

Multiaxial Fatigue Behaviour of 1050 H14 Aluminium Alloy by a Biaxial Cruciform Specimen Testing Method

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ABSTRACT. *In this paper the mechanical behaviour of 1050 H14 aluminium alloy is investigated under in-plane biaxial fatigue. Both experimental and theoretical methods are applied to validate multiaxial fatigue criteria. In order to cover a large range of multiaxial stress states, a new biaxial testing machine was developed and applied in the fatigue tests with a specially designed cruciform specimen. Different multiaxial fatigue criteria, including those based on octahedral shear stress amplitude combined with hydrostatic pressure, and more recent models based on the critical plane approach are evaluated. A modified Minimum Circumscribed Ellipse (MCE) approach is proposed that offers a possible compromise and seems to significantly improve the assessments.*

INTRODUCTION

Machine components and structures in service are generally subjected to multiaxial fatigue loading conditions. Fatigue life evaluation of mechanical components under complex loading conditions is of great importance in order to optimise structural design, and improve inspection and maintenance procedures. However fatigue experiments are much more easily performed under uniaxial loading and constant amplitude but most practical problems associated with metal fatigue in structural elements and machine components are associated with multi-axial loading. For example, rotor shafts in electric power plants, propeller shafts in ships, and so on. The most common multiaxial fatigue specimens and testing fixture are therefore associated with bending-torsion or tension-torsion testing machines and in-phase and out-of-phase fatigue tests are available in literature for a wide range of materials and loading paths, [1].

Less attention has been paid to fatigue tests performed under biaxial loading such those present on pressure vessels or pressurized aircraft cabins. These examples cover different circumstances of cyclic nature of loading and also variations in biaxiality including in-phase versus out-of-phase, different ratios of biaxiality, etc. The cost and availability of biaxial fatigue testing machines that can perform biaxial loading for example in cruciform specimens is certainly the cause. While considerable advances have been made in analytical modelling of stress response of materials under biaxial

loading, fatigue under biaxial loading conditions remains very much an unexplored science, demanding appropriate testing technology. Test systems have been developed over the years to perform tests under static and cyclic biaxial loading using cruciform specimens. To this end, a wide variety of cruciform specimens have also been developed. Some of these systems constitute simple and robust designs whose application using fewer actuators can perform a limited combination of biaxial loading conditions on sheet material.

This work presents the results of tests performed with a new in-plane biaxial fatigue testing machine built with four of the most powerful iron-core linear motors available on the market for industrial applications, [2]. In phase and out-of-phase constant amplitude fatigue tests were carried out on cruciform specimens of an aluminium alloy. Selected stress based multiaxial fatigue models were used to analyse the experimental results. Since it is known that classical von Mises, [1], equivalent stress shall not be used to analyse the multiaxial fatigue tests, results were analysed through ASME code for pressure vessels, [3], and Minimum Circumscribed Ellipse (MCE), [4]. Also the presence of mean stress on the loading conditions is discussed. Results show that MCE model allows fitting very well the different fatigue lives obtained for three different biaxial loading paths.

MATERIALS AND SPECIMENS

The specimens were built in a CNC machine from Aluminium A1050 – H14 sheet plate with 5 mm thick; being the direction of lamination the longitudinal direction, 1 as indicated in Fig. 1. The H14 means that this material was strain hardened up to ½ full hard that is possible to achieve with this material.

Several static tensile tests were made in specimens with 16x5mm cross section, according to ISO 6892-1:2009 standard, being obtained the mechanical properties provided in table 1.

Table 1 – Mechanical properties obtained for A1050-H14 aluminium sheet plate with 5mm thick.

Rolling Direction	Yield strength [MPa]		Tensile strength [MPa]	
	\bar{X}	σ	\bar{X}	σ
0°	88.65	2.22	98.85	2.90
90°	100.90	4.32	106.46	2.68

According to table 1, the mechanical properties at 90° are within the limits given by EN 485-2:2007. For the 0° direction (rolling direction) the tensile strength is less than for 90° and below the minimum limit given by EN 485-2:2007.

The biaxial test specimen geometry, as represented in Fig. 1, is a combination of cruciform shape with a reduced thickness section centre and was optimized for a low force capacity testing machine, [2]. At the centre the specimen has a thickness of about

0.5 mm, generated by a revolving spline which starts horizontally at the centre and ends with approximately 21° at a diameter of 16 mm, Fig. 2, where the specimen has 3 mm thickness. In the grips region the specimen has the original sheet thickness that is approximately 5mm. The way how the spline is generated ensures that the specimen is almost plain at centre with minimal stress concentrations, [5].

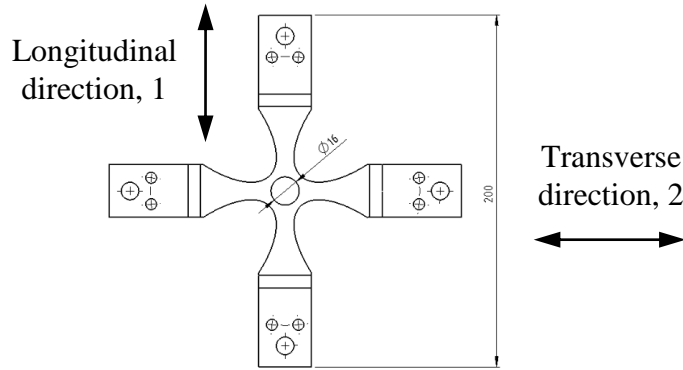


Figure 1 – Biaxial specimen shape (dimensions in mm).

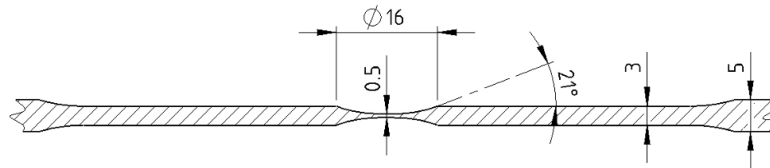


Figure 2 – Biaxial specimen section at centre (dimensions in mm).

When this specimen is loaded a ring effect is observed at the centre of the specimen, as verified by other authors, [6]. This means, that if the specimen is loaded in one direction, the stiff ring that is around the centre of the specimen deforms to an ellipse shape, making compression in the perpendicular direction.

In order to determine the ring effect in terms of stresses a finite element analysis was made for each specimen according to their final dimensions. A load of 1 kN was applied between both arms of the longitudinal direction maintaining free the transverse direction. The values $K\sigma_1$ and $K\sigma_2$ are the stresses calculated at the centre of each specimen in the longitudinal and transverse directions, respectively. These values were calculated by finite element method and validated experimentally for 2 specimens with rosette strain gages bonded. Stresses at the centre of the specimen for any loading condition can be calculated using the principle of superposition:

$$\begin{aligned}\sigma_1 &= F_1 \times K\sigma_1 + F_2 \times K\sigma_2 \\ \sigma_2 &= F_2 \times K\sigma_1 + F_1 \times K\sigma_2\end{aligned}\quad (1)$$

being F_1 and F_2 the forces applied and σ_1 and σ_2 the stresses in the longitudinal and transverse direction, respectively.

Forces for biaxial experimental tests were selected such that the final calculated stress ratio was $R=0.1$. The biaxial loading cycle is given by:

$$\begin{aligned} F_1 &= F_a \times \sin(\omega \times t) + F_m \\ F_2 &= F_a \times \sin(\omega \times t + \delta) + F_m \end{aligned} \quad (2)$$

in which $\omega = 2\pi.f$, f is the frequency, t the time and δ the phase shift angle between the loads in direction 1 and 2.

To study the effect of non-proportional loads three different load paths with a phase shift of 0° , 90° and 180° were applied to the specimens. In Fig. 3 are represented all the loading paths carried out in the experimental tests that gave a fatigue life close to 600 000 cycles.

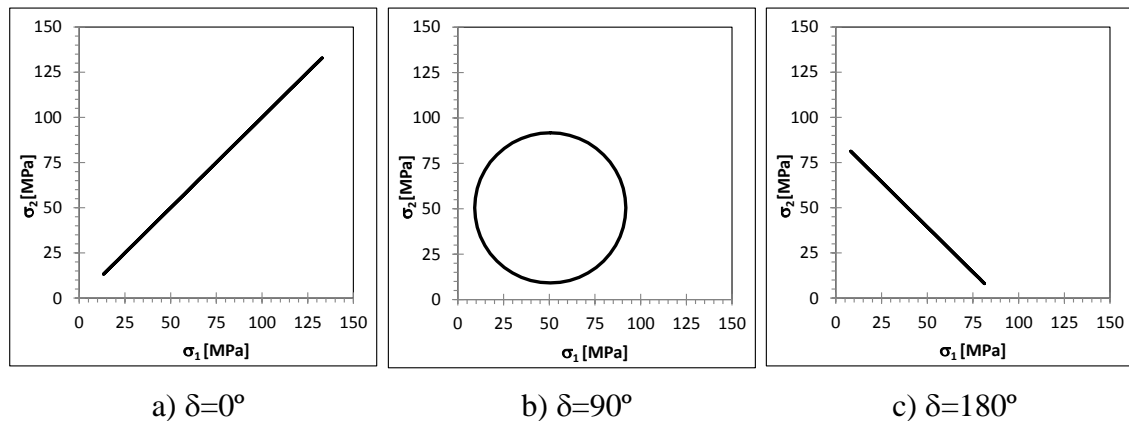


Figure 3 – Biaxial loading paths performed.

EXPERIMENTAL PROCEDURE

Fatigue tests were performed using a new in-plane biaxial test machine developed by the authors, [2]. This new test machine has four of the most powerful linear iron core motors available on the market for industrial applications, which include non-conventional guiding device allowing an adjustable and precise linear movement without contact and almost no friction. The controller was programmed with several modified cascade PID controllers and an algorithm to ensure that the specimen is stable during the loading cycle, [2]. The control is made in closed loop through the ± 5 kN dynamic load cell, installed in each motor. All experimental tests were made at room temperature in laboratory air at 10 Hz and increased to 20 Hz when the number of cycles was above 100 000 cycles. As shown in Fig. 4a) a digital USB microscope with a magnification of 20X was used to monitor the specimen surface. At every 5 000 loading cycles the test machine holds automatically at mean load and the camera takes a photo to be recorded, Fig. 4b). Tests end up when the machine stops by position limits (about

0.2 mm increase in one arm). The number of cycles up to crack initiation (approximately 0.8 mm) was determined by observing the recorded images.

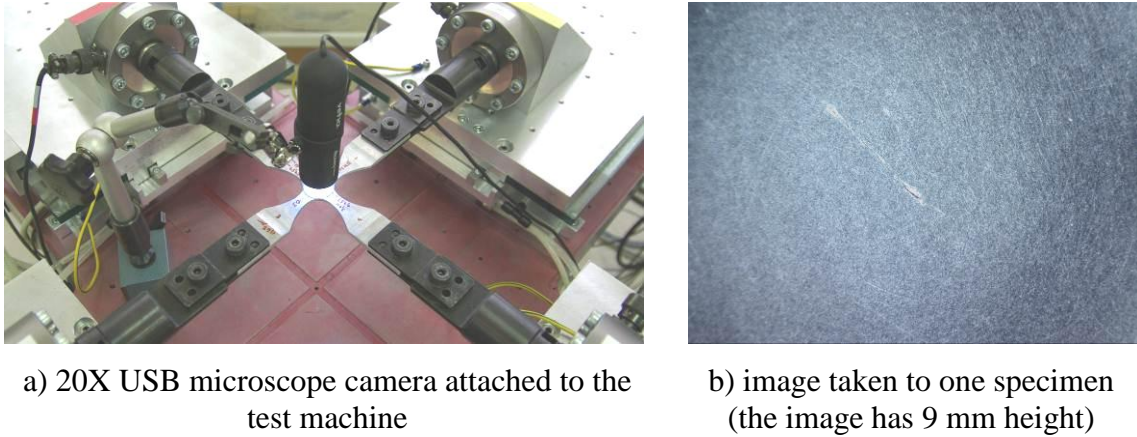


Figure 4 – Details of the crack monitoring system.

EXPERIMENTAL RESULTS

Fourteen specimens were tested successfully, giving fatigue lives in the range of approximately 15 000 cycles up to 670 000 cycles, whose experimental results are presented in table 2. Specimens that broke outside this range were not taken into account for this study. The number of cycles presented in the right column of table 2 is for a crack length of approximately 0.8 mm.

Table 2 – Numerical and experimental results.

Phase δ (°)	Centre Thick. (mm)	$K\sigma_1$ (MPa/kN)	$K\sigma_2$ (MPa/kN)	$\sigma_{1a} = \sigma_{2a}$ (MPa)	$\sigma_{1m} = \sigma_{2m}$ (MPa)	Number of cycles
0	0.260	92.47	-23.80	1.046	1.279	15 038
0	0.360	73.85	-19.61	1.260	1.540	40 248
0	0.313	78.31	-20.54	1.080	1.320	110 590
0	0.314	82.45	-21.68	1.035	1.265	215 070
0	0.341	75.91	-20.09	1.071	1.309	605 354
90	0.500	63.79	-17.28	0.747	1.253	52 461
90	0.507	63.38	-17.18	0.710	1.190	134 536
90	0.503	63.59	-17.23	0.673	1.127	195 368
90	0.507	63.23	-17.15	0.654	1.096	669 551
180	0.474	66.07	-17.84	0.544	1.156	31 697
180	0.508	63.26	-17.16	0.531	1.286	62 365
180	0.503	63.73	-17.24	0.509	1.234	105 075
180	0.480	65.15	-17.69	0.479	1.021	110 222
180	0.495	64.32	-17.41	0.447	0.953	640 660

RESULTS AND DISCUSSION

Several models were used to determine a multiaxial fatigue damage parameter for the specimens tested experimentally. The first approach used is the octahedral shear stress theory, sometimes termed as the classical von Mises theory, which can be expressed as:

$$\Delta\sigma_{eq} = \frac{1}{\sqrt{2}} \left[(\Delta\sigma_1 - \Delta\sigma_2)^2 + (\Delta\sigma_2 - \Delta\sigma_3)^2 + (\Delta\sigma_3 - \Delta\sigma_1)^2 \right]^{1/2} \quad (3)$$

being $\Delta\sigma_1$, $\Delta\sigma_2$ and $\Delta\sigma_3$ the principal stress ranges during a complete loading cycle.

However eq. (3) is only valid for proportional or in-phase loadings. For non-proportional cases, and if the principal stress directions remains fixed during a loading cycle, ASME pressure vessel code, [3], recommends to use the value of $\Delta(\sigma_1 - \sigma_2)$ instead of $\Delta\sigma_1 - \Delta\sigma_2$.

Most of the high-cycle multiaxial fatigue criteria have a general form as follows:

$$\tau_a + k(N)\sigma = \lambda(N) \quad (4)$$

where τ_a is a parameter related with shear stress amplitude and σ a parameter related with normal stress during a cycle. All the models differ in the interpretation of how shear stress and normal stress in eq. (4) are defined.

Both Sines and Crossland multiaxial fatigue damage criteria use the octahedral shear stress as shear stress parameter and the hydrostatic stress as normal stress becoming:

$$\sqrt{J_{2,a}} + k(N) \cdot P_H = \lambda(N) \quad (5)$$

where $\sqrt{J_{2,a}} = \Delta\sigma_{eq} / (2\sqrt{3})$ is the second deviatoric stress invariant, which is proportional to the root-mean-square of the shear stress over all the planes, $P_H = (\sigma_x + \sigma_y + \sigma_z) / 3$ is the hydrostatic stress and k and λ are two material constants, functions of the material cyclic life.

The difference between Sines and Crossland criteria is in the value of the hydrostatic stress. While Crossland suggests to use the maximum value of the hydrostatic stress $P_{H,max}$, Sines uses the mean value of hydrostatic stress $P_{H,mean}$.

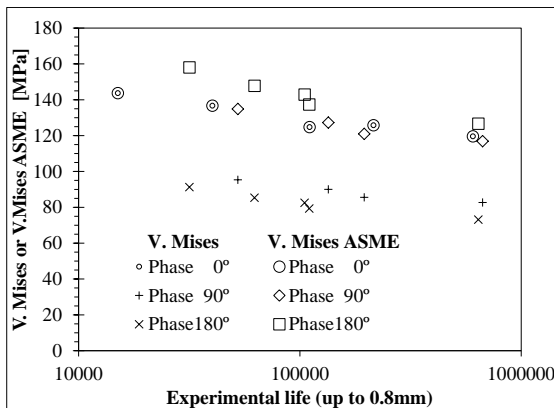
In practical Crossland and Sines criteria provide good approximations for proportional multiaxial loading. For non-proportional loading, the method of the minimum circumscribed ellipse (MCE) proposed by Freitas et al. [4], provides an efficient way to apply Crossland criterion with improved accuracy.

The MCE approach defines the shear stress amplitude as $\sqrt{J_{2,a}} = \sqrt{(R_a^2 + R_b^2)}$ where R_a and R_b is the major radius and minor radius respectively of the whole loading path

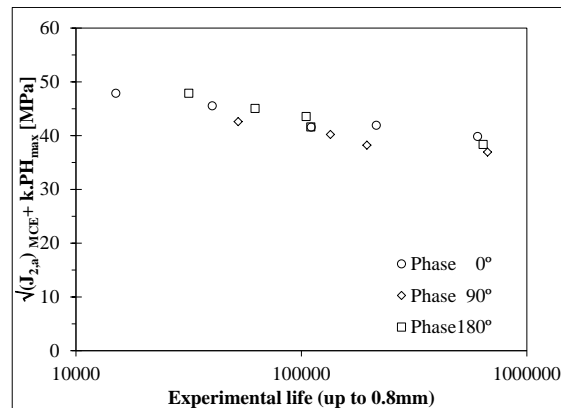
in the transformed deviatoric space, [4]. The value $\sqrt{J_{2,a}}$ can be easily calculated by knowing the alternating loading stress and the phase shift applying the equations provided in [7].

In Fig. 5 a) is shown that the classical Von-Mises approach does not provide good results for non-proportional loadings. The Sines and Crossland criteria were not presented in this paper because the way how octahedral shear stress is calculated is similar do the classical Von-Mises approach ($\Delta\sigma_1 - \Delta\sigma_2$), which does not include the non-proportional effect.

The modification proposed by ASME code provided an important improvement for non-proportional loadings. However some differences can still be found especially for $\delta=180^\circ$, whose results are overestimated, being attributed to mean stress effect that is not included in this model (note that for $\delta=180^\circ$ the mean stress is much below than for the others). The MCE method, without mean stress correction (not shown), provides similar results as the modification proposed by ASME code for the three phase shifts studied in this work (bearing in mind that Von Mises is based on normal stresses and that MCE is based on shear stress). For other phase shift angles (not considered in this work) MCE gives different results than the ones provided by ASME code modification. Fig. 5 b) shows an improvement when hydrostatic stresses are included in MCE approach. In this case a constant value of k was estimated as 0.06 but can be obtained by eq. (31) given in ref. [7] if both reversed bending and torsion fatigue strength are known.



a) Von Mises approach and modified according to ASME code.



b) MCE approach.

Figure 5 – Fatigue life criteria against experimental life.

CONCLUSIONS

Several experimental tests were conducted in a new biaxial in-plane fatigue test machine based on linear electrical motors. In these tests three different phase shifts were considered (0° , 90° and 180°) with a load ratio of $R=0.1$ and applied stresses such that fatigue life was in the range of 10^4 to 10^6 cycles covering the mid-life and long-life fatigue range.

The results were analysed in terms of the classical von Mises equivalent stress, through ASME code for pressure vessels and the Minimum Circumscribed Ellipse approach.

As expected the classical von Mises equivalent stress did not provided satisfactory results for the non-proportional loads. The modification proposed by the ASME code improved considerably the results for non-proportional loads, however some differences can be found especially for the 180° phase shift. This can be attributed to the lack of mean stresses in this model as for $R=0.1$ the phase shift introduces changes in this parameter.

MCE has an important advantage over ASME modification because it includes mean stress, improving considerably the results, providing a reliable and faster fatigue evaluation under multiaxial loading conditions.

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