineering drawing Less than half minimum fillet radius	Cast Steel Specified on engineering drawing Size depends on shape and size of fillets, intensity and desired finish	Cast Steel Specified on engineering drawing Recommended smallest size practical to produce required intensity.	Cast Steel S170-230	Cast Steel Specified on engineering drawing Less than half minimum fillet radius S230 preferred shot size	Specified on engineering drawing
Hardness of Shot (HRC)	-	55-65	52-62	55-65	55-65	-
Surface Coverage	100% - Check by visual examination with x10 magnification	100% - Check by visual examination with x10 magnification and liquid tracer	200% - Check by visual examination with x10 magnification and liquid tracer	100% - Check by suitable means or use peening time required to saturate test strip	At least 100% coverage - visual examination.	100% - Check by visual examination with x10 magnification and liquid tracer
Angle of Impingement	Greater than 45° and as near to 90° as possible	-	Greater than 45°	Greater than 45°	-	-
Condition of Shot	Continuous removal of defective shot. Check every 8 hours less than 2% by weight defective.	<10% deformed or broken. Check every 8 hours of operation	Continuous removal of defective shot. 20/in^2 allowable for shot size S170-320	Continuous removal of defective shot. Check every 8 hours	20 deformed shot per 12.7mm^2 area allowable	Continuous removal of defective shot. Check every 8 hours - 2% by number defective and 5% marginal acceptable
Post Peening Treatments	Do not exceed 204°C. Remove shot without damaging surface. Do not remove material layers more than 10% of minimum 'A' intensity Arc height.	Do not exceed 246°C. Remove shot without damaging surface. Protect from corrosion	Do not exceed 246°C. Operations which relieve the stresses developed by peening are prohibited. Do not remove material layer greater than 10% of induced compressive layer.	Do not exceed 210°C. Protect from corrosion. Processes which would remove the peening stresses or develop detrimental stresses are prohibited Do not remove material layers more than 10% of minimum 'A' intensity Arc height.	Do not exceed 200°C. Protect from corrosion. Processes which would remove the peening stresses or develop detrimental stresses are prohibited Do not remove material layers more than 10% of minimum 'A' intensity Arc height.	Do not exceed 246°C. Protect from corrosion. Processes which would remove the peening stresses or develop detrimental stresses are prohibited Do not remove material layers more than 10% of minimum 'A' intensity Arc height.

Table 4 Shot Peening Intensity Recommendations From the Standards Used in the Manufacture of Steel Landing Gear Components [45, 52-57]

Section thickness (inches)	up to 0.090		up to 0.090		up to 0.125
Recommended shot peening intensity	0.003 - 0.006A		0.003 - 0.006A		not recommended
Section thickness (inches)	0.090 to 0.375	0.090 to 0.375	0.091 to 0.375		
Recommended shot peening intensity	0.008 - 0.010A	0.008 - 0.010A	0.008 - 0.010A		
Section thickness (inches)	over 0.375	over 0.375	over 0.376	over 0.125	over 0.125
Recommended shot peening intensity	0.006 - 0.010A	0.006 - 0.010A	0.006 - 0.010A	0.006 - 0.009A	0.008 - 0.012A
Comments		Peening intensity shall be as specified on drawing	If only a minimum intensity is specified, the maximum intensity should not exceed the minimum intensity by more than 0.004A		

Table 5 Summary of the Abrasive Blasting Standards Used in the Manufacture of Steel Landing Gear Components [58-61]

	Individual Standards							
Pre-Blasting Procedure	Degrease	Degrease in an organic solvent	Clean as per MIL-S-5002					
Grit Blasting Pressure	Do not exceed 25 psi	Not specified	Do not exceed 90 psi	Not specified	Not specified	Not specified	40-60psi	Not specified
Grit Type and Size	Alumina grit 90 Mesh	Alumina or iron grit	Alumina or Silica 80-180 Mesh	Alumina 100-180 Mesh	Alumina or Silica 100-180 Mesh	Dry abrasive preferred	Alumina, silica or glass beads	Alumina, alumina-zirconia, 80-120 Mesh
Coverage	Until a uniform matt finish is obtained		Blasting time no longer than to clean the surface					
Stand- Off Distance	4in-6in		3in-12in					
Other Requirements	Blast at 45° angle Avoid overheating by continuous movement of nozzle across surface		Blast at 90° angle Screening or classification process to remove undersize or broken abrasive particles	Avoid overheating by continuous movement of nozzle across surface				
Post Blasting Requirements			Blow off dust with clean, dry compressed air	Blow off dust with clean, dry compressed air				
Quality Control	Visual inspection by operator		Visual inspection Rejected on grounds of warpage, distortion or excessive material removal					

Table 6 Summary of the Cadmium Plating Standards Used in the Manufacture of Steel Landing Gear Components [61-69]

	Individual Standards						
Pre-Plating Requirements	Stress relieve 4 hours at 190°C Shot peen Clean and mask	Stress relieve Shot peen Degrease	Stress relieve 4 hours at 190°C Shot peen Vapour degrease handle with gloves	Stress relieve 4 hours at 190°C Shot peen Vapour degrease handle with gloves	Heat treat and peen	Stress relieve and shot peen Solvent degreasing	Stress relieve and shot peen
Grit Blasting Procedure	See Table 5	See Table 5	See Table 5	See Table 5	See Table 5	See Table 5	See Table 5
Plating Solution	Cyanide	Cyanide and others meeting standard requirements	Cadmium - Titanium Cyanide	Cyanide	Cyanide	Cadmium - Titanium Cyanide	Cyanide, sulfate, fluoborate, sulfamate, sulfate-fluoborate
Plating Cycle	Cold water wash, plating bath, acid rinse, cold water swill		Cold water wash, acid rinse, plating bath, cold water swill, hot water swill and blow dry	Cold water wash, plating bath, cold water swill, hot water swill and blow dry	Cold water wash, cyanide dip, plating bath, cold water swill, hot water swill and blow dry	Cold water rinse, plating bath, cold water rinse, acid rinse, hot water rinse, air dried	Alkaline solution dip, water rinse, plating bath, water rinse, acid rinse, hot water rinse, air dried
De-Embrittlement Treatment	Minimum 24 hours at 190°C	Minimum 18 hours at 190-230°C	Minimum 12 hours at 190°C	Minimum 23 hours at 190°C	Minimum 23 hours at 190°C	23 hours at 190°C	Minimum 23 hours at 190°C
Post plating inspection	Test for plate thickness, adhesion, embrittlement and corrosion resistance	Test for plate thickness and adhesion	Inspection as per standard QQ-P-416 Embrittlement and titanium content test	Inspection as per standard QQ-P-416 Embrittlement and titanium content test	Test for plate thickness, adhesion, embrittlement and corrosion resistance	Test for plate thickness, adhesion, embrittlement and corrosion resistance	Test for plate thickness, adhesion, embrittlement and corrosion resistance

Table 7 Certified chemical analysis of UHSS 300M steel

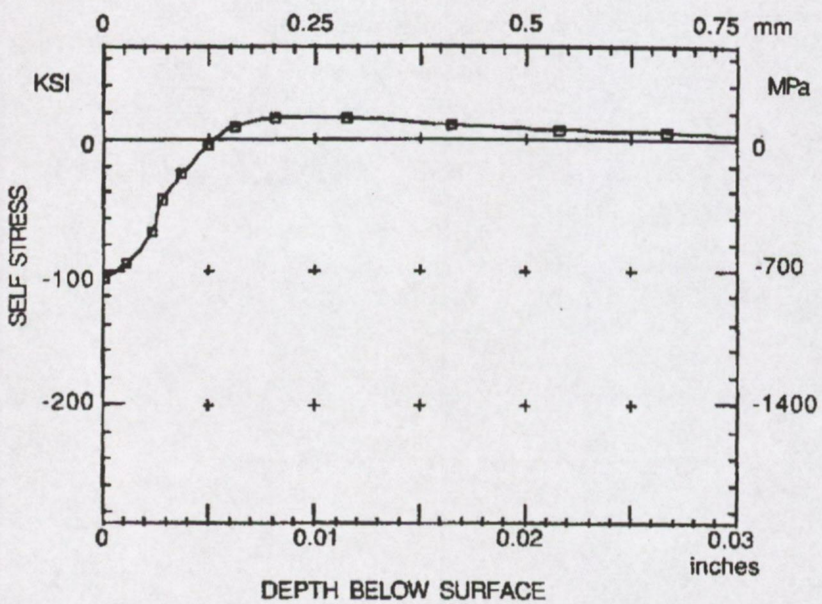
Element	C	Si	Mn	P	S	Cr	Mo	Ni	Cu	Sn	Al	Fe	Sn	Ti	V
Wt%	0.41	1.53	0.79	0.004	0.0009	0.80	0.41	1.79	0.05	0.005	0.023	Rem.	0.005	0.005	0.066

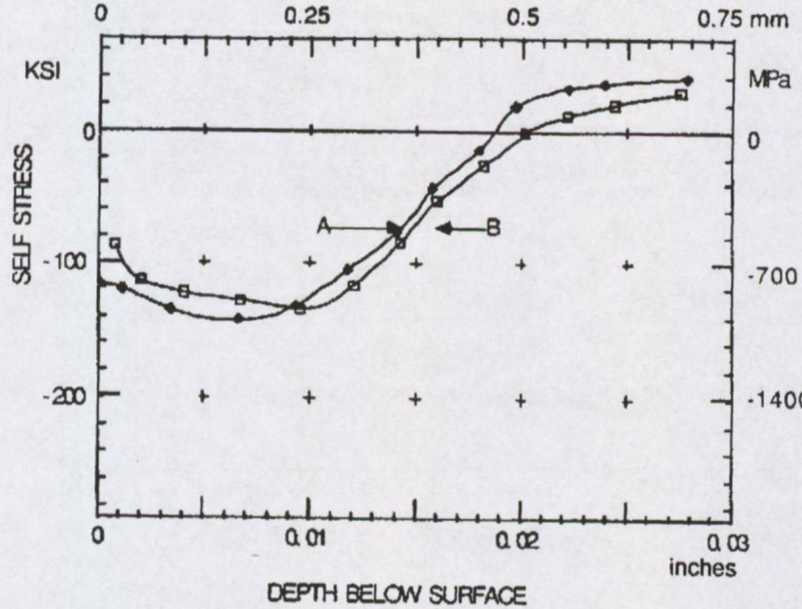
Table 8 Conditions of shot peening and grit blasting of fatigue specimens

Condition 0	Condition 1	Condition 2	Condition 3
As-ground	Shot peened	Shot peened and grit blasted (grit of size 120/220 mesh)	Shot peened and over grit blasted (grit of size 40/60 mesh)

Table 9 Individual data for S-N curve tests

Condition 0		Condition 1		Condition 2		Condition 3	
σ_{max} (MPa)	N	σ_{max} (MPa)	N	σ_{max} (MPa)	N	σ_{max} (MPa)	N
1600	1.32E+04	2000	1.49E+04	2100	1.88E+04	2000	1.55E+04
1500	1.53E+04	1900	1.65E+04	2000	2.66E+04	1900	1.42E+04
1400	1.90E+04	1800	2.43E+04	1900	3.10E+04	1800	3.00E+04
1300	1.88E+04	1700	3.19E+04	1800	2.81E+04	1700	4.59E+04
1200	2.49E+04	1600	3.52E+04	1700	4.21E+04	1600	5.90E+04
1200	2.36E+04	1500	8.05E+04	1600	3.79E+04	1600	5.41E+04
1100	4.84E+04	1400	8.60E+04	1500	2.91E+05	1500	6.15E+04
1050	6.46E+04	1300	9.97E+05	1400	1.95E+05	1450	1.28E+05
1000	1.96E+06	1250	6.95E+05	1250	1.28E+06	1400	6.46E+05





<u>Material:</u> 4340 steel

<u>Hardness:</u> Rockwell C 30
<u>Tensile strength:</u> 131 ksi (905 MPa)
<u>Yield strength:</u> 107 ksi (740 MPa)

<u>Specimen:</u> 2x2x1/4 in (50x50x6.3 mm)

<u>Intensity:</u> 4 A
<u>Shot:</u> S110 (o.28 mm nominal)
<u>Coverage:</u> Complete (95%)

<u>Reference:</u> Brodrick,R.F., Protective Shot Peening of Propellers, Part 1, June 1955, p.51. WADC Technical Report 55-56 Part1.

<u>Material:</u> 4340 steel, two slightly different hardnesses.

	A	B
<u>Hardness:</u> Rockwell C	51	50
<u>Tensile strength:</u>	251 ksi (1730 MPa)	244 ksi (1685 MPa)
<u>Yield strength:</u>	221 ksi (1525 MPa)	217 ksi (1500 MPa)

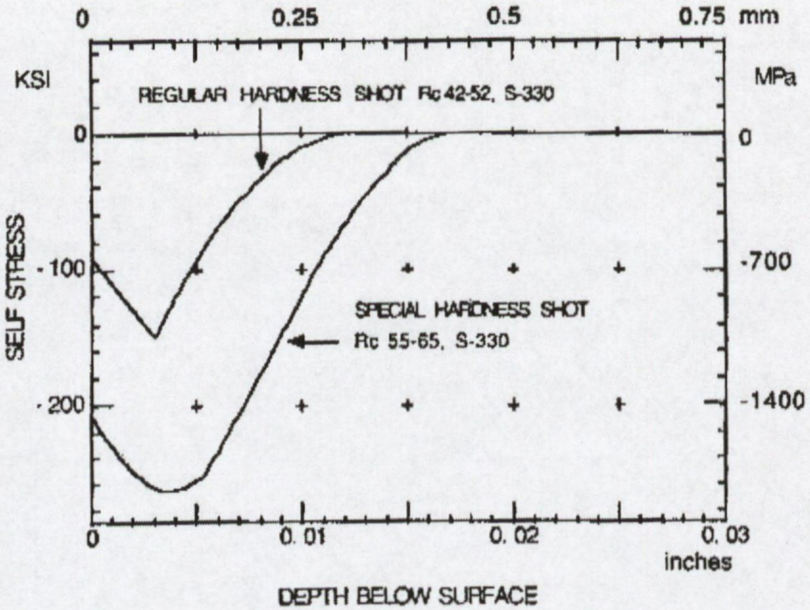
<u>Specimen:</u> 2x2x1/4 in (50x50x6.3 mm)

<u>Intensity:</u> 10 C
<u>Shot:</u> 1/8 in . (3.2 mm) diameter

	A	B
<u>Coverage:</u>	400%	95%
<u>Air pressure:</u>	30 psi (200 kPa)	50 psi (350 kPa)

<u>Reference:</u> Brodrick, R.E., Protective Shot Peening of Propellers, Part1, June 1955, pp 306,309. WADC Technical Report 55-56 Part 1.

Figure 1a A selection of stress profiles measured on shot peened ultra high strength steels. After Fuchs [30]

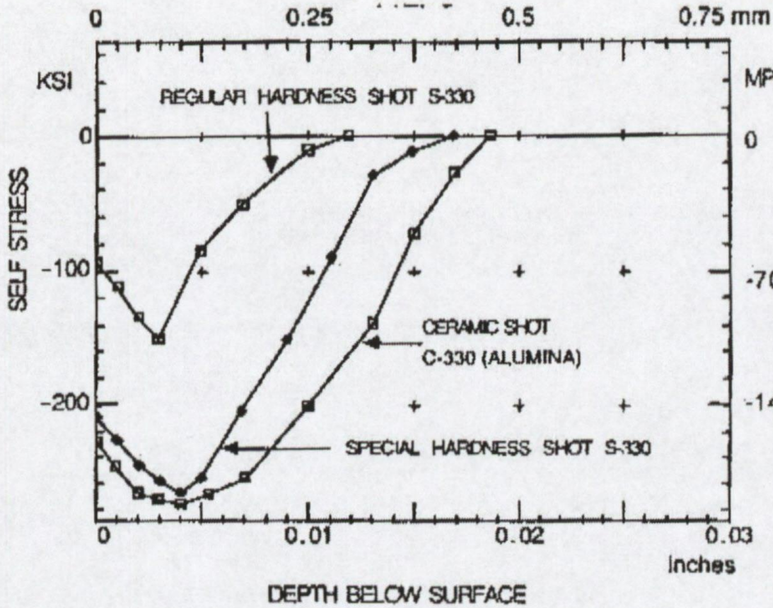


Material: 4340 M steel

Tensile Strength: 275 - 300 ksi (1900 - 2070 MPa)

Intensity: 14 A
Shot size: S 330 (o.84 mm nominal)

Reference: Boeing Materials Technology Summary Report
BMT-SR-846, November 1978



Material: 300 M steel

Hardness: Rockwell C 54 (estimated)
Tensile strength: 280 ksi (1930 MPa) (specified)
Yield strength: 230 ksi (1590 MPa) (specified)

Intensity: 15 A
Shot size: S 330 (o.84 mm nominal)

Reference: Lauchner, E., Peening of High Strength Steel Using Hard Shot. Presentation at WESTEC, March 1974.

Figure 1b A selection of stress profiles measured on shot peened ultra high strength steels. After Fuchs [30]

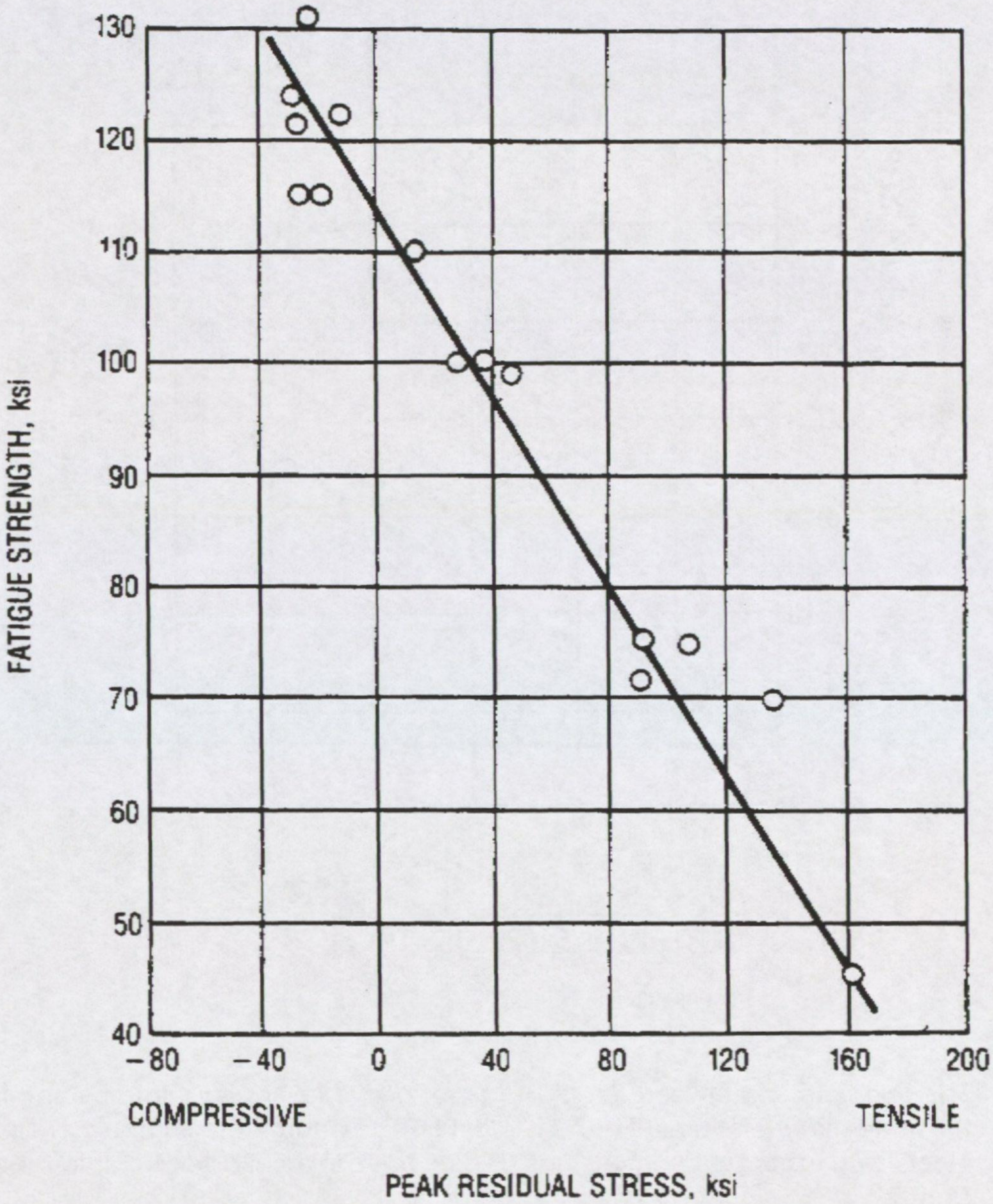


Figure 2 **The effect of peak residual stress on fatigue strength of an ultra high strength steel 4340. After Metal Improvements Company [31].**

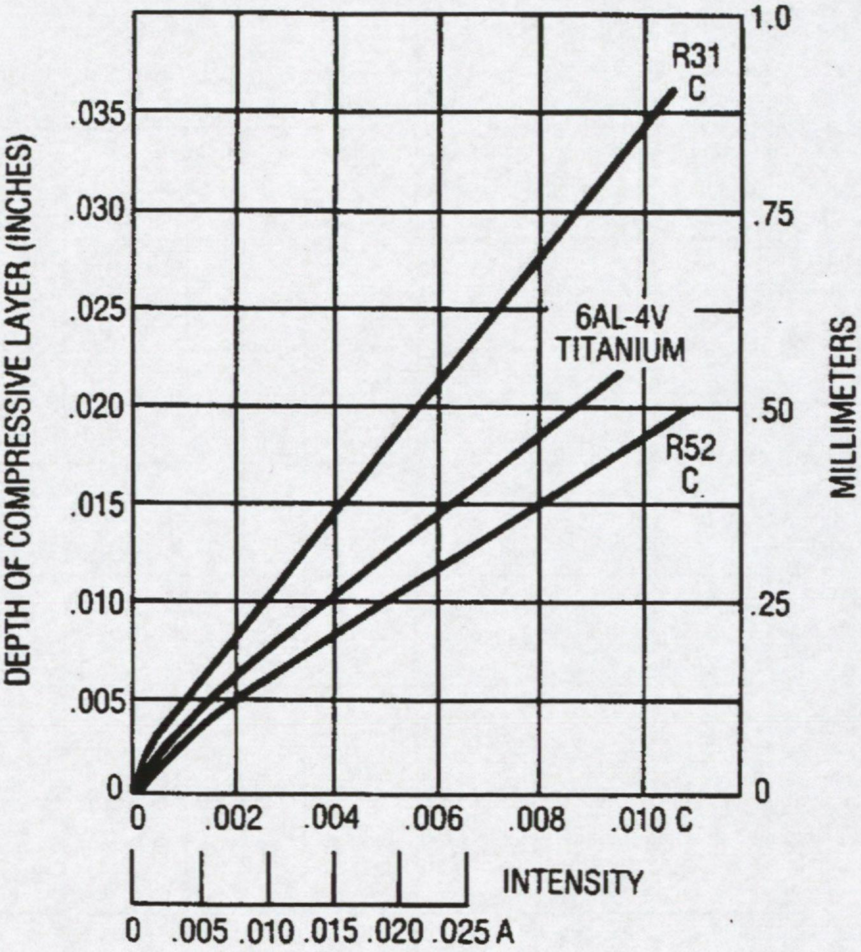


Figure 3 The relationship between depth of compressive layer and shot peening intensity for three materials: steel HRC 31, steel HRC 52 and a titanium alloy. Depths for steels with other hardness values can be interpolated. After Metal Improvements Company [31].

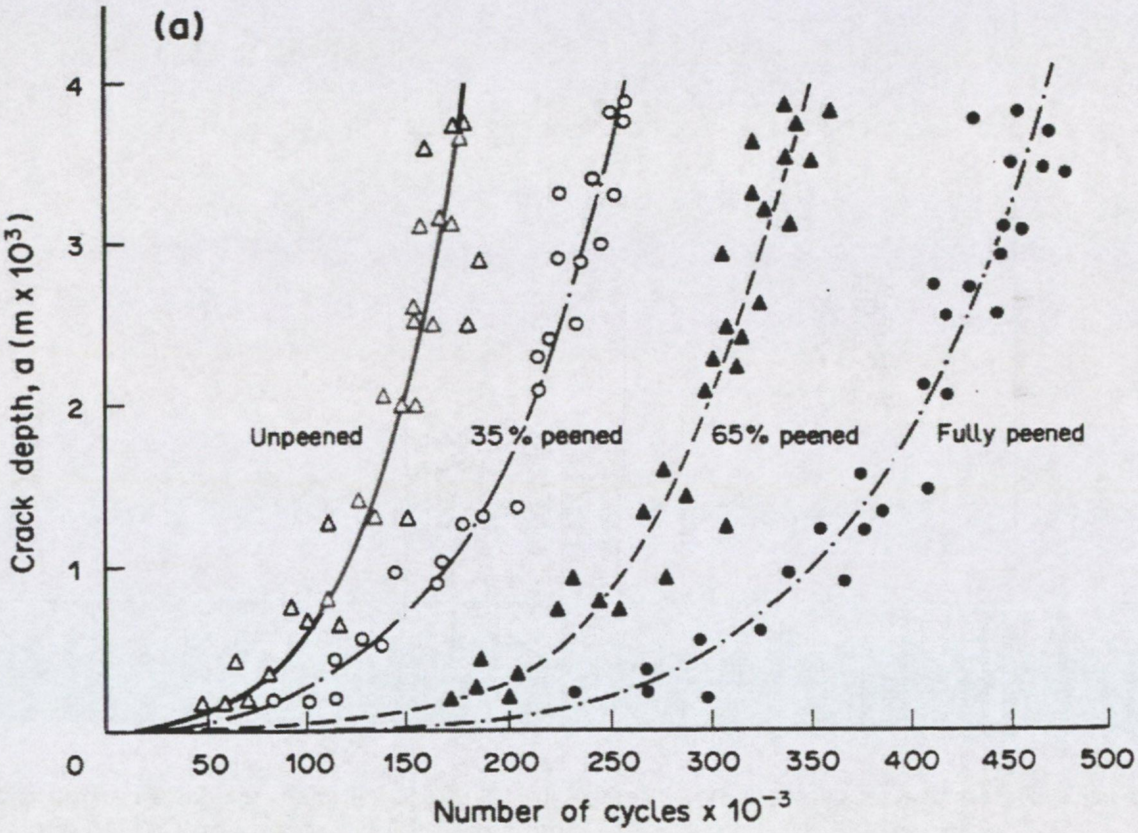


Figure 4 Semi-crack depth a vs fatigue life N for fully, partial and unpeened medium carbon steel (En 8) specimens. After Meguid [32].

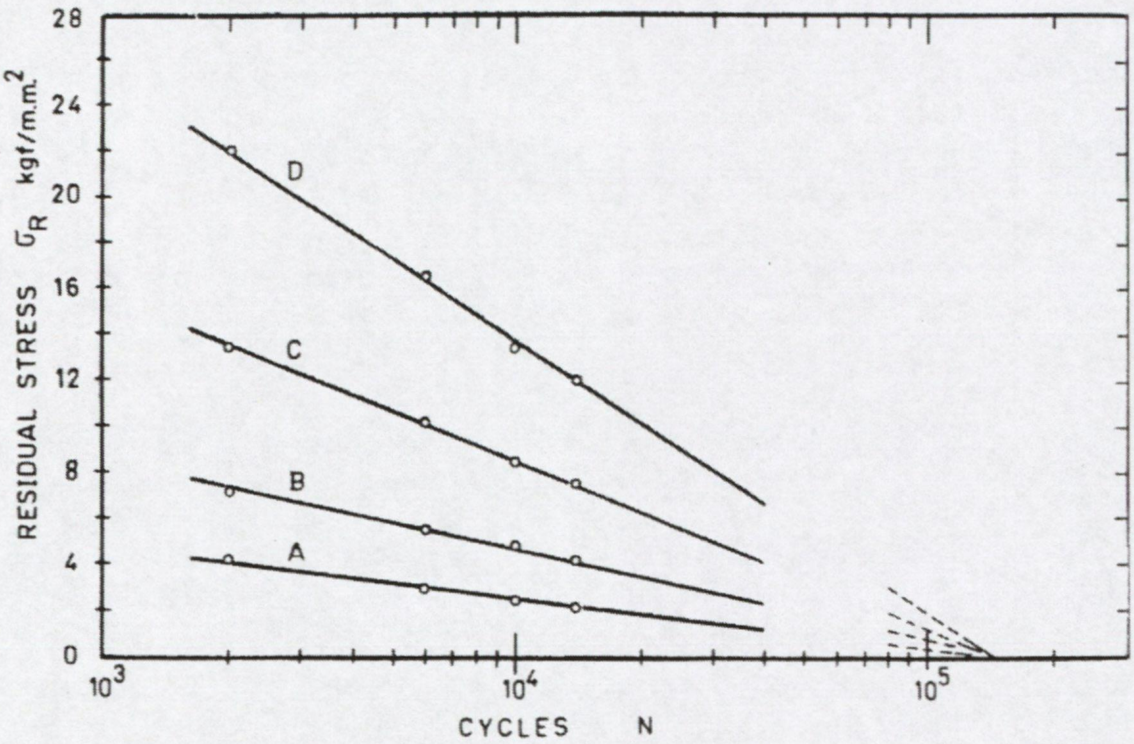


Figure 5 **Relaxation of the residual stress with fatigue cycling on a 0.23% carbon steel. Conditions A, B, C and D refer to plastic residual pre-strains of 3, 6, 10 and 18% respectively. After Radhakrishnan and Prasad [39]**

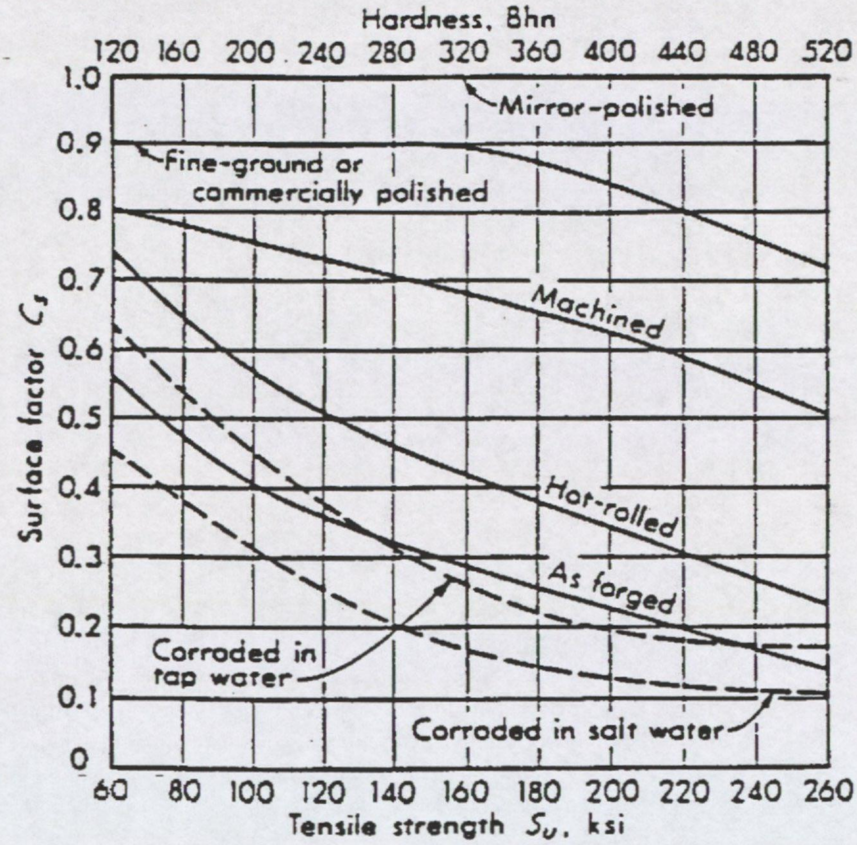


Figure 6 Reduction factor for fatigue limit of steel due to various surface treatments. After Dieter [18]

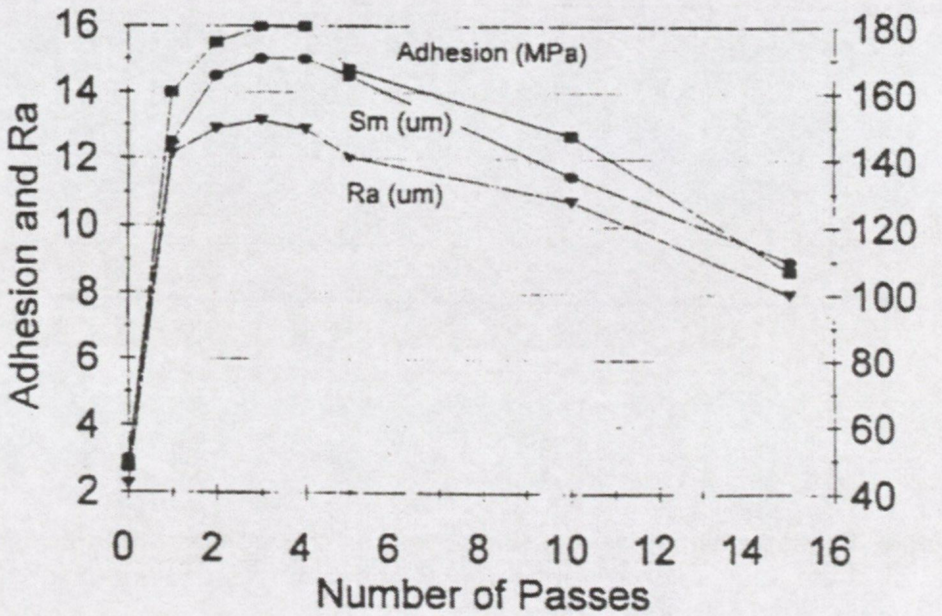
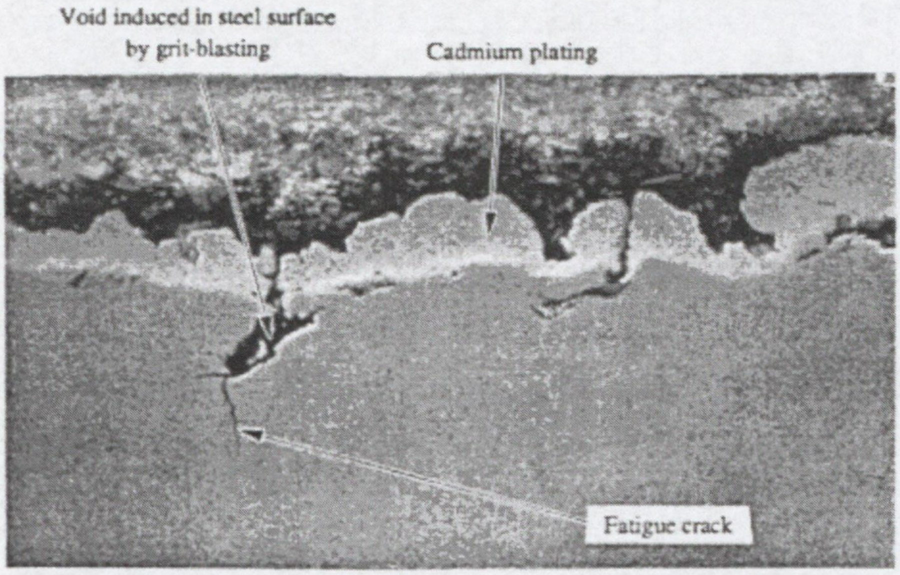
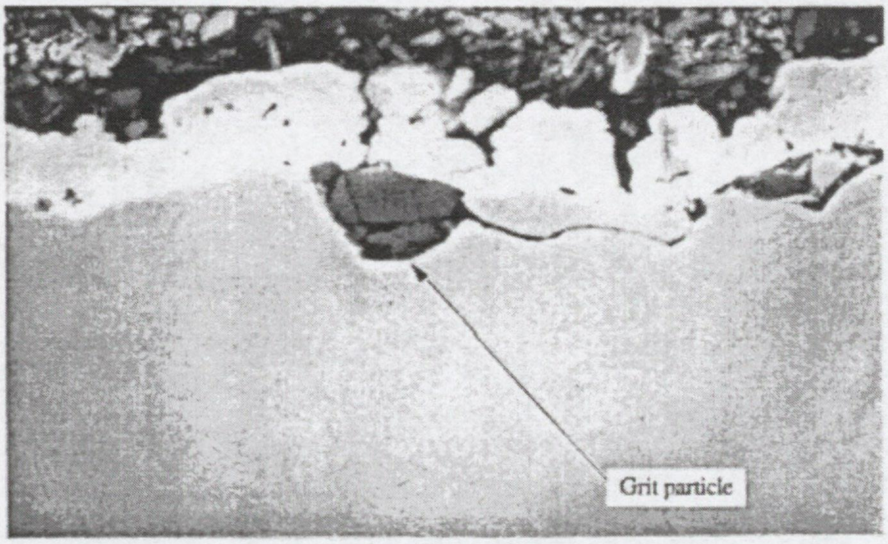


Figure 7 The relationship between the number of passes of the grit blasting nozzle and centre line average roughness (R_a) and mean peak spacing (S_m). After Griffiths et al. [46]



Scanning Electron Microscope view of fatigued area showing irregular surface finish and 'lumpy' appearance of Cadmium plating. Note embryonic fatigue crack growing from larger fold (magnification x1000)



Scanning Electron Microscope view of surface showing particle of alumina grit trapped beneath Cadmium plating (magnification x1900)

Figure 8 Cross sectional view of the surface of a ultra high strength steel landing gear. Note rough surface topography and embedded alumina grit particle trapped beneath cadmium plating. After King [1]

$$2d\sin\theta = n\lambda$$

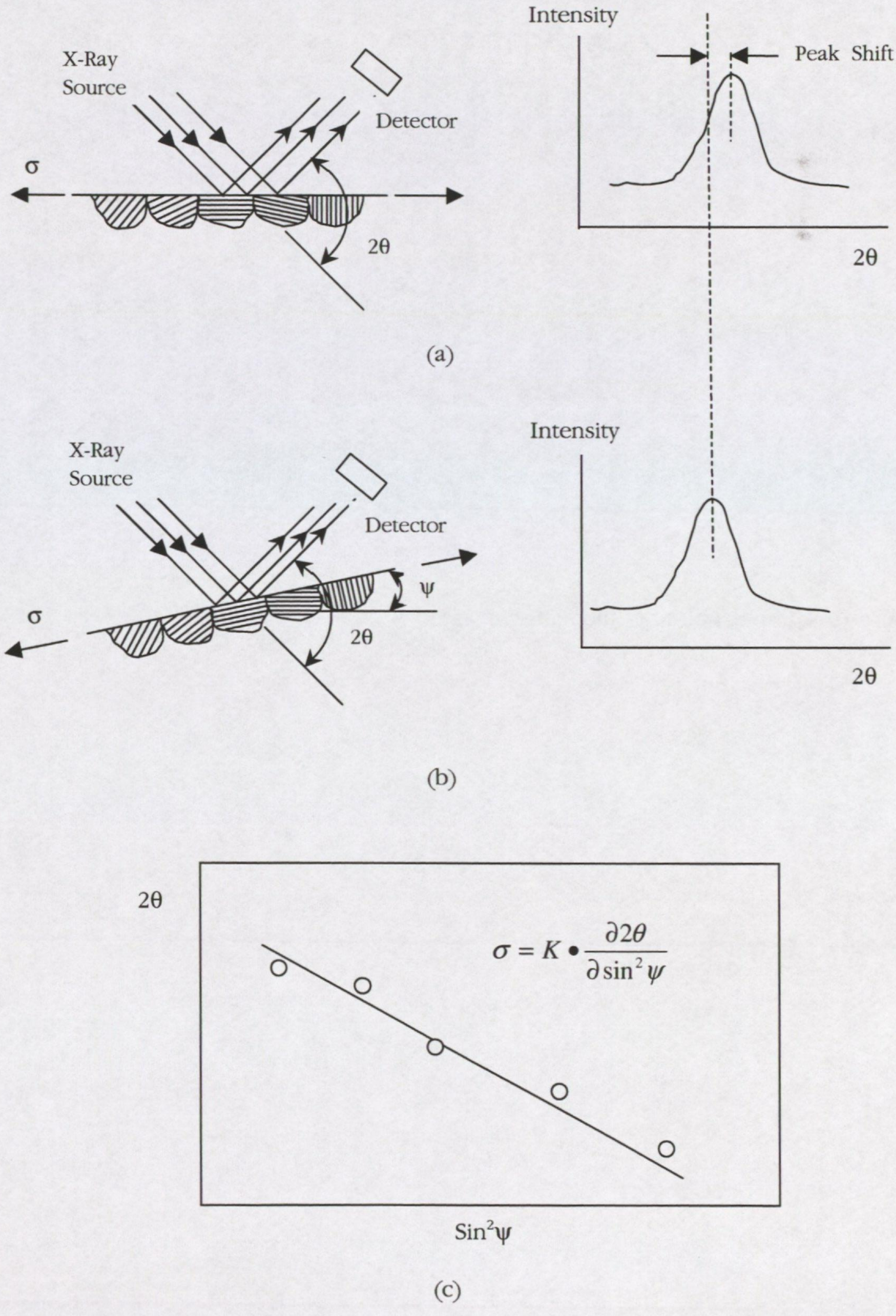
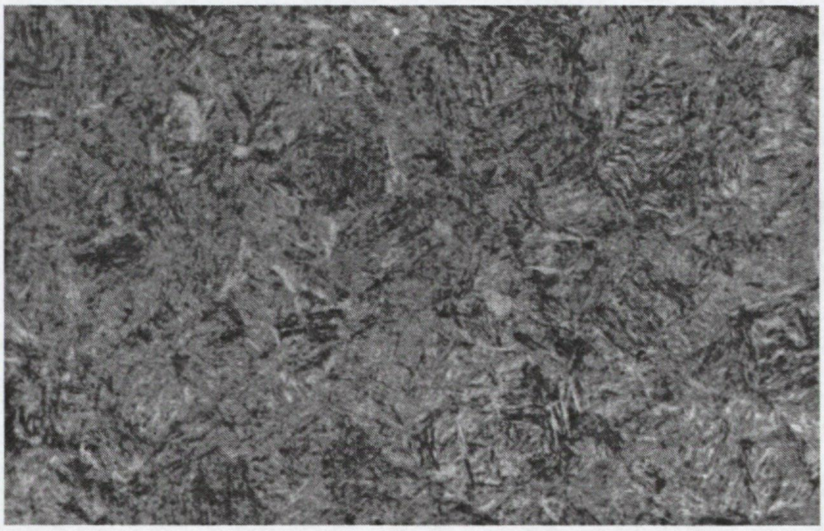


Figure 9 Principle of the Sin$^2\psi$ technique for measurement of residual stress by x-ray diffraction



50 µm

Figure 10 Microstructure of the material tested

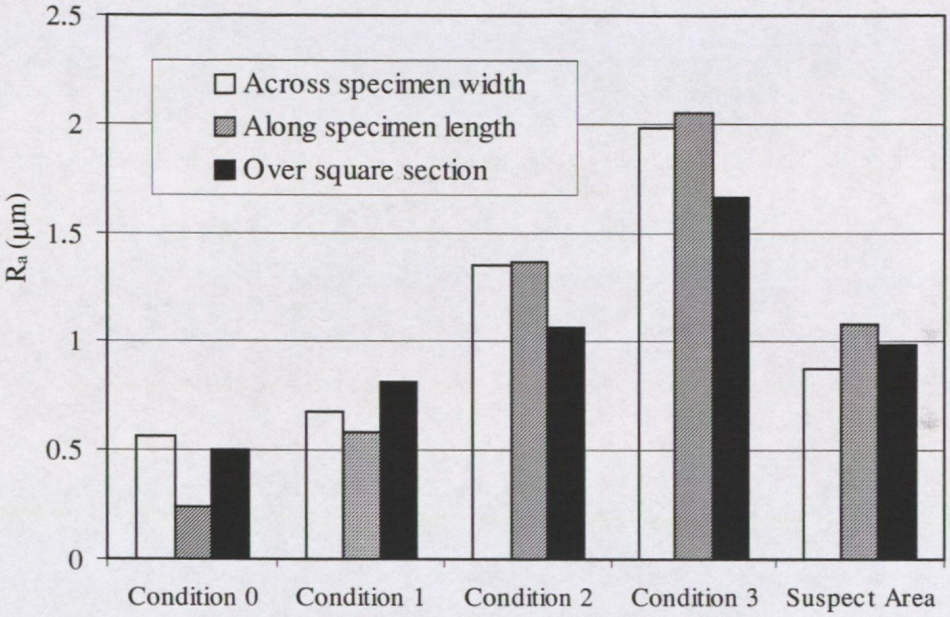


Figure 11 Comparison of surface roughness R_a for different surface conditions

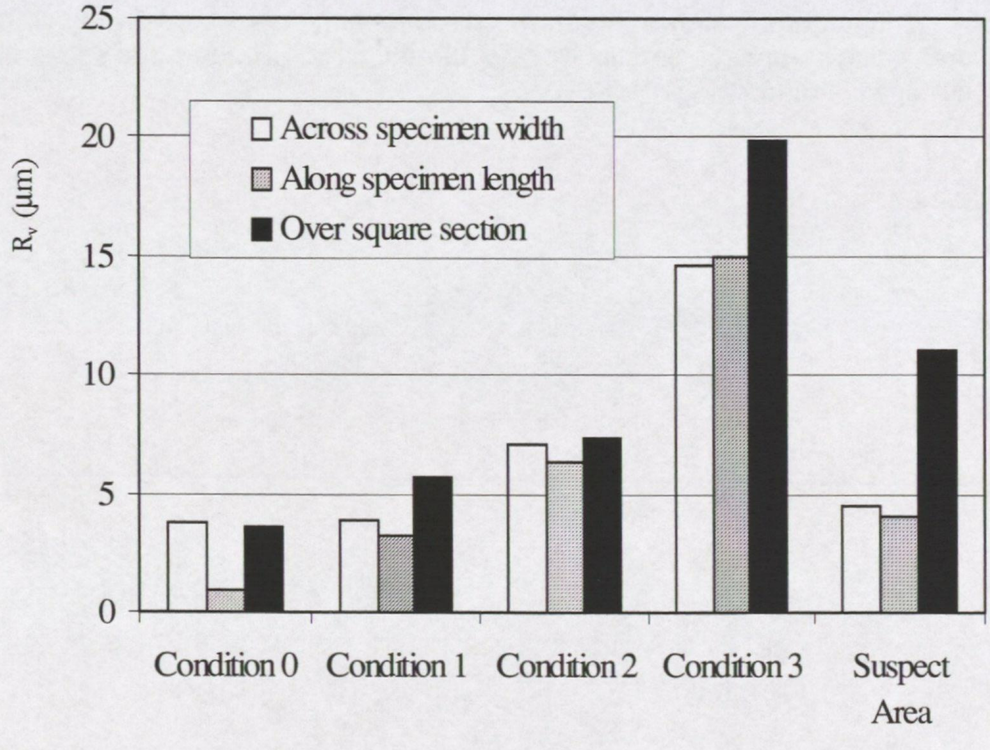


Figure 12 Comparison of surface roughness R_v for different surface conditions

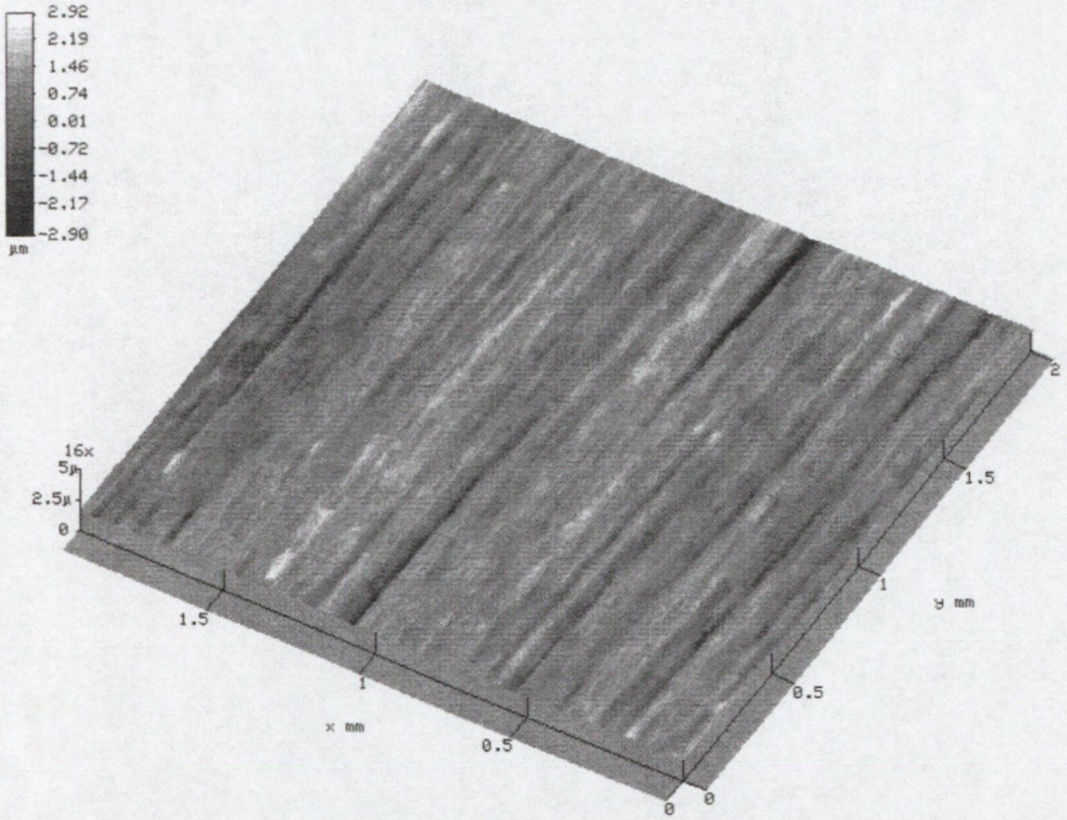


Figure 13 **A 3-D topography shows the strong directionality in surface profile with peaks and valleys running parallel to the direction of grinding for the as-ground surface condition 0**

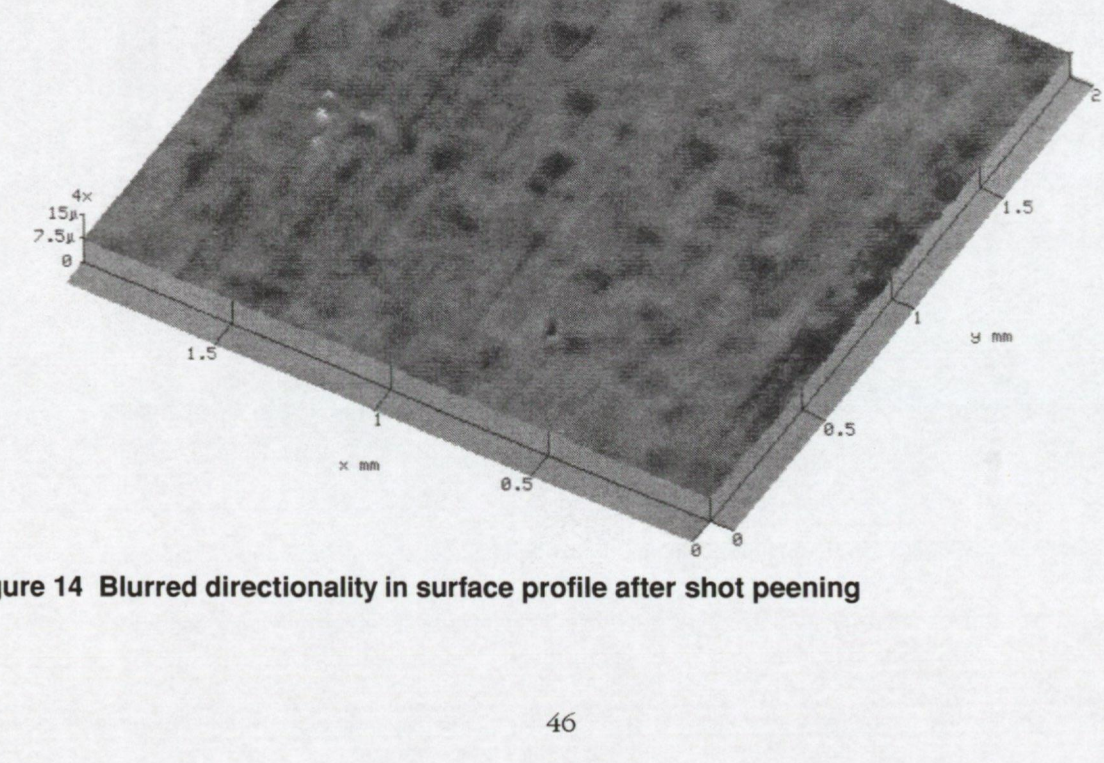


Figure 14 **Blurred directionality in surface profile after shot peening**

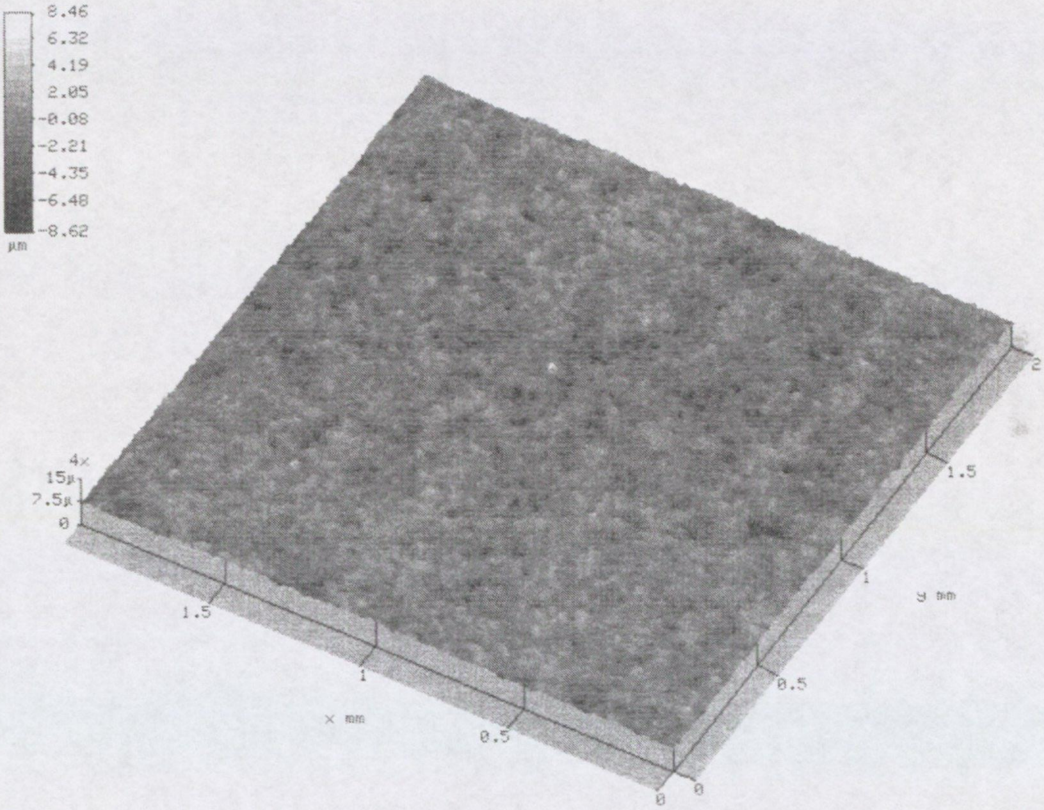


Figure 15 Blurred directionality in surface profile after shot peening and grit blasting

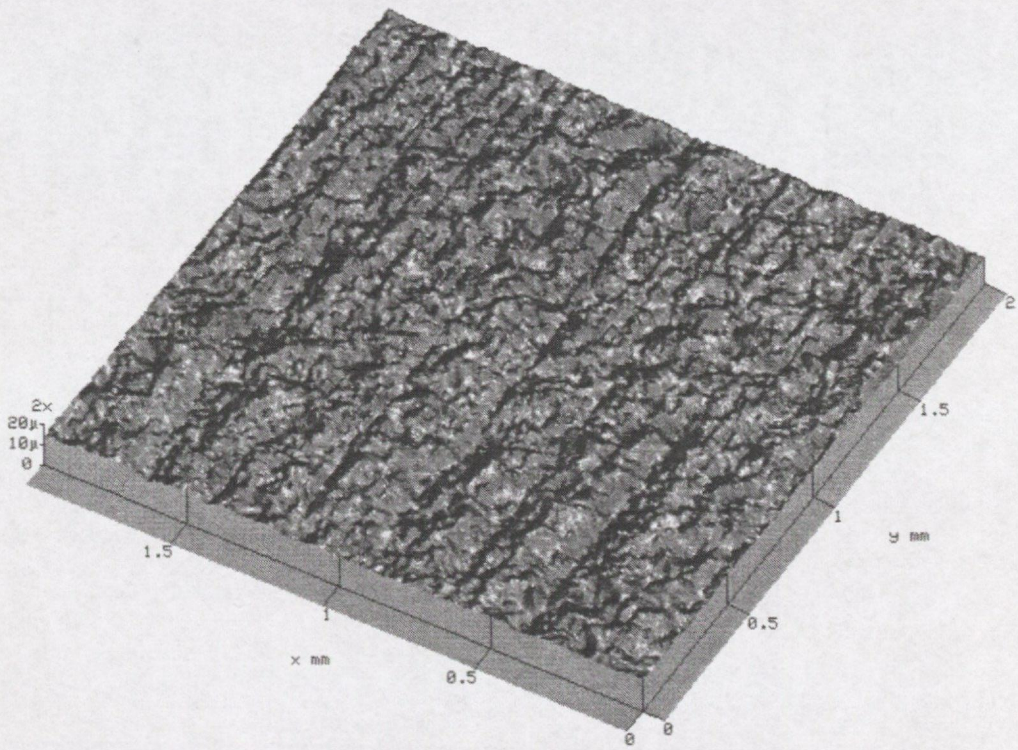


Figure 16 Clear directionality in surface profile even after shot peening and grit blasting (condition 3) in a suspect area

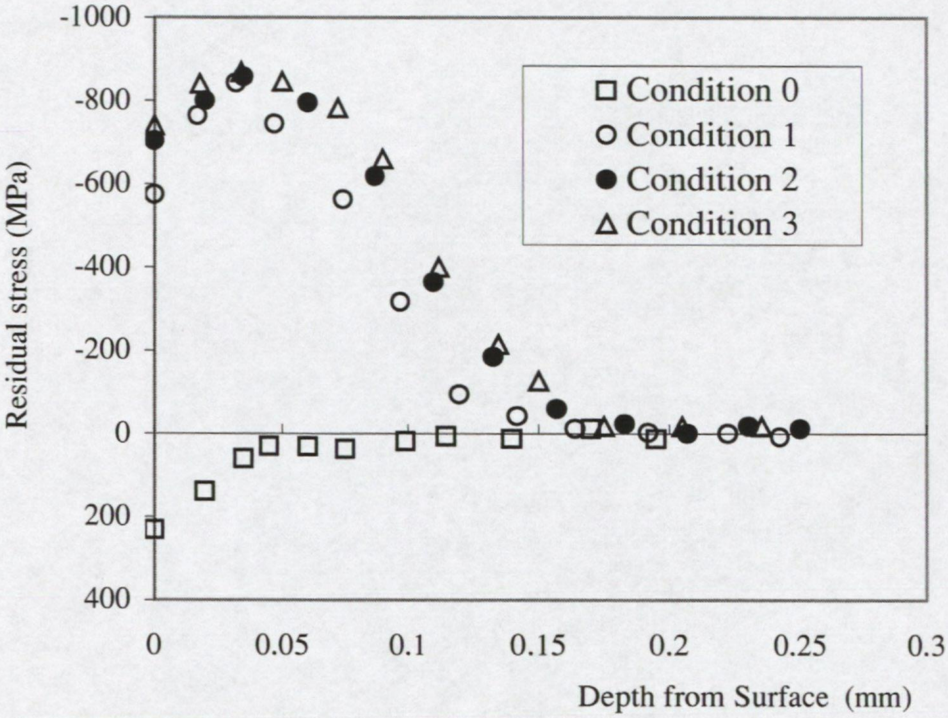


Figure 17 Residual stress profiles for different surface conditions

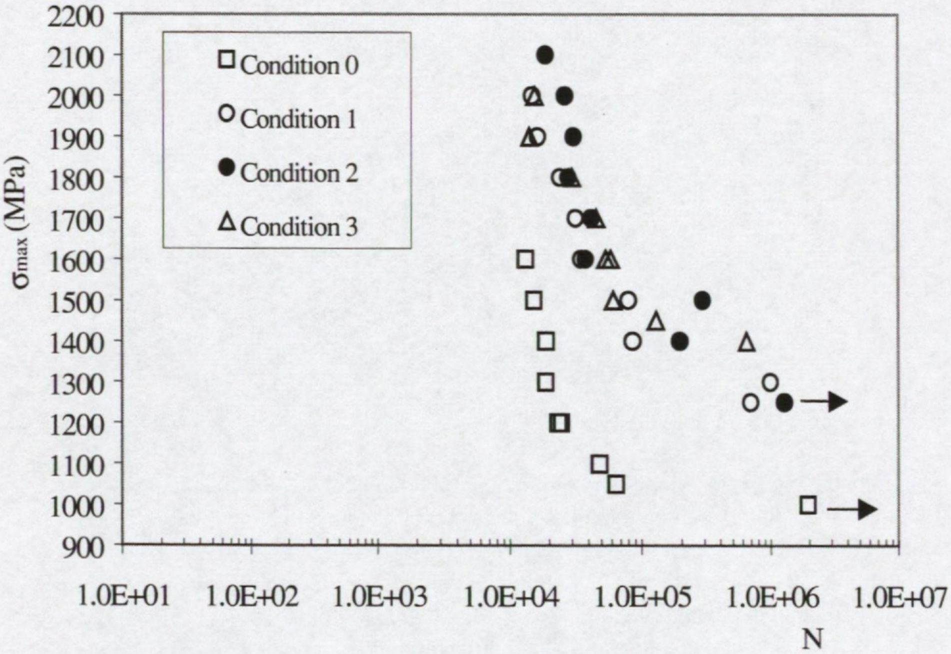


Figure18 The results of S-N tests

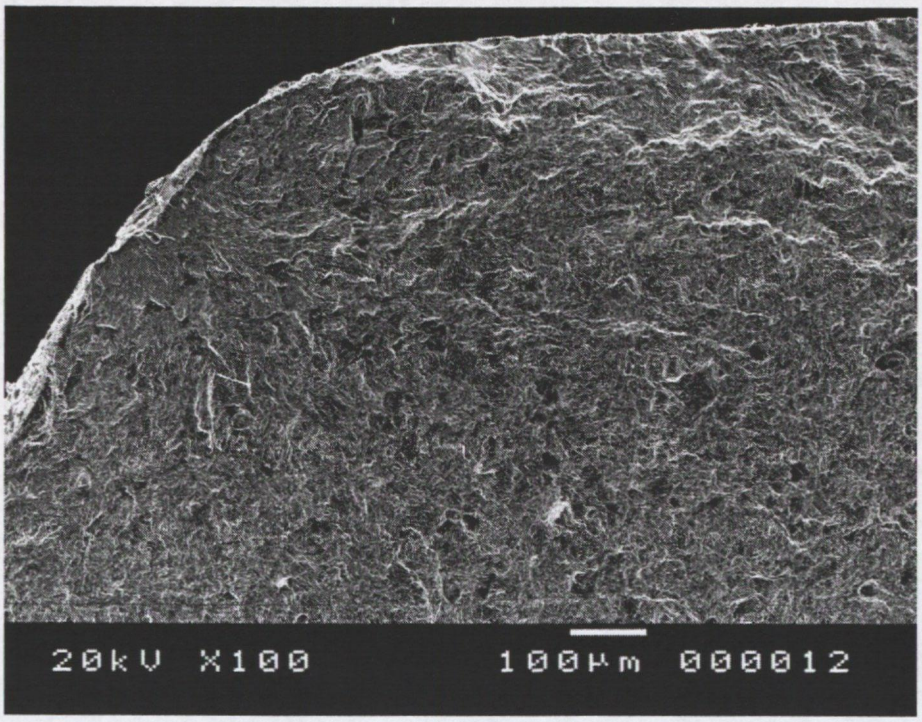


Figure 19 Crack initiation from a corner of the surface having the highest stress

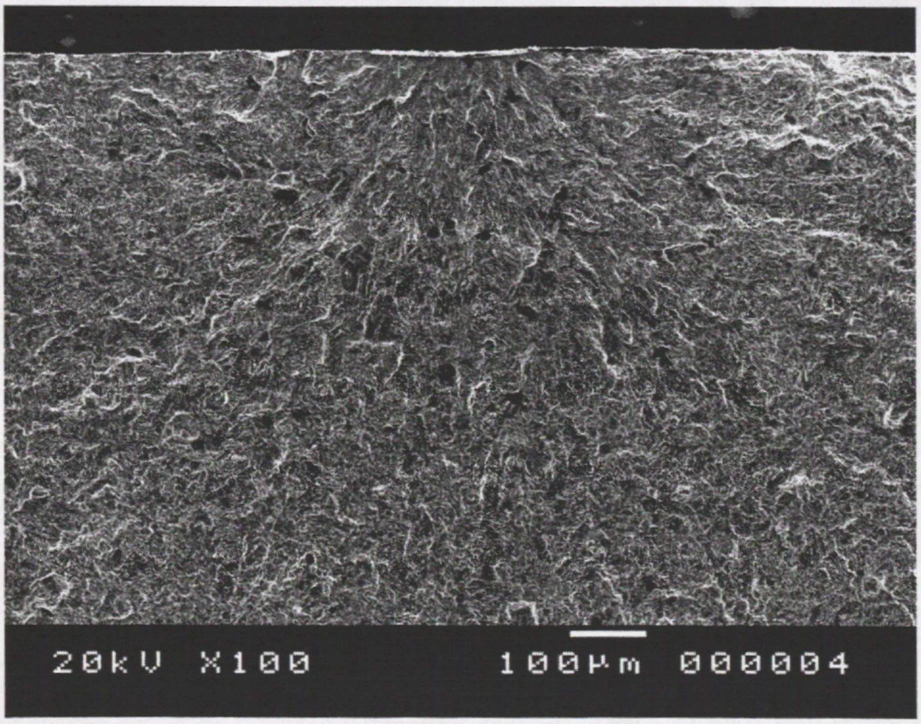


Figure 20 Crack initiation from the centre of the surface having the highest stress

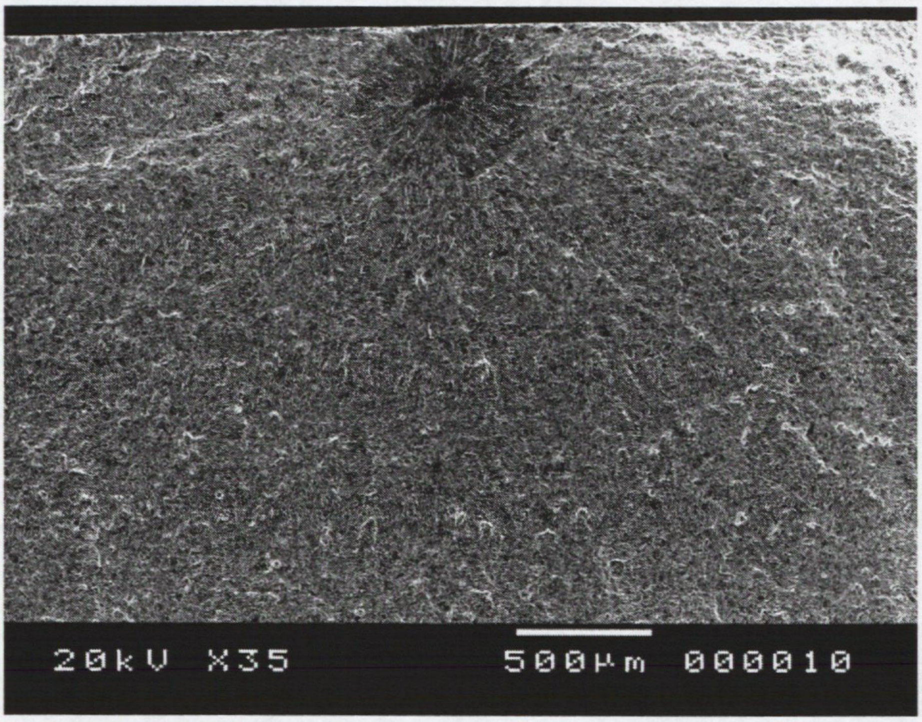


Figure 21 Crack initiation from sub-surface

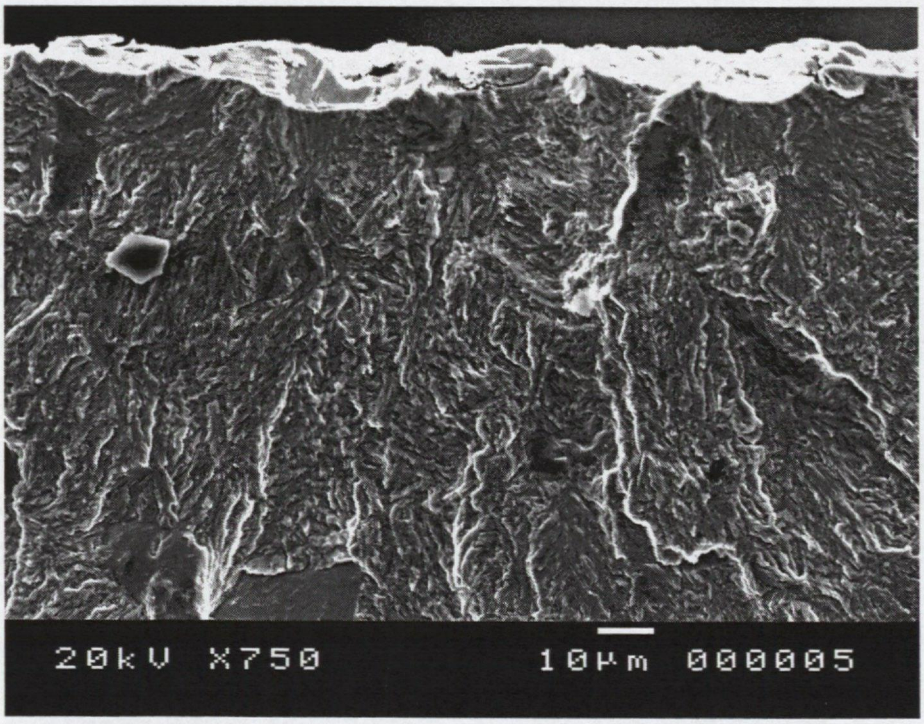


Figure 22 Crack initiation from damaged surface features

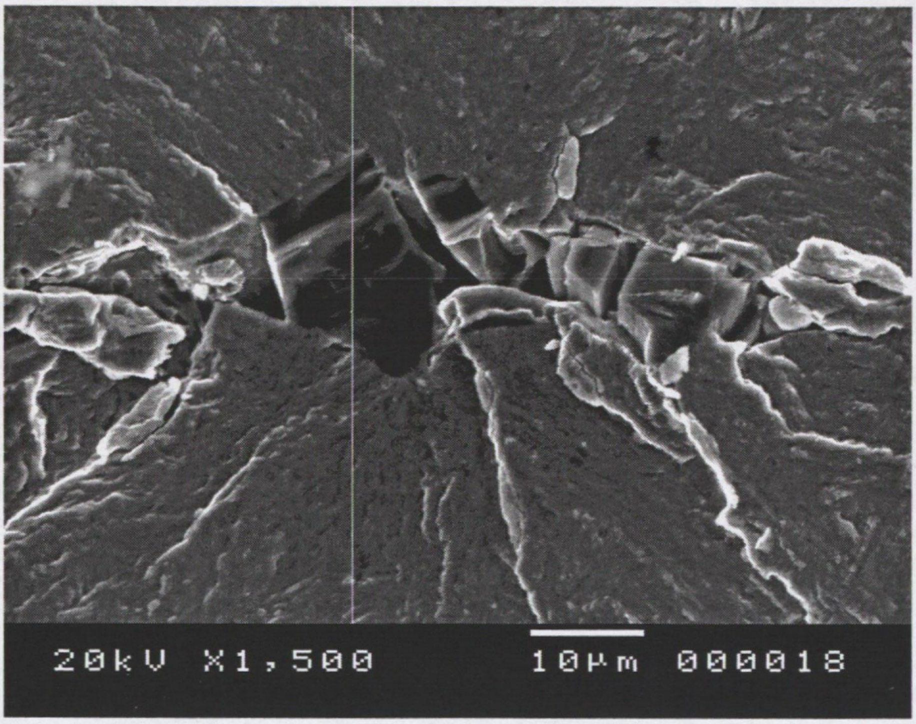


Figure 23 Crack initiation from Ti-containing inclusions

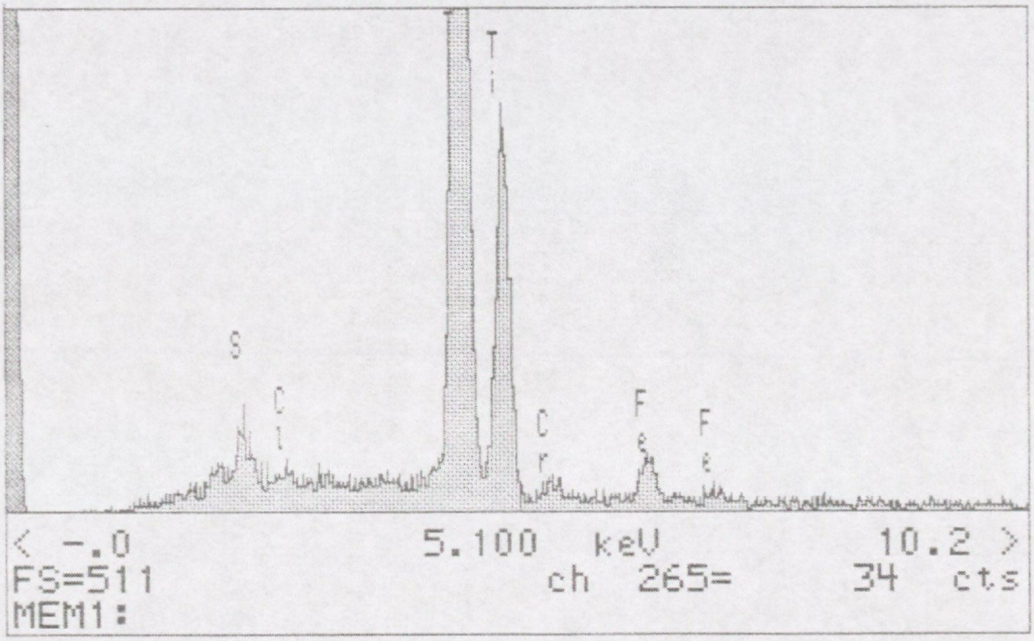


Figure 24 EDX profile of a Ti-containing inclusions

50 μm

Figure 25 Ti-containing inclusions under optical microscope

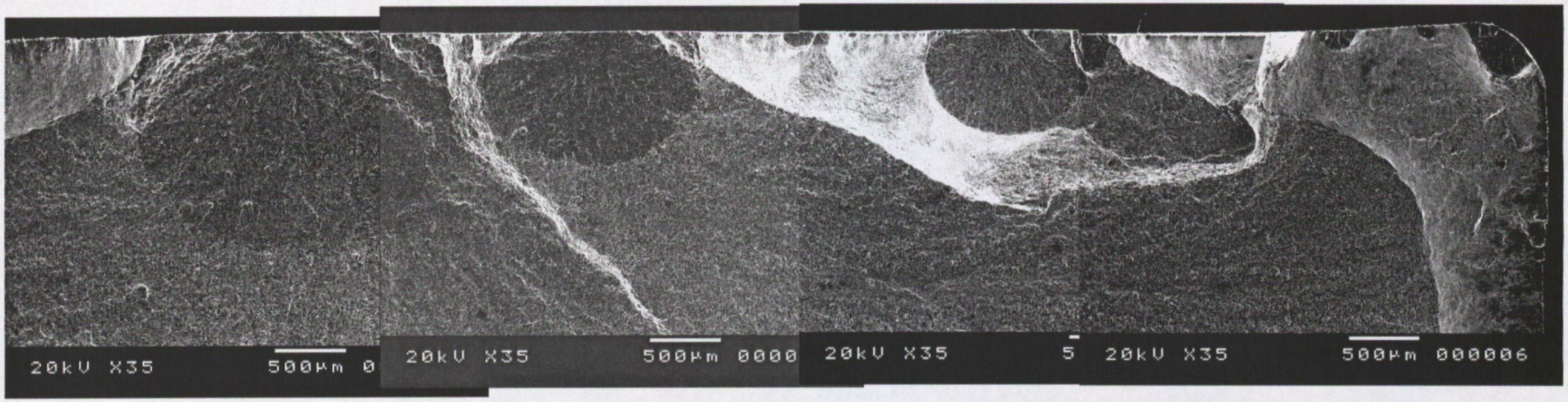


Figure 26 Multiple crack initiation at higher stress levels

Appendix A Shot peening intensity measurement using Almen strips

Calibration of the impact energy or peening intensity of the shot stream is essential to controlled shot peening. In order to specify, measure and calibrate peening impact energy the Almen strip method is generally used [31]. In this method, an unpeened Almen strip is fastened to a steel block and exposed to a stream of peening shot for a given period of time. Upon removal from the block, the residual compressive stress and surface plastic deformation produced by the peening impacts will have caused the Almen strip to curve, convex to the peened surface. The height of this curvature when measured in a standard Almen gauge is called the arc height. Figure A1 illustrates the concept of the Almen system. An Almen strip should not be reused after peening.

There are three standard Almen strips currently in use: 'A' strip 1.25mm thick, 'C' strip 2.30mm thick and 'N' strip 0.75mm thick. The approximate relationship between the A,N and C strips is: 3N=A=0.3C. The usable range of curvature on the Almen strips is 0.10mm to 0.60mm. Intensity designations should include both the arc height and the type of Almen strip used.

Intensity verification locations will vary depending on part size, geometry and stress critical areas. Whenever possible, Almen strip holders should be mounted in a scrap part so that intensity is verified under the same conditions as will be experienced by the part. The depth of the compressive layer is proportional to the Almen intensity. Intensity control is regarded as one of the essential means of ensuring process repeatability [31].

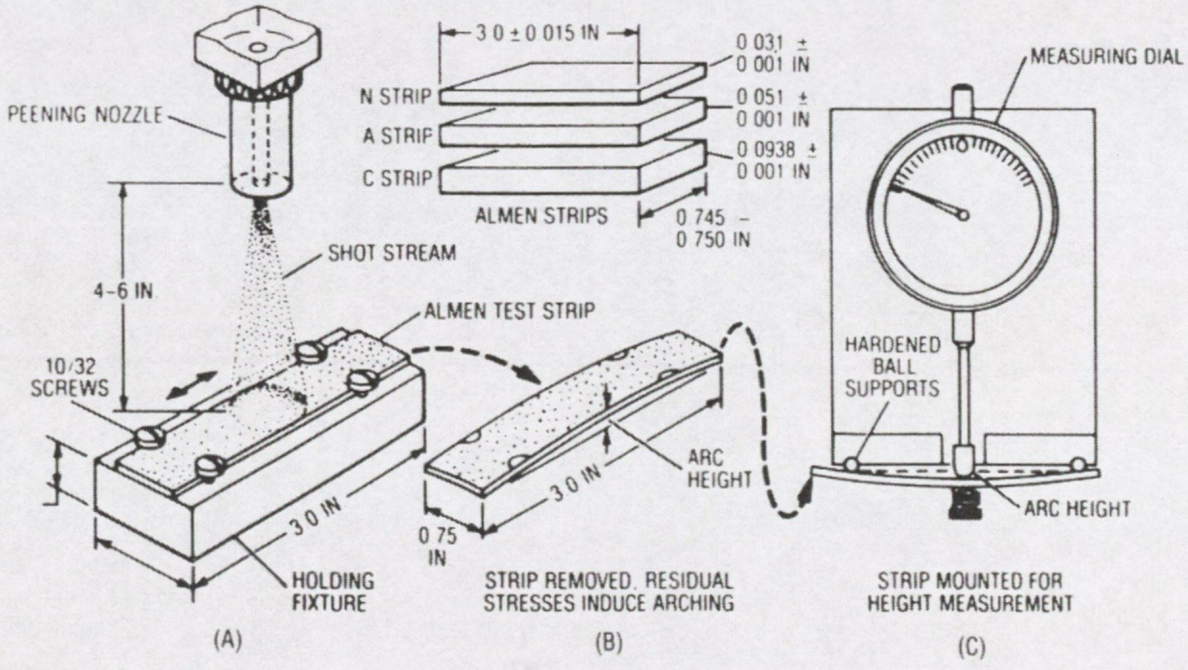


Figure A11 The Almen Strip System, After Metal Improvements Company [31]