Cruciform specimen's analysis and experiments in ultrasonic fatigue testing

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Abstract The reliability of any given structure or machine subjected to dynamic loads is mainly dependent on the detailed fatigue study of the applied materials. As the demand for higher life cycles with more complex stress applications increases, so does the necessity for new and more complex fatigue testing methods. Since it was proven before that a fatigue limit should no longer be considered, ultrasonic fatigue tests were developed for the study of the life beyond that point. This is now known as the Very High Cycle Fatigue (VHCF) regime. In these tests, specimens are subjected to stress cycles in frequencies as high as 20 kHz. Most ultrasonic fatigue tests apply uniaxial stresses, but it is important to be able to apply complex multiaxial loading since most components are subjected to a complex stress state when under cyclic loading. In this work, cruciform specimens are used in an ultrasonic fatigue machine. Two different geometries, capable of inducing in-plane biaxial stress combinations (in-phase and out-of-phase) in the VHCF range, are studied. The geometries are subjected to both numerical analysis and experimental testing to understand if they are working as intended. For those who do so, a test until failure was carried through to observe and evaluate the fracture surface.

***Keywords**:* Cruciform specimens; Biaxial stresses; axial-axial; Ultrasonic fatigue; VHCF

1. Main text

The study of material damage in dynamic systems or structures is necessary to ensure their safety and reliability, since fatigue is one of the main causes for material failure [1]. As more complex and demanding machines and systems (in both reliability and performance) are required, more thorough fatigue studies are required.

Since the realisation that the fatigue limit in the classical sense is no longer applicable [2], the corresponding fatigue regime needs to be fully comprehended and characterised. This corresponds to life beyond 10E07 cycles, the Very High Cycle Fatigue (VHCF) regime Because conventional fatigue machines would take an unreliable time to achieve cycles between 10E06 and 10E09 (VHCF regime) a new type of machine was developed capable of inducing high frequency cycles: the ultrasonic fatigue testing machine. Mason in 1950 was the first to build successfully such machine establishing the standard frequency of 20 kHz [3]. In ultrasonic testing the components' set are excited in resonance in order to apply high enough stresses in such a high frequency. The specimen is then excited at a specific resonance mode that applies higher stresses in only a single and well-determined section for the fatigue study.

With the development of ultrasonic fatigue testing, new trends capable of applying different stress combinations than the first uniaxial tension/compression were created, like bending [4], torsion [5] or even multiaxial tension/compression and torsion [6].

In this work, two specimens, based on the ones from [7] and [8], were adapted following the guidelines from [9], so that they could be tested under ultrasonic fatigue loads in the uniaxial tension-compression test machine developed at Instituto Superior Técnico (University of Lisbon) [10]. The specimens have a cruciform shape and both induce in-plane axial-axial stress combinations, although in one design the stresses are in-phase while in the other they are out-of-phase. This specific geometrical shape is already in use in the conventional way of applying loads with actuators [11].

For the transformation from the conventional to the ultrasonic fatigue testing the base shape is kept but the dimensions are altered for the specimens to have a specific resonance mode of interest around the working frequency of 20 kHz. The dimensions are dependent on the material of choice and the resonance mode of interest; thus, two geometries are created for tension-tension (T-T) and compression-tension (C-T) stress induced combination.

2. Methodology

There are two cruciform specimens in study that are excited in two different resonance modes. Both specimens follow a certain geometry with special relations between the dimensions showed in [12]. In order to achieve a working specimen several dimension combinations are numerically tested until they have the resonance mode of interest within the working frequency. The two specimens are the T-T (in-phase) and C-T (out-of-phase). A representation of the deformation along both resonance modes is shown through the software Abaqus in the Figure 1.

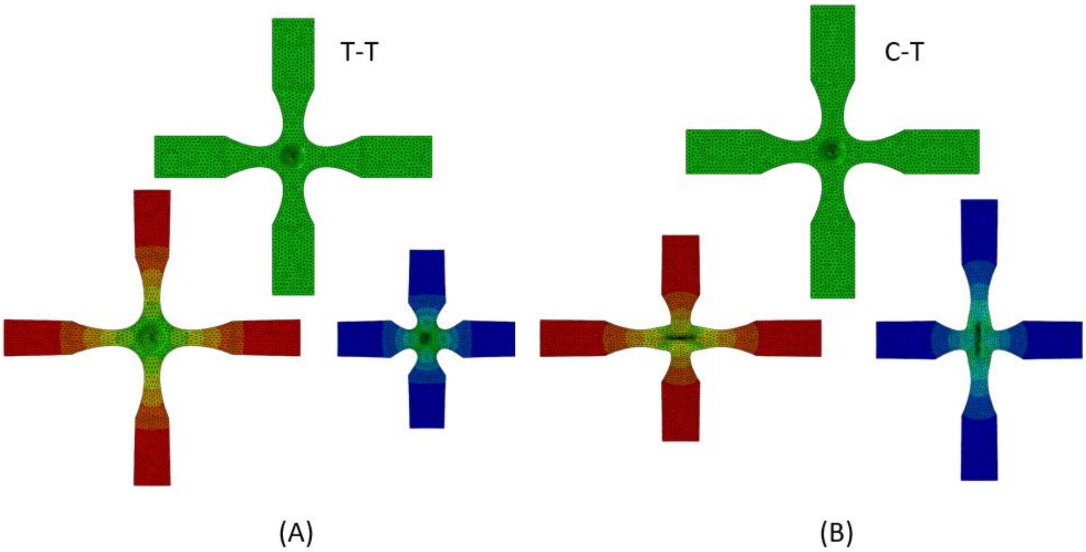


Figure 1: Representation of the displacements of resonance modes of interest for: (A) T-T; (B) C-T

The material used for the initial testing of these specimens' shapes was the 6082-T651 Aluminum alloy. Before performing any test, a frequency analysis of the component set with each of the machined specimens was made using the transducer's software. This analysis helps to understand if it is possible to excite in resonance any specimen and at what frequency.

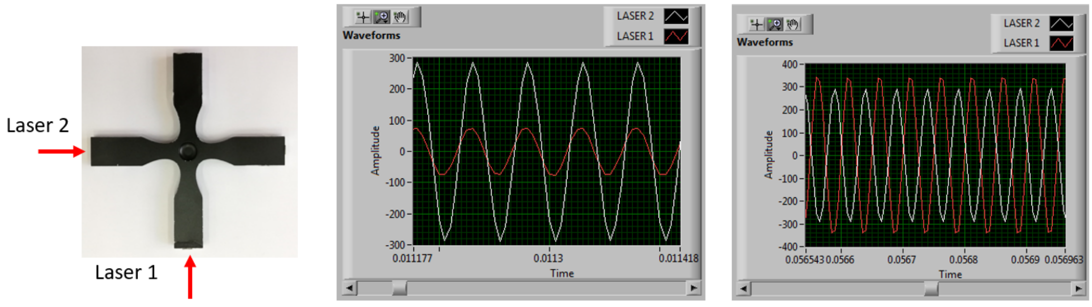
Both T-T and C-T specimens dynamic behaviours were analysed using a two-channel Polytec Laser Doppler Vibrometer (LDV) measuring axially (at the extremities of the arms) and transversely (along the longitudinal length of the arms) in pairs. This allowed determining the phase and amplitude differences between channels. From the measurements at the extremities, this helps understanding if each specimen is being excited as intended. By measuring transversally along the length of the arms, this helps understanding if the displacement had any discrepancies to the supposed motion of the arms.

In resonance, the material's damping has a large influence on the amplitude of the obtained resonance frequency of a given geometry and the resulting stress, as the results with finite element analysis showed in [8]. The damping effect is also responsible for the generation of heat, this means that where the material is deforming (in the sense of strain) the most (highest stress region) the heat generated is the highest. With the use of a thermal camera, all specimens were observed in order to view if the centre showed generation of any heat, since it is the expected area of highest stress. To obtain the thermal response on the camera the specimen's side on film was painted mate-black beforehand.

3. Results and discussion

The frequency analysis performed to all machined specimens showed that all C-T and T-T could be excited within the working frequency range of the transducer.

The Laser measurements at the extremities are shown in Figure 2 for each type of specimen. It is clear that, even though both type of cruciform specimens proved to have the correct and expected phase, only C-T showed to have similar amplitudes on both extremities. All T-T specimens produced showed to have the displacements at the extremities in phase, but with a considerable shift in amplitude, being systematically larger in the transversal arms.



(A) (B)

Figure 2: Displacement measurements of the specimens’ extremities; (A) T-T; (B) C-T

From the Laser measurements and numerical analysis, it is observed that the T-T specimen has a considerable undesired vertical movement in the transversal arms. There are a few reasons why this may be happening, a nearby resonance mode (at approximately 19.8 kHz) that alters the specimen’s deflection shape and desired operation could be one possible reason. A more detailed study is being conducted to understand and correct the T-T geometry for a functioning one. However, the C-T geometries proved to have an acceptable performance. Thermal imaging also helps to reinforce the latter statement as Figure 3 shows a higher heat generation at the centre of a C-T specimen. The T-T specimens did not show a heat generation at their centres.

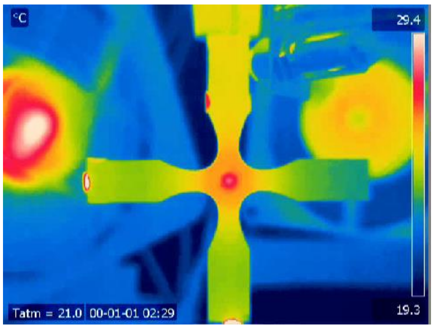
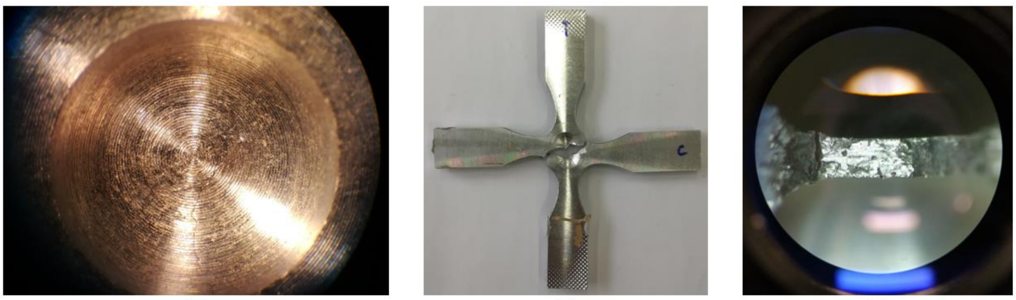


Figure 3: Thermographic image of a C-T specimen under an ultrasonic fatigue test.

Knowing that the C-T specimen was being excited in the resonance mode of interest with a correct displacement, a power-controlled test was performed until failure. In this test, an estimated power was applied to the specimen with temperature control. The number of cycles was counted from the waveform measured through the Laser mentioned before. After more than a million cycles the specimen “lost” its resonance at around 20 kHz due to the appearance of a fatigue crack at its centre (the stiffness decreased, hence the natural frequency decreased as well until it reached the lower operating frequency of the machine at 19.5 kHz). In order to expose the fatigue crack surface for observation, the specimen was introduced to a hydraulic machine for a tensile test until complete failure. Figure 4 shows the crack before and after applying total failure to the specimen.



(A) (B) (C)

Figure 4: (A) Amplification of the crack after ultrasonic testing (B) C-T specimen after tensile test with the showed crack (C) Microscopic image of the fatigue crack surface of the C-T specimen

The created fracture showed two different types of crack surface zones. One with a more regular and shinier surface, showed in figure 4.C, and a rough dark surface which dominates most of the crack surface area. The former appears to be where the fatigue initiated and propagated, the latter appears to be ductile fracture due to the big enough fatigue crack size, it just didn't break in all specimen's length due to the sudden increase of thickness, and also due to the sudden "loss" of frequency which made the test come to a stop (due to limitations of the machine with regards to its operating bandwidth). The fatigue induced crack surface shows to be at around 45º with respect to the induced stresses directions. This angle seems adequate for the applied biaxial state considering that uniaxial tension/compression specimens have a crack surface normal to the specimen's length. Thereby having a in plane axial-axial with a 90º degree relation with similar induced stress, it is a fair assumption that the fracture angle should be in between the applied stress. The 45º degree angle of the fatigue crack is showed in Figure 5.

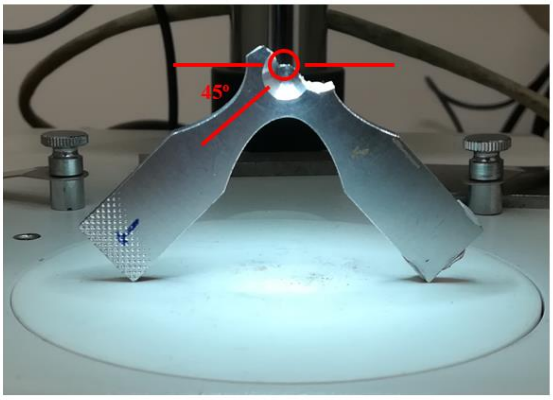


Figure 5: Fatigue crack angle in relation to the arms in a C-T specimen.

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