Evaluation of an ultrasonic device to test fretting-fatigue in very high cycle regime

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Abstract

Traditional fatigue tests are not suitable for very high cycle fatigue (VHCF) problems, because of the enormous time spent to reach this regime. Many mechanical components may, however, be subjected to VHCF. Fatigue strength beyond certain limit is usually estimated using statistical approaches or establishing a threshold for crack nucleation.

Fretting may take place whenever two fixed parts are under mechanical vibration and variable bulk load. It can have catastrophic effects for parts under fatigue, mainly in VHCF, virtually eliminating crack initiation period.

The objective of the present work was to evaluate an ultrasonic device to accelerate very high cycle fretting-fatigue tests. Axial load was imposed by a piezoelectric transducer to round cross-section specimens. Fretting was induced by forcing at right angle cylinder pads, which were replaceable and could be specified for each case. It was possible to choose, at the same time, both fretting amplitude and bulk load. Normal load was imposed by an adjustable spring.

Results confirmed that fatigue strength decreased significantly when specimens were subjected to fretting. Besides this, worn surfaces showed many characteristics evidencing the occurrence of fretting. Upgrades are necessary to decrease the influence of the apparatus on fretted amplitude and to facilitate surfaces alignment.

Keywords very high cycle fatigue, fretting-fatigue, ultrasonic fatigue testing

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1. Introduction

The study of materials behaviour under Very High Cycle Fatigue (VHCF) is of real interest of researchers on different engineering fields and several industrial sectors. Many mechanical components can be subjected to VHCF once that their loading histories easily exceed the assumed high cycle fatigue limit, usually established between 10^6 and 10^8 cycles, depending basically on the material in analysis. For example, the crankshaft of a car equipped with 30in. diameter tires, considering an average 1:3 reducing factor, will attain 10^8 cycles after 80,000km in service. To reach the same number of cycles, a 1.02m diameter train wheel will take around 100,000km and a aircraft turbine running at 10,000rpm will take about 170h of service.

The transportation industry exemplified on the three cases above is perhaps where the study of VHCF is of importance. During their normal lives, vehicles', trains', and turbines' parts can run up to 10^9, 10^{10}, and 10^{11} cycles, respectively[1]. The time spent to reach such a high number of cycles using conventional fatigue testing machines is too long, making the study of VHCF in traditional ways prohibitive. The 100Hz testing line in Fig. 1 illustrates this problem: vertical layers delimit the span of cycles usually attained by each kind of craft's parts during their lives, while horizontal shadows divide the ordinate in subparts, giving the reader an idea of time length.

Beyond the usual limit of high cycle fatigue regime, fatigue properties are usually estimated based on statistical approaches, being a horizontal asymptote usually assumed for steels and other metals, while for aluminium alloys a steady decreasing in fatigue strength is supposed[2]. Nevertheless, the increasing necessity of full understanding of engineering phenomena made mandatory the acceleration of fatigue testing. One of the evolutions that made possible the evaluation of VHCF was the ultrasonic fatigue testing device, frequency first reached by Mason[3] *apud* Bathias & Paris[1], in which fatigue experiments are carried out at 15kHz or more. The 20kHz testing line in Fig. 1 shows, in comparison with the 100Hz one, how greatly fatigue experiments carried out in such a high frequency can be achieved quicker, becoming feasible and affordable.

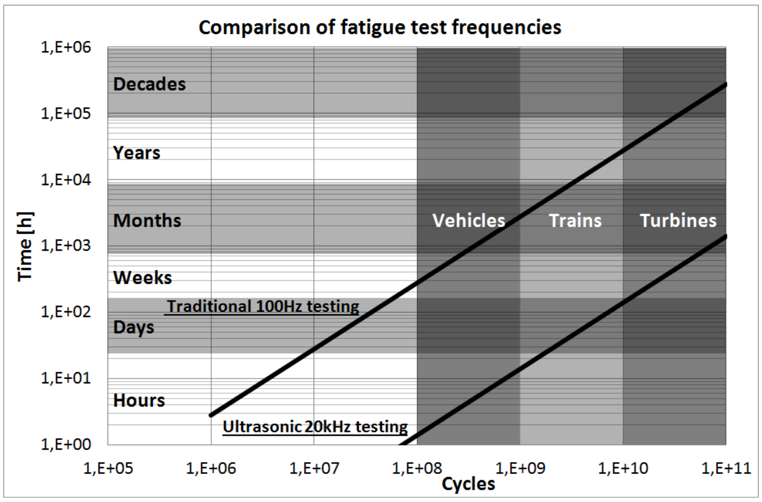

Figure 1 – Comparison of time spent to reach a certain number of cycles in 100Hz and 20kHz fatigue tests

As tests in the VHCF regime became more accessible and frequent, several studies [1,4-6] showed that the infinite fatigue life assumption for steels and other metals did not represent faithfully the reality of this phenomenon. On the contrary, fatigue strength of ferrous materials tends to decrease as the number of cycles increases. Moreover, it was proved that even crack nucleation mechanism in VHCF regime is different from low and high cycle ones. For the latter, cracks typically arise from the surface, while for the former, subsurface initiation preponderates [1,4-7].

Fatigue properties of a component can be deteriorated by many external reasons; a very common factor is the fretting phenomenon, which occurs whenever two surfaces subjected to mechanical vibration are fixed against each other, i.e., there is no nominal displacement between them. This vibration will result in minute displacement between both parts, mostly in regions of geometric or loading discontinuities. This random or cyclic movement will induce wear of surfaces in contact and, under specific conditions, will trig fretting cracks, which has been remarked in minute displacement as small as 0.1µm[8]. Many practical situations can be subjected to this phenomenon, like, for example, bolted connections, interference assemblies, flanges, keyways, cables, and ropes.

The effect of fretting can be catastrophic, once that it diminishes crack initiation period because of stress concentrations over the contact surfaces[9]. Virtually eliminating this span of life, fretting decreases a material's fatigue strength to very low levels, dropping it to values as low as ⅓ of its original value[8]. This effect is still more remarkable when a steel body is subjected to VHCF, where crack initiation period accounts for the most of its fatigue life, such as in high cycle fatigue[10].

Unlike plain fatigue experiments, just a few works have been done using ultrasonic frequency to accelerate fretting tests[11-13]. These authors criticize the technique of increasing the oscillatory movement's amplitude in order to accelerate fretting experiments, inasmuch as it changes the contact conditions with simultaneous change in crack initiation and wear mechanisms. These studies conclude that many observed wear mechanisms exhibit the features described in some of the most accepted models for fretting. So ultrasonic testing seems to be a promising technique for accelerated fretting wear experimenting. However, Söderberg *et al.*[11] and Bryggman *et al.*[13] recommend precaution to use it in low amplitude fretting, where fretting wear is less important than fretting corrosion and fretting fatigue. Moreover, it appears that the two latter phenomena rates improved by increasing the frequency of vibration. Although there is no apparent change in contact conditions, frequency influences both interfacial strain rate and temperature.

Finally, only one study was found in literature using ultrasonic frequency to accelerate fretting-fatigue tests[14]. These authors concluded that the developed ultrasonic fretting-fatigue testing machine worked well, reproducing the phenomenon rightly. Thus, the objective of the presented paper was to evaluate the same machine used by Sun *et al.*[14], presented in details in [15].

2. Materials and Methods

In order to evaluate the testing device first presented by Sun *et al.*[14], fretting-fatigue tests were run in ultrasonic frequency, i.e., around 20kHz, until specimens either fail or run out at the life of 10^9 cycles. Fretting was induced by a cylindrical pad in right angle with the specimen (crossed-cylinder configuration) with a normal load of 30N and constant fretting amplitude at 10μm. Axial bulk load was imposed by a piezoelectric transducer in ultrasonic frequency at one of the fundamental frequencies of the specimen. Plain ultrasonic fatigue results in VHCF region for the material in analysis is available from earlier experiments. All tests were made at the *Laboratoire Energétique Mécanique Electromagnétisme*'s facilities, at *Institut Universitaire de Technologie de Ville d'Avray*, France, directly linked to *Université Paris Ouest*.

The device in analysis can be split in two subsystems: the ultrasonic core, responsible to axially stress the specimen, and the fretting-apparatus, in charge of rubbing it. The ultrasonic core imposed full reverse axial stress cycles to specimens by vibrating in a frequency near to one of fundamental frequencies of the entire assembly. To achieve one these modes, a sinusoidal displacement was imposed by a piezoelectric transducer connected to a high frequency power source, which was piloted by a control unit. In general, displacements generated in a piezoelectric transducer are too small, so it was necessary to attach at one of its ends a horn (sonotrode), or mechanical amplifier, to reach desired displacements and consequently higher stress levels through specimens. A schema of core's main units can be seen in Fig. 2.

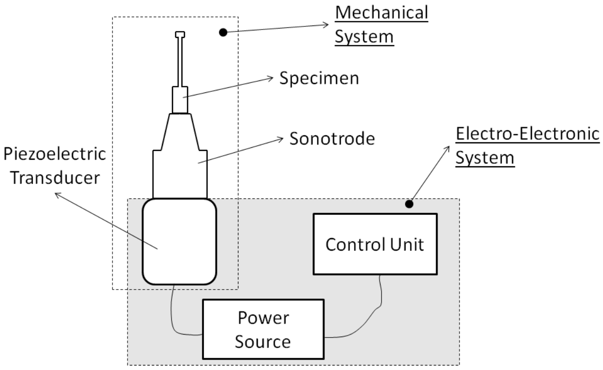

Figure 2 – Schema of the main units composing the ultrasonic core of the testing device

Once that specimen's fundamental modes and frequency and amplitude of imposed displacements at the specimen's bottom were known, it was easy to calculate displacement and stress fields through the piece and generate the iso-amplitude of displacement abacus. Using this powerful tool allowed the determination of the position where fretting pads were going to be placed in order to assure both desired fretting amplitude and bulk stress. An example of this kind of abacus is shown in Fig. 3: if a X_i=10μm amplitude displacement is required with 300MPa bulk stress, it is only necessary to identify the intersection of the 10μm displacement line (dashed) with the 300MPa line coming from the vertical axis. This point, marked with a cross in the chart, shows where the fretting pads must be placed (around 45mm from the specimen's bottom – horizontal axis) and the displacement amplitude to be imposed at the specimen's bottom ($X_{(0)}$=14μm) – full line that intersects the cross.

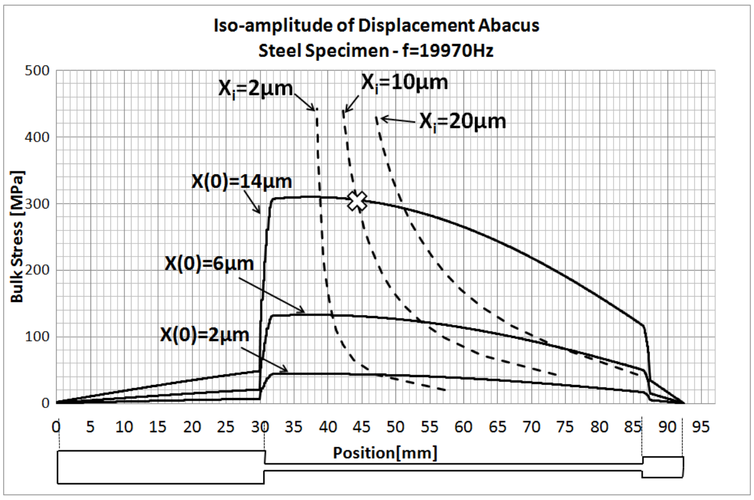

Figure 3 - Example of an iso-amplitude of displacement abacus.

The fretting-apparatus consisted of two 5-mm diameter cylindrical pads made of AFNOR XC48 steel, similar to ASTM510[16], soaked at 830°C for 30 minutes and quenched in water, carefully polished with 1000 CAMI graded sandpapers. Pads were diametrically opposed, pressing specimens with 30N normal load, imposed by two parallel springs, as shown in the schema of the mechanical assembly in Fig. 4. A rigid apparatus supported springs and pads, which were glued with Araldite®.

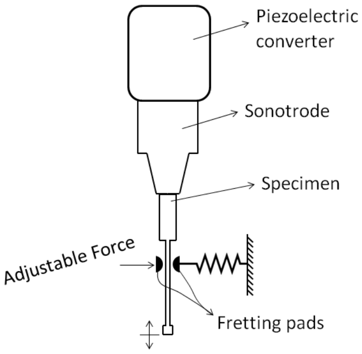

Figure 4 –Schema of mechanical assembly

At last, a cooling system using compressed air was necessary to keep specimens at room temperature, since that ultrasonic strain cycling and high fretting frequencies generate high heat rates.

2.1. Specimens

The material studied was a low alloy medium strength steel provided by an external supplier. All specimens were sequentially polished with 180, 320, 600, and 1000 CAMI-graded sandpapers in its axial direction. Their dimensions are shown in Fig. 5, and in Table 1.

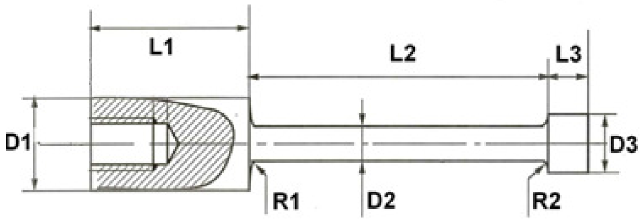

Figure 5 - Dimensions' codes

Table 1 – Nominal values and geometric tolerances

	D1	D2	D3	L1	L2	L3	R1	R2
Nominal value [mm]	10.00	4.00	7.00	30.00	57.40	5.00	2.00	1.00
Tolerance [mm]	0.05	0.02	0.05	0.10	0.05	0.05	0.1	0.1

3. Results and Discussion

3.1. Comparison between plain fatigue and fretting-fatigue

The fatigue curves are presented in Fig. 6. The fretting curve, calculated by using the least-squares method, showed good linearity (R^2=0.68). The data with triangular mark was excluded from linear regression calculations, because its value was completely out of general behaviour of the other tests. Further statistical analysis must be done to confirm this hypothesis. Despite the relatively low coefficient of determination of linear regression, it is a good result, taking into account the number of variables that influences fretting-fatigue. Moreover, it is necessary to remember that this phenomenon was investigated beyond the 10^7 cycle limit, which is historically hard to analyze, due to its complex stochastic behaviour. Finally, synergy between both phenomena when explored in ultrasonic regime was not deeply studied until the present time.

It also can be seen in Fig. 6 that fatigue strength in VHCF region decreased when specimens were subjected to fretting. With both linear regression data, a fatigue strength reduction factor (r) was defined. This factor represented the ratio of plain fatigue strength to fretting-fatigue strength at a given number of cycles. As shown in Fig. 6, this factor remained almost constant at around 1.5 in the whole VHCF region, decreasing less than 3% from 10^6 to 10^9 cycles.

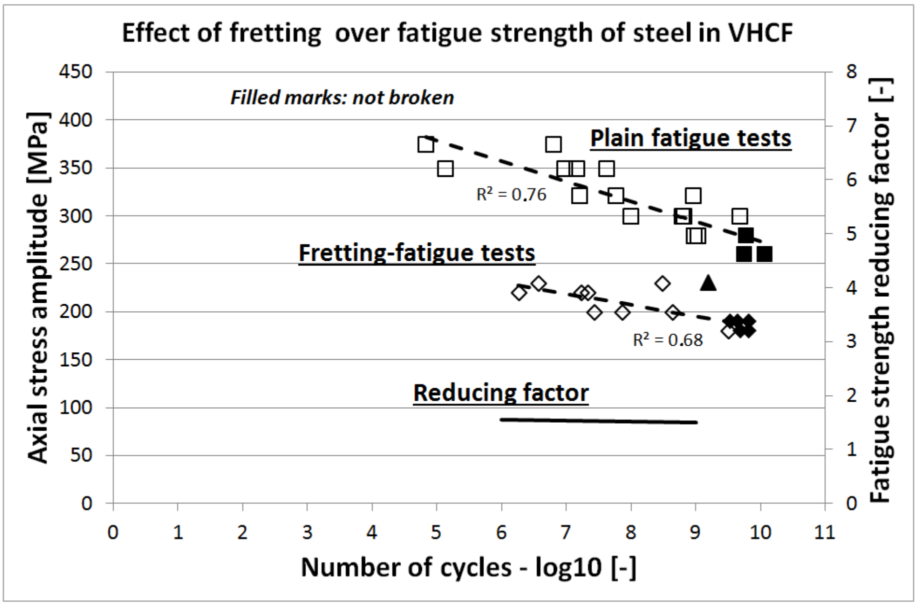

Figure 6 - Comparison between fatigue strength with and without fretting

3.2. Fretting evidences

A brief analysis of results can show some indirect clues of the reproduction of fretting in tests. It was observed that somehow superficial factors highly influenced fatigue life of component. First of all, as one can see in Fig. 6, the drop in fatigue strength of material in analysis was remarkable. Another indication was that cracks nucleated on surface, as exemplified in Fig. 7, unusual behaviour in VHCF regime, in which subsurface initiation preponderates.

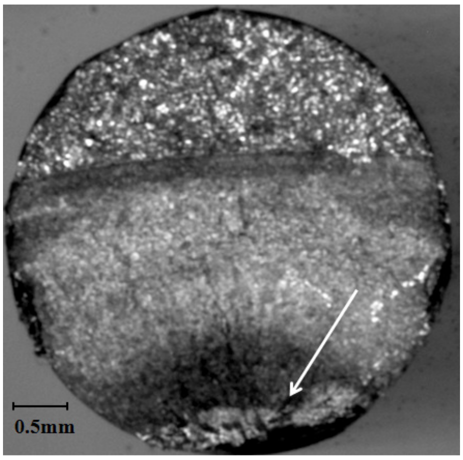

Figure 7 – Crack nucleation on surface

Fretted surfaces of tested specimens were analyzed and most of them showed fretting characteristics described by some of the most accepted fretting models in literature[8]. The presence of two clearly distinguishable areas can be seen in Fig. 8: smooth stick region and rough slip zone with scars in rubbing direction. Damaged surfaces were crossed vertically by a smooth and shinny section, which corresponds to stick zone, located about the centre of the contact ellipse. This stick zone is surrounded in its left and right sides by a rougher and deeper region, the slip zones.

The formation of oxidized regions and debris, mainly when excessive fretting occurs, is also very characteristic. Debris could be found in great quantity far from fretted surfaces, because they were really slender and were blown away by cooling apparatus. Red-brownish spots, characteristic of steel oxidization, were found in almost every worn surface, predominantly in regions subjected to heavy wear, as expected[8]. An example is illustrated in Fig. 8, where bright white spots represent the oxidized regions.

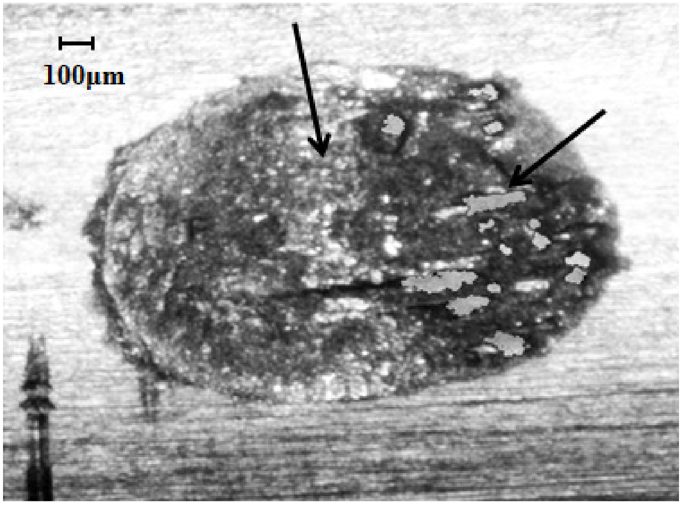

Figure 8 –Example of factors usually found in surfaces under fretting

Finally, the last aspect analyzed were the crack initiation sites. Fretting cracks are usually nucleated next to one of two existing bounds: stick-slip zones limit and the limit between slip zone and region out of contact surface[9,17]. Although it is very hard to determine which of these zones will predominate, authors linked crack nucleation site to contact pressure[17]. However, in the present work, crack nucleation site changed from test to test: in a few cases, crack nucleated near stick-slip zones bound (Fig. 9a), in specimens, cracks nucleated in the bound between region under contact and free region (Fig. 9b).

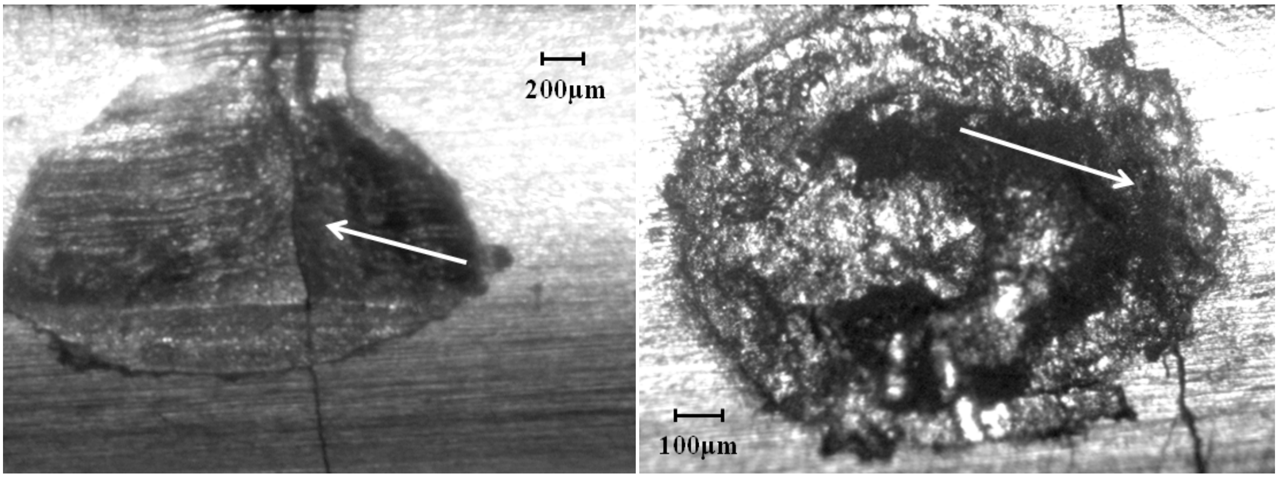

Figure 9 – Examples of crack nucleation sites: stick-slip zones limit (a) and bound between under contact and free region (b)

3.3. On the device

The most advantageous innovation of the ultrasonic device was clearly the possibility of accelerating enormously tests, as presented before. Some other benefits could be pointed out though. The mechanics of the machine is simple, resulting in easy maintenance and facilitating operators training. Also, setting-up and operating are easy, except for the alignment process. The components of the machine and instruments are light and inexpensive when compared to other axial fatigue machines. Finally, another great advantage is that, within certain limits, as discussed later in this paper, the choice of fretting amplitude and bulk stress is uncoupled. It used to be a problem in machines used in several studies[18-20] in which one factor was dependent on the other.

On the other hand, a few drawbacks were found linked to specimen manufacture costs and alignment problems. The necessity of extremely well polished specimens is inherent to the process, once that superficial problems can trig crack nucleation before reaching VHCF. Polishing this kind of geometry – cylinder 100mm long, 4mm diameter – can be very time and money consuming. Still more troubling is the necessity of very strict geometric tolerance in manufacture process. As one can see in Fig. 10, nonconformities can be very harmful to tests, once that small deviations in geometry can significantly change fretting displacement amplitude and bulk load at a given position (see Fig. 5 to dimensions' codes). In this chart, vertical axis represents the percentage of deviation in both properties per deviation percentage in geometry, e.g., 1% of deviation in diameter D1 provokes almost 2% of deviation in bulk load and around 0.3% in displacement amplitude.

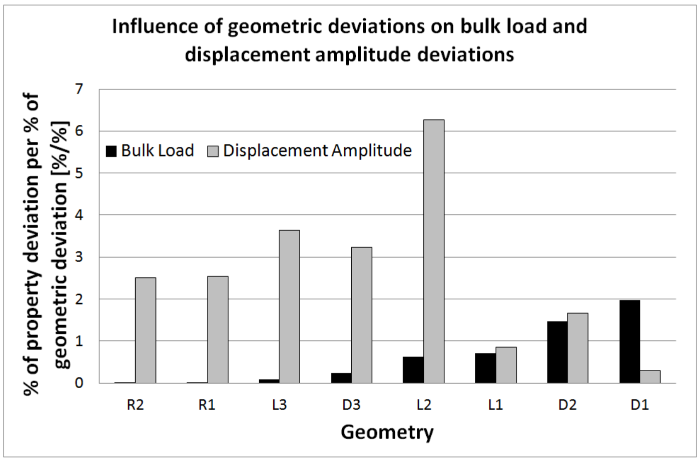

Figure 10 –Influence of geometry on bulk load and fretting amplitude deviations

Alignment was found to be another problem on the ultrasonic device. Position both pads such that their axis were parallel to each other and at the same height of the specimen, in order to avoid bending, was very difficult using the current fixture system. Complications came from the attachment process using Araldite® and from the loosing apparatus. It is advisable to revamp the support apparatus, aiming to facilitate the operation of the machine and to broaden its range of application, allowing the use of other types of contact configurations, e.g., line contacts as cylinder on flat or cylinder on cylinder, which are harder to align.

3.3.1 The overheating matter

Temperature rise in ultrasonic fretting-fatigue tests can be caused by two different methods. The first one is due to high strain cycling, which generates high heat rates. Specimen overheating must be avoided, because it modifies its mechanical properties and, beyond certain limit, changes fundamental frequency of specimen, killing the test. That is why the cooling apparatus is so necessary. The problem is that, as observed during tests, air coming out in high velocity from the apparatus blew away slender oxide debris formed in fretting contact. Nevertheless, the role of these debris in fretting is very important[8] and their forced expulsion from the area between surfaces clearly changes contact conditions. It is necessary to dedicate further efforts to understand its consequences to fretting-fatigue behaviour.

The second phenomenon is linked to wear caused by fretting, even more important at high frequencies. All other parameters being held constant, heat generated increases when wear volume per cycle raises. Superficial temperature, mainly at contact must remain in reasonable levels, in accordance with practical situations. Otherwise, high temperature tends to increase oxidation rates and to degenerate mechanical properties of materials in contact, affecting fretting conditions. In some tests, it was observed that superficial temperature raised when apparatus presented looseness and compliance, undergoing excessive vibration or when Araldite® softened because of high temperature. In both cases, it is probable that fretting pads were not properly fixed and was able to develop small displacements, increasing both surface and volume worn. It is recommended to rethink the apparatus that supports fretting pads, stiffening it, decreasing looseness, and principally changing how pads are attached to it, stop using gluing process.

3.3.2 Decoupling of fretting displacement amplitude and bulk stress

Decoupling fretting displacement amplitude and bulk stress at a given point without any additional equipment is a great advantage of the machine in study, so almost any combination of these properties can be chosen. Nevertheless, as one can see in Fig. 3, given a bulk stress at the rubbing point, the higher the fretting amplitude (X_i) desired, the higher must be the amplitude imposed at specimen's bottom ($X_{(0)}$), therefore improving the maximum bulk stress over the specimen. As a result, a more elevated heat rate will be generated, rising specimen's temperature, leading to the implications discussed earlier. So, summarizing, maximum fretting amplitude is limited: the higher the desired amplitude at a place, the lower the bulk load that can be chosen at this same point.

4. Conclusions

The ultrasonic machine is a promising device to accelerate fretting-fatigue experiments, which can be carried out more than 200 times faster than in regular fatigue testing machines currently in use. Fretting could be reproduced, decreasing fatigue strength by a factor of 1.5 in the whole VHCF region. Surfaces under fretting presented many patterns characteristic of this phenomenon: presence of two distinguishable areas of stick and slip contact, formation of oxidized regions and debris in the slip zone, and crack initiation near the stick-slip regions bound or near the stick regions-region out of contact bound. Moreover, superficial factors brought crack nucleation to surface, unlike to happen in plain VHCF.

The mechanism of the machine is simple, of easy maintenance and operation. Its components are lighter and cheaper than usual axial fatigue machines. In contrast to other fretting-fatigue devices usually found in literature, choice of fretting displacement amplitude and bulk stress in specimen is decoupled within certain limits. On the other hand, the necessity of extremely well polished specimens with very strict geometric tolerances is inherent to the ultrasonic testing machine, making specimen manufacture expensive.

The use of a cooling system is mandatory in the ultrasonic machine device, especially on fretting-fatigue tests. The current system, using compressed air, was responsible for blowing away oxide debris out of the fretting contact. These debris play, nevertheless, a very important role in fretting and their forced expulsion changes contact conditions. Further work must be done to understand the consequences of this fact to fretting-fatigue phenomenon.

The main problems are, however, linked to the apparatus that supports fretting pads. Looseness and compliance caused excessive vibration, letting pads developed small displacements. Therefore, surface and volume worn as well as superficial temperature raised in some tests. Also, alignment was found to be very hard using the current fixture system. It is advisable to revamp the support apparatus, aiming to facilitate the operation, to allow the use of other types of contact configurations, and to decrease its influence on fretting amplitude.

Acknowledgments

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