

Effects of Ultrasonic Cleaning on Integrity of Components: A Review

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ABSTRACT

A review of the state-of-the-art in ultrasonic cleaning and its potential effects on the integrity of the components being cleaned has shown that fatigue damage can be induced or developed by use of anomalous operating conditions including long cleaning times and high power densities. Recent publications on fatigue failures in the ultrahigh cycle fatigue regime, $N > 10^7$, are also reviewed. Recommendations are made for guidelines in the use of ultrasonic cleaning with safety-critical or function-critical components.

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OBJECTIVES

A growing number of companies in the UK and elsewhere in manufacturing and service (repair and maintenance) sectors are interested in the use of the ultrasonic technique for cleaning large components. Ultrasonic cleaning of such components has the potential to significantly reduce cost (millions of pounds), time and effort compared to the largely chemical or manual methods currently in use. Industry is, however, concerned about whether ultrasonic cleaning will cause fatigue failure or contribute to the development of existing damage in the components being cleaned.

The initial objective of this report was to review the state-of-the art of the technique, its effectiveness and known effects on material behaviour. During the course of preparing this report, however, it became apparent that it must be extended to also include the following aspects: (i) cleaning of electronic devices and (ii) recent advances in understanding material behaviour in the ultrahigh cycle, low-stress, fatigue regime.

INTRODUCTION TO ULTRASONIC CLEANING

Chlorinated and fluorinated solvents are excellent cleaners, with and without ultrasonics, but the Montreal protocol, which called for the elimination of key ozone-depleting substances by 1996, banned them as they readily form highly hazardous vapours and so were subject to ever-increasing regulatory and legal constraints, which strongly dictated the use of alternative technologies. The cleaning industry has struggled to replace these solvent-degreasing chemicals with alternative "environmentally friendly" means of cleaning. Although substitute water-based, semi-aqueous and petroleum based solutions are available, they are often somewhat less effective as cleaners than the solvents and may not perform adequately in some applications unless a mechanical energy boost is added to assure the required levels of cleanliness. Ultrasonic agitation with aqueous or semi-aqueous cleaners is, therefore, rapidly increasing in popularity as it enables the avoidance of most of the regulatory problems inherent with CFC hazardous and environmentally undesirable characteristics. The technique involves using high-frequency sound waves (> 18 kHz) to enhance removing contaminants such as dirt, oil, grease, oxides and mould release agents from items, just to name a few. Materials that can be cleaned include metals, polymers, glass, ceramics and so on. Applications are wide-ranging from cleaning jewellery, sterilization of medical equipment to on-line industrial-scale production of wires. Ultrasonic cleaning is powerful enough to remove tough contaminants yet, when used properly and carefully, gentle enough not to damage the substrate being cleaned. It provides excellent penetration and cleaning in the smallest crevices and between tightly spaced parts in a cleaning tank.

Refs [1-13] describe the general principles of the technique and the equipment used.

1.1 Process Description

The following is an extract from Ref. [10]. "In a process termed *cavitation*, micron-size bubbles form and grow due to alternating positive and negative pressure waves in a

solution. The bubbles continue to grow under these alternating pressure waves until they reach resonant size. Just prior to bubble implosion, there is a tremendous amount of energy stored inside the bubble itself.

Temperatures inside a cavitating bubble can reach 5500°C with pressures up to 500 atmospheres. The implosion event, when it occurs near a hard surface, changes the bubble into a jet about one-tenth the bubble size, which travels at speeds up to 400 km/hr toward the hard surface. With the combination of pressure, temperature, and velocity, the jet frees contaminants from their bonds with the substrate”.

The role of the ultrasonic energy is, therefore, merely to provide a powerful *scrubbing* action that dislodges the dirt and move it away from the substrate. The cleaning action itself is done by the solution but enhanced greatly by the added agitating action of ultrasonic bubbles.

1.2 Equipment for Ultrasonic Cleaning

Ultrasonic cleaning equipment ranges from the small tabletop units often found in dental offices or jewellery stores to huge systems with capacities of several thousand litres used in a variety of industrial applications. Selection or design of the proper equipment is paramount in the success of any ultrasonic cleaning application [14].

The basic components of an ultrasonic cleaning system include: an electrical *generator*, a bank of ultrasonic *transducers* mounted on a radiating diaphragm, and a *tank* filled with *aqueous solution*.

1.2.1 The Generator

In order to produce the positive and negative pressure waves in the aqueous medium, a mechanical vibrating device is required. This is provided by a series of transducers that convert electrical energy into mechanical vibrations. The ultrasonic generator converts a standard electrical frequency of 50 or 60 Hz into the high frequencies required in ultrasonic transmission, generally in the range of 18 to 80 kHz. Higher frequency operations (above 50 kHz) are believed [10] to be desirable to reduce damage to very sensitive substrates, but may lack the power required for typical industrial ultrasonic cleaning applications.

There have been several relatively recent innovations in ultrasonic generator technology, which may enhance the effectiveness of ultrasonic cleaning equipment. These include "sweeping" the frequency of the generator output around the central operating frequency, square wave outputs, and slowly or rapidly pulsing the ultrasonic energy on and off [1, 4]. The most advanced ultrasonic generators have provisions for adjusting a variety of output parameters to customize the ultrasonic energy output for the task. The development of sweep-frequency generators has greatly improved the uniformity of the ultrasonic vibration fields and has suppressed or eliminated what is called the "standing waves" and "hot spots" in the tank that are characteristic of older fixed-frequency generators, which caused uneven cleaning [10].

Transducers

There are two general types of ultrasonic transducers in use today - piezoelectric and magnetostrictive. Both accomplish the same task of converting alternating electrical energy to vibratory mechanical energy but do it through the use of different means.

Piezoelectric transducers are made up of several components. The ceramic (usually lead zirconate) crystal is sandwiched between two strips of tin. When voltage is applied across the strips it creates a displacement known as the *piezoelectric effect*. When these transducers are mounted to a diaphragm (wall or bottom of the tank), the displacement in the crystal causes a movement of the diaphragm, which in turn causes the pressure wave to be transmitted through the aqueous solution in the tank.

Magnetostrictive transducers utilise the principle of magnetostriction in which certain materials expand and contract when placed in an alternating magnetic field. "Zero-space" magnetostrictive transducers consist of nickel laminations attached tightly together with an electrical coil placed over the nickel stack. When current flows through the coil it creates a magnetic field, and nickel has a unique property of expanding or contracting when it is exposed to the magnetic field. When an alternating current is sent through the magnetostrictive coil, the stack vibrates at the frequency of the current.

Magnetostrictive transducers are known for their ruggedness and durability in industrial applications. They are most suitable, therefore, for heavy industry. Because of inherent mechanical constraints on the physical size of the hardware as well as electrical and magnetic complications, high power magnetostrictive transducers seldom operate at frequencies much above 20 kilohertz. Piezoelectric transducers, on the other hand, can easily operate well into the megahertz range.

Magnetostrictive transducers are generally less efficient than their piezoelectric counterparts. This is due primarily to the fact that the magnetostrictive transducer requires a dual energy conversion from electrical to magnetic and then from magnetic to mechanical.

Ultrasonic Tanks

Ultrasonic tanks are generally rectangular, sturdy, made of stainless steel, and can be manufactured in almost any size. Transducers are usually placed in the bottom or on the sides, or sometimes both when power density (watts per litre) is a concern. The transducers can be welded directly into the tank, or inside watertight immersible units that can be placed directly into the aqueous solution.

Cleaning Solutions

The solution used in ultrasonic cleaning is a very important consideration. The selected chemical must be compatible with the base metal being cleaned and have the capability to remove the soils that are present. It must also cavitate well. Solvents such as 1,1,1-trichloroethane and freon are very effective cleaners and were in use for very many years, with and without ultrasonics. However, they were completely banned in 1996 by the Montreal protocol, which calls for the elimination of key ozone-depleting

substances. Companies have since been searching for more environmentally friendly alternatives. Whenever possible, it is best to use a water-based detergent in the ultrasonic cleaning process. Water is an excellent solvent, non-toxic, non-flammable, and, most importantly, environmentally friendly. However, rinsing and drying can be difficult. Disposing of soiled water can also be difficult and expensive. Detergents can be added to enhance the cleaning action and loosen the bond of a contaminant to a substrate. As an added bonus, the cavitation energy in a water-based solution is more intense than in an organic solvent.

Further information on ultrasonic cleaning agents can be found in Refs [10, 15].

1.3 Effectiveness of Ultrasonic Cleaning

Properly utilised, ultrasonic energy can contribute significantly to the speed and effectiveness of many immersion cleaning and rinsing processes. It is especially beneficial in increasing the effectiveness of today's preferred aqueous cleaning solutions and, in fact, is necessary in many applications to achieve the desired level of cleanliness. With ultrasonics, aqueous solutions can often give results surpassing those previously achieved using solvents.

Cleaning in most instances requires that a contaminant be dissolved (as in the case of a soluble soil), displaced (as in the case of a non-soluble soil) or both dissolved and displaced (as in the case of insoluble particles being held by a soluble binder such as oil or grease). The mechanical effect of ultrasonic energy can be helpful in both speeding dissolution and displacing particles. Just as it is beneficial in cleaning, ultrasonics is also beneficial in the rinsing process [6]. Residual cleaning solutions are removed quickly and completely by ultrasonic rinsing.

In removing a contaminant by dissolution, it is necessary for the solvent to come into contact with and dissolve the contaminant. The cleaning activity takes place only at the interface between the cleaning solution and the contaminant.

As the cleaning solution dissolves the contaminant, a saturated layer develops at the interface between the fresh cleaning solution and the contaminant. Once this has happened, cleaning action stops as the saturated solution can no longer attack the contaminant.

Ultrasonic agitation (i.e. cavitation and implosion) effectively displaces the saturated layer to allow fresh solution to come into contact with the contaminant remaining to be removed. This is especially beneficial when irregular surfaces or internal passageways are to be cleaned.

1.4 Process Controlling Parameters

Effective application of the ultrasonic cleaning process requires consideration of a number of parameters. While time, temperature and cleaning solution remain important in ultrasonic cleaning as they are in other cleaning technologies, there are other factors that must be considered to maximize the effectiveness of the process. Especially

important are those variables that affect the intensity of ultrasonic cavitation in the liquid [12].

The **solution** used in ultrasonic cleaning is of fundamental importance to the overall success of the ultrasonic cleaning process [see 1.2.4 above].

Solution temperature has a profound effect on ultrasonic cleaning effectiveness and is the most important single parameter to be considered in maximizing cavitation intensity. In general, higher temperatures will result in higher cavitation intensity and better cleaning [4]. This is because so many liquid properties affecting cavitation intensity are related to temperature. Changes in temperature result in changes in viscosity, the solubility of gas in the liquid, the diffusion rate of dissolved gasses in the liquid, and vapour pressure, all of which affect cavitation intensity. In pure water, the cavitation effect is maximized at approximately 70°C; a caustic/water solution, on the other hand, cleans most effectively at about 82°C [10]. Solvents should be used at temperatures at least 6°C below their boiling points [12].

Cavitation intensity is inversely related to **ultrasonic frequency**. As the ultrasonic frequency is increased, cavitation intensity is reduced because of the smaller size of the cavitation bubbles and their resultant less violent implosion. The reduction in cavitation effect at the higher frequencies may be overcome by increasing the ultrasonic power.

Cavitation intensity is directly related to **ultrasonic power** at the power levels generally used in ultrasonic cleaning systems. The ultrasonic power delivered to the cleaning tank must be adequate to cavitate the entire volume of liquid with the workload in place. Watts per litre is a unit of measure often used to measure the level of ultrasonic power in a cleaning tank. Cleaning parts that are very massive or that have a high ratio of surface to mass may require additional ultrasonic power. Excessive power may, however, cause cavitation erosion or “burning” of soft metal parts.

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1.5 Typical Applications

Cleanliness has become an important issue in many industries where it previously was not [3]. In industries such as electronics, cleanliness has always been important [e.g. 16-17, 25-39]. It has now become even more critical in support of the growing use of electronic devices.

Typical applications in the metals industry include removing chips and cutting oils from machining operations, removing buffing/polishing compounds prior to plating operations and cleaning grease and sludge from rebuilt components in aircraft and automotive applications [10, 18]. Examples of using ultrasonics for on-line cleaning of wires and rods are described in Refs [22-24].

2 DOES ULTRASONIC CLEANING DAMAGE COMPONENTS?

2.1 Electronic Packaged Devices

It has long been recognised that effective cleaning of printed circuit boards (PCBs) presents a major problem, especially with surface mount technology (SMT) and other complex packaged types. One of the most effective means of cleaning PCBs, especially when excess flux and flux residues are held by capillary action, is to subject them to ultrasonic agitation. However, it has long been suspected [25-39] that the ultrasonic cleaning process might give rise to irreversible fatigue damage in the devices and soldered joints, and/or to long-term reliability problems. The two major effects in the components themselves were expected to be: (i) breaking of internal bond wires as a result of forced vibration (possibly exacerbated by resonance effects determined by lead length and ultrasonic frequency), and (ii) fatigue fractures of the legs or soldered joints (see example in Fig. 1)

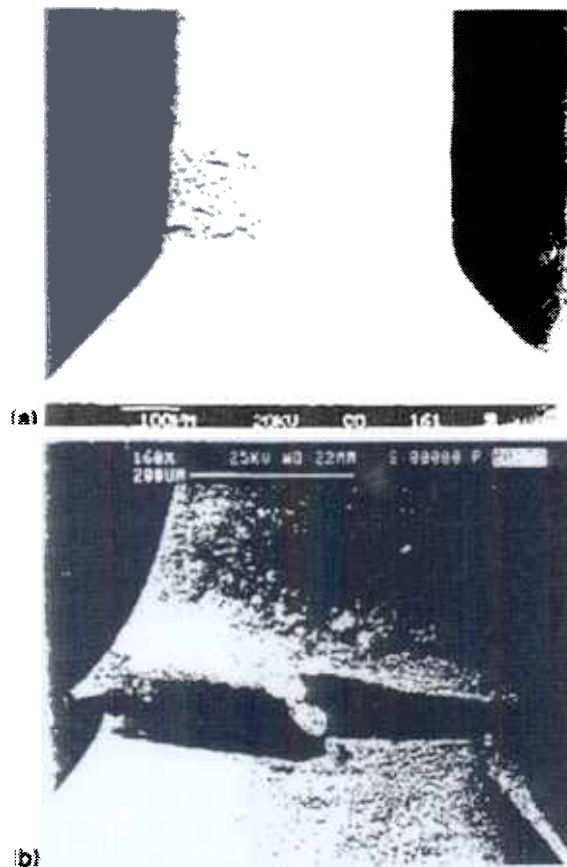


Figure 1 SEM micrographs illustrating progressive fatigue damage in legs of DIL devices [Ref. 31]

On these grounds the use of this technique in US military applications was effectively prohibited [33] until 10 years or so ago. This had meant that, for contractual reasons, a large proportion of UK defence industry could not employ ultrasonic cleaning, even though it may have severe doubts about the reasons for the prohibition of this particular method of cleaning. Similar doubts had been subsequently expressed by UK military

[33]. Most of those worries appear to have been based on early work [30] in which the data were obtained using ultrasonic equipment operating at 25 kHz, and on devices and boards of old technologies. Since those early papers, there have been dramatic improvements in bonding technologies, and replacement of ultrasonic cleaners with new equipment operating at about 40 kHz [31, 34]. de kluizenaar [34], from Philips, demonstrated that ultrasonic cleaning of surface-mounted circuits on ceramic substrates could occasionally lead to component failure by fatigue. However, until recently, little or no unambiguous data existed in the literature to substantiate these fears of using ultrasonic cleaning or to quantify any detrimental effects.

A systematic but limited study was carried out by Richards et al [31-33], GEC-Marconi, to evaluate potential degradation on a variety of electronic devices (mounted on boards or loose) as well as to assess the efficiency of cleaning using ultrasonic techniques. Only chlorofluorocarbon (CFC) solvents were used in this investigation, mirroring their extensive use in the industry at the time (late 1980s - early 90s). The study showed that modern components are robust and difficult to damage using ultrasonic cleaning techniques under optimum conditions of 40 kHz frequency and exposure times and power densities of the order of 2 minutes and 10 W/litre, respectively. These recommendations had also been made by Philips [34]. Using abnormally long ultrasonic exposure times (i.e. 100 hours at standard power densities) or abnormally high power densities (i.e. about 30 W/litre) caused damage in some components. In all cases in which damage was induced, it was of a purely mechanical nature due to fatigue, and was located on the device bond-wires and/or the package legs. The study showed that under standard power density conditions, cleaning (as assessed using a combination of visual, electrical and analytical techniques) was complete within two minutes.

The extensive evaluations of failed PCB components at the GEC-Marconi Hirst Research Centre [30] seem to support the notion that tightly-controlled ultrasonic cleaning (in terms of duration and power density) does not cause of itself failure in the components but it may well serve to highlight quality problems in the components (e.g. by propagating pre-existing damage or micro-cracks in passive components, or detaching unsatisfactory bonds). The authors of the work emphasised that their conclusion applied only to the range of components studied in that investigation and to components of proven quality. If incipient defects were present in components, the ultrasonic agitation will simply highlight their poor quality. Damage to good quality components can only be induced by the use of anomalously long times or high power densities [30].

Further evidence of fatigue failure during ultrasonic cleaning of gold wire bonds [25, 35] and fine pitch component leads [28] were reported.

More recent work by the GEC-Marconi group following the enforced phasing out of CFCs as a result of the Montreal Protocol, was carried out on PCBs and hybrid devices using aqueous or semi- aqueous cleaning media [29]. A similar strong dependence of the damage accumulation on power density was observed. Fatigue damage when using aqueous or semi-aqueous solvents was generally less than that which occurred using CFCs. However, an additional failure mechanism (cavitation erosion and cavitation-enhanced corrosion) was encountered with aqueous solvents after a few hours' exposure at high power density. Hybrid devices were found to be relatively more sensitive to damage from ultrasonic effects, depending on the package/mounting

construction. However, using the same optimum conditions of power density/time combination as with the CFC solvents, similar levels of cleanliness were achieved in all cases with either aqueous or semi- aqueous cleaning media. This was considered encouraging for those already using or potential users of ultrasonic agitation to enhance the cleaning effect.

2.2 Metallic Components

Despite the current widespread usage of ultrasonic cleaning in manufacturing, aerospace, automotive and maintenance industrial sectors, no publications were found of investigations of effects of ultrasonic agitation on the integrity of mechanical components. The following is a summary of the very small number of papers that were found of interest and relevance in this context.

The effect of ultrasonic agitation in water on AISI 304 stainless steel was investigated [40] using an in-house built high-power ultrasonic generator working at a frequency of 20 kHz. It was found that high-intensity ultrasonic waves introduced a very high compressive residual stress at the surface (due to work-hardening) even for short durations of exposure at ambient temperature. With increased exposure time, the stresses increased but seemed to reach a saturation value. The maximum depth of hardening was found to be approx 70 microns. A mild roughening of the surface was also observed. An incidental observation using X-Ray diffraction measurements of the surface revealed the formation of both "alpha" and "epsilon" martensites at the surface.

The erosion of stainless steel during ultrasonic cleaning was investigated [41] using several combinations of ultrasonic frequencies, powers and water-based and solvent cleaning liquids.

Aluminium foil erosion was utilised to characterise and optimise the operating conditions of new ultrasonic cleaning tanks acquired at Boeing [42]. The study involved inspection of aluminium foil samples for uniformity and manner of cavitation damage across the surface. It also involved measuring weight loss as an objective parameter.

Accurate microstructural analysis of thermally sprayed coatings is possible only if each step of the preparation process is performed in a careful manner. Various methods have been used to evaluate the characteristics of thermally sprayed coatings, but metallographic examination provides the most information about the many different coating characteristics. Any one step that is improperly performed during the metallographic preparation process will potentially produce incorrect coating characterization information. Ultrasonic cleaning of coated samples between preparation steps and after the completion of the entire process is *not* an accepted practice [43]. The possibility of enlarging existing porosity is a concern due to the ultrasonic action. A study was conducted [43] on five different coating types specifically evaluating the effects of ultrasonic cleaning on each coating. Variations in the coating porosity were quantified using image analysis and photomicrography.

3 FATIGUE IN THE GIGACYCLE REGIME – RECENT DEVELOPMENTS

As described in 2.1 many investigations [25-39] reported fatigue as the cause of failure in electronic devices after being subjected to ultrasonic cleaning. Because of the high frequencies involved, a very large number of stress cycles (of albeit very small amplitudes) can be reached in a very short period of time. For example, with a typical 40 kHz ultrasonic frequency, ten million cycles are reached in just over 4 minutes, a long but not unusual cleaning time. Ten million cycles correspond to the material's design or "fatigue limit". A better understanding of materials fatigue behaviour in the regime where $N > 10^7$ cycles is, therefore, needed in order to explain the observed fatigue failures.

During the last few years, many fatigue studies on different metallic materials have indicated that *fatigue failures can occur even at amplitudes below the conventional "fatigue limit"* [44-63]. The classical "fatigue limit" (which usually corresponds to 10^6 - 10^7 cycles) of ferrous metals is a consequence of testing materials at a constant range of cyclic stress and determining the cyclic stress range below which fatigue failures do not occur. This classical fatigue limit of a material is equated to the condition for which fatigue cracks cannot propagate beyond microstructural barriers [54]. Ultrahigh cycle fatigue (UHCF), sometimes called "gigacycle fatigue", is defined here as the regime where the number of cycles to failure $> 10^7$.

The S-N curves in the high and ultra-high cycle fatigue display a multi-stage shape, sometimes with a second lower "fatigue limit". Figure 2 shows an example of an S-N curve [45] obtained from cantilever-type rotary bending fatigue tests using hour-glass shaped specimens of high carbon-chromium bearing steel. This remarkable duplex S-N curve, which is composed of two different S-N curves corresponding to the respective fracture modes is different from the classic step-wise one reported in previous literature.

Two distinct fracture modes have been identified according to the crack origin. The first is on the specimen surface, which is associated with shorter fatigue life ($< 10^7$) and higher stress levels. The other is due to subsurface non-metallic inclusions, which was associated with longer fatigue life and lower stress levels. The inclusions developed a fish-eye fracture mode (Fig. 3) that was distributed over a wide range of stress amplitude not only below but also above the "fatigue limit".

Bathias et al [47] have argued that the concept of infinite fatigue life is not correct even in BCC metals and that fracture can occur in metals even beyond 10^9 cycles. Current design methods that utilise a statistical approach, which is the standard deviation applied to the average fatigue limit at 10^7 cycles, are not satisfactory. They suggested using the fatigue strength at 10^{10} cycles as the design limit of the fatigue life of many components.

A study was carried out [53] to characterise high-cycle fatigue behaviour of a high-strength spring steel wire by means of an ultrasonic fatigue test and analytical techniques. Two kinds of induction-tempered ultra-high-strength spring steel wire, 6.5 mm in diameter and with a tensile strength of 1800 MPa, were used. The fatigue strength of the steel wires between 10^6 and 10^9 cycles was determined at a load ratio $R=-1$. The experimental results showed that fatigue rupture can occur beyond 10^7 cycles. For Cr-V spring wire, the stress-life (S-N) curve became horizontal at a

maximum stress of 800 MPa after 10^6 cycles, but the S-N curve of the Cr-Si steel continued to drop at higher numbers of cycles ($>10^6$ cycles) and did not exhibit a fatigue limit. By using scanning electron microscopy, crack initiation and propagation behaviour were examined.

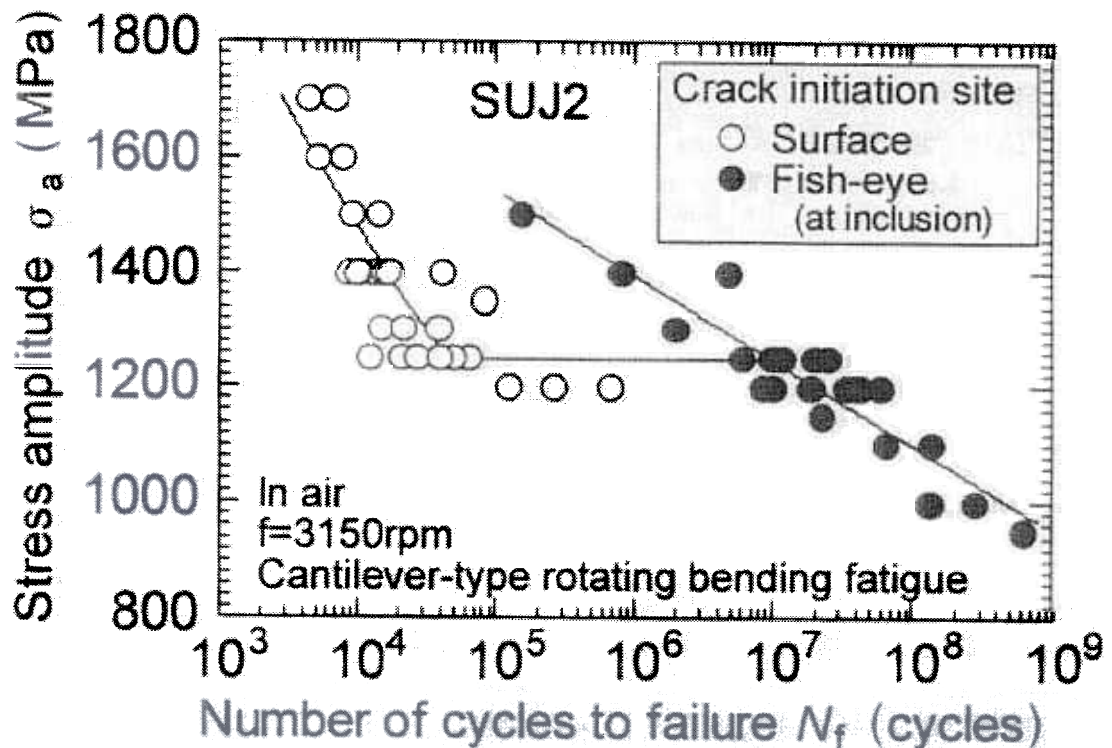


Figure 2 An example of a duplex S-N curve for a high carbon-chromium bearing steel [Ref. 45]

Stanzel-Tschegg [56] described the development and performance of an ultrasonic fatigue testing facility. Performing fatigue tests at ultrasonic frequencies, e.g. 20,000 Hz, allows one to perform experiments beyond 10^9 and 10^{10} cycles within half a day or a week, respectively. The testing technique has led to the construction of a number of fatigue machines. Use of the ultrasound technique to study the mechanisms of crack initiation in pure metal single crystals, in cast alloys where voids are crack initiation sites, and in complicated fibre-reinforced laminates is reported. Additional experimental possibilities, e.g. random loading, variation of mean load, superposition of shear loads, variation of temperature and environment are investigated - not only in axial but also in torsional loading.

Ref [52] describes tests at an ultrasonic frequency of 20 kHz on ferrous alloys with fatigue life up to 10^{10} cycles. Good agreement was found with results from conventional tests on a spheroidal graphite cast iron and at a frequency of 25 Hz by Renault. The experimental results confirm that fatigue failure can occur over 10^7 cycles, and the fatigue endurance stress continues to decrease with increasing number of cycles to

failure between 10^6 and 10^9 cycles. During their ultrasonic fatigue tests, specimen heating occurred as a result of absorption of ultrasonic energy. The middle section of the specimen was cooled by compressed air so that the temperature was controlled between 2 limits depending on the R ratio ($=\sigma_{\min}/\sigma_{\max}$) in the tests. The highest controlled temperature was 120°C.

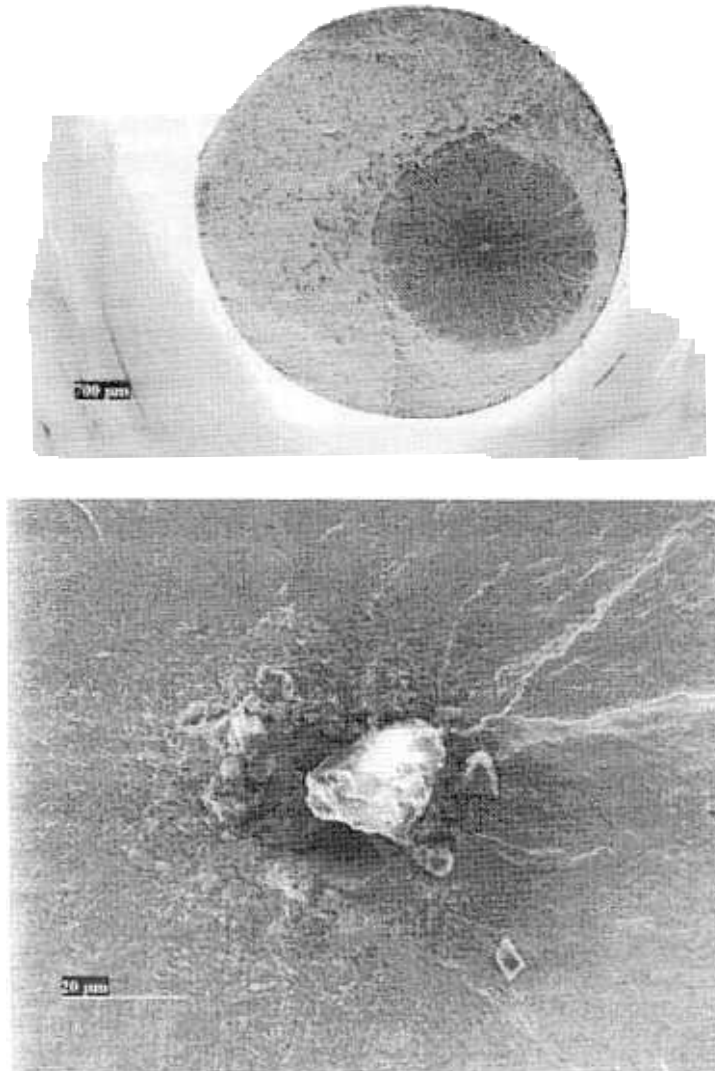


Figure 3 A micrograph showing a “fish-eye” inclusion inside a Cr-Mo steel specimen [Ref. 49]

Mughrabi [61] presented arguments to support the hypothesis that, at the very low amplitudes of the UHCF regime, fatigue crack initiation, resulting from cyclic strain localisation, and slow early Stage I fatigue crack propagation, are the life-controlling mechanisms and that these processes can essentially be described in terms of the microstructurally irreversible portion of the cumulative cyclic plastic strain. Emphasis is placed on the important role of the so-called slip irreversibility which decreases as the amplitude becomes lower and lower. Materials discussed included copper, alpha-brass and ferritic carbon steel.

Conditions under which internal and/or surface fatigue failure can occur at low load levels below the conventional fatigue limit were discussed in Ref [46]. Fatigue threshold models were proposed for two classes of materials (Fig. 4), namely pure single-phase metallic materials (type I) without internal defects and materials such as steels or cast materials (type II) with internal defects (inclusions or pores). In the case of type II materials, the probability of surface versus internal fatigue is discussed in terms of the volume density, size and location of the inclusions and the relevant cracking mechanisms. It was argued that, in both type I and type II materials, multi-stage S-N curves or Coffin-Manson plots can be expected under certain conditions.

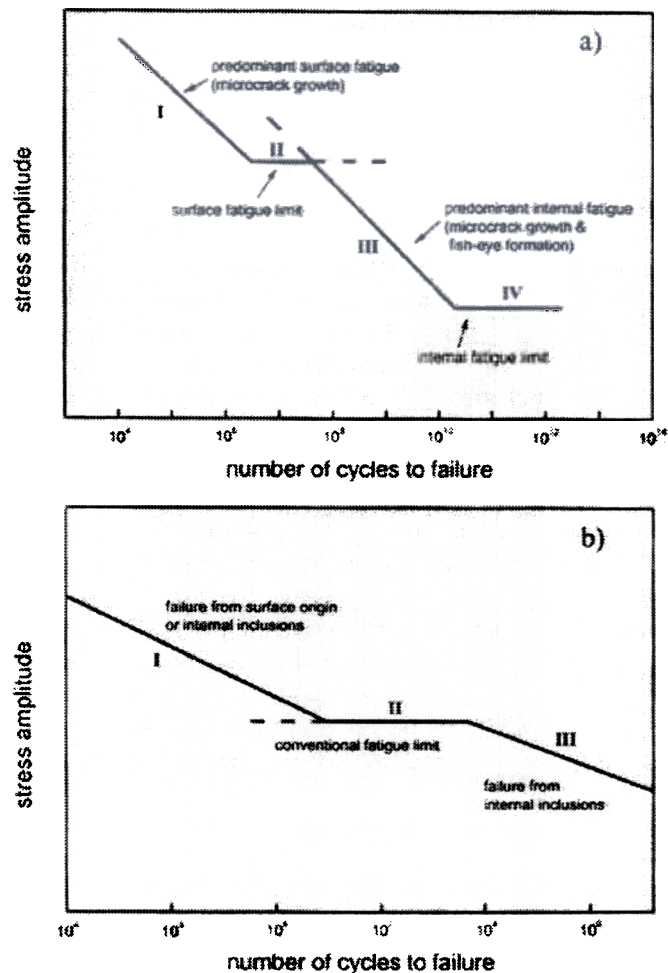


Figure 4 Schematic illustration of shapes of multi-stage S-N curves proposed by Mughrabi. The different ranges are numbered as in Ref. [46].

4 SUMMARY AND RECOMMENDATIONS

It was noted that a high proportion of the papers published on this subject were authored by ultrasonic cleaning equipment manufacturers. It is understandable, therefore, that the main emphasis was on educating potential users on how the technique works, its efficiency and effectiveness as a cleaning aid. Possible effects on component life or function integrity received little attention. Almost all published investigations on material-related issues concerned electronic devices and very few concerned metallic components.

The efficiency and effectiveness of the ultrasonic cleaning process is beyond question. No other current technique can provide similar qualities. However, as described in section 2, ultrasonic cleaning can develop fatigue damage and can cause fatigue failure in the parts being cleaned.

During ultrasonic cleaning, ultra-high numbers of stress cycles can be experienced by the part being cleaned. This is a cumulative process during the whole lifetime of the part being cleaned, e.g. aircraft engine component in a maintenance schedule or repair.

Recent studies have shown that fatigue failures can occur at stress amplitudes that are well below the conventional “fatigue limit” - the corresponding number of cycles to failure can be $> 10^9$ cycles.

Recommendations

- 1 For safety-critical and function-critical components, a fatigue damage assessment must be made in conjunction with a tight procedure that specifies the appropriate control variables during the cleaning operation. Particular care must be given to components that might contain damage (pores, cavities, fatigue cracks, etc). The hypothesis here is that further damage can develop in already damaged components. Ultrasonic bubbles when they implode will release highly concentrated energy coupled with a high hydrostatic pressure inside a crack or a defect. This can open the crack or defect and cause it to grow. It is believed that ultrasonic cleaning may have beneficial effects on sound, i.e. undamaged, or non-porous materials due to the increase of surface residual stresses as observed in Ref. [40].
- 2 For safety-critical and function-critical components, tight operational procedures must be developed to (i) limit the maximum power density used in the tank, (ii) specify the range of frequencies that can be used safely (from a fatigue assessment) with the components, (iii) specify the maximum operating temperature allowed in the tank and (iv) minimise cleaning times. Similar procedures are already being used when cleaning electronic devices [e.g. Refs. 30 and 34].
- 3 For general use the technique is safe to use. Equipment manufacturers' recommendations on usage should always be consulted.

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