Multiaxial Fatigue Simulation of an AZ31 Magnesium Alloy using ANSYS and a Plasticity Program

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Abstract

Magnesium and its alloys are becoming more and more used in the aerospace and automobile industry because of its low weight. The technology has suffered many improvements allowing magnesium alloys to have a mechanical performance close to aluminum alloys and corrosion protection. These unleash many possible applications for magnesium alloys subjected to multiaxial fatigue.

The objective of this work is to do multiaxial fatigue simulations in ANSYS and in a Plasticity program using Jiang & Sehitoglu plasticity model adapted for nonproportional effects of an AZ31 magnesium alloy. The damage parameters of Findley, Brown & Miller, Smith-Watson-Topper, Fatemi & Socie, Liu I and Liu II are applied.

The fatigue life results show that all the damage parameters don't take into account how much time the multiaxial loading is above the yield value. New damage parameters which take into account this effect are presented. The results shown during ANSYS and Plasticity program simulations, show that for some cases the work done not considering nonproportional effects (ANSYS) is greater than considering them. However, other cases show the opposite.

Introduction

Magnesium and its alloys have always been of interest for general structural applications because of its low weight [1]. They are becoming more used in the industry due to improved corrosion protection technology, e. g., Tagnite coating [2] and better mechanical performance. In terms of mechanical performance the magnesium alloys are reaching a level similar to aluminum alloys [3], the principal competitor of magnesium alloys in the aerospace and automobile industries. New forming technologies for magnesium alloys are developed for aerospace [4] and automobile [5] applications too. The development of magnesium alloys and associated technology is considered so important that the United States Automotive Materials Partnership made a report about what technologies to develop to magnesium alloys become more used in reference [6]. In this report performing life-cycle analyses or fatigue analyses of magnesium alloys are a major research need to reduce cost/ quality challenge. So the objective of this work is to study the magnesium alloy AZ31 behavior subjected to multiaxial fatigue for combined axial and torsion loads. Multiaxial fatigue simulations are done considering symmetric hysteresis loops in ANSYS and in a Plasticity program with the Jiang & Sehitoglu plasticity model adapted for nonproportional effects. Eight multiaxial loading cases are simulated for ANSYS and Plasticity program.

Damage Parameters

To quantify how much damage a loading path does to the material and to estimate fatigue life time, damage parameters are necessary. In this works the critical plane damage parameters of Findley, Brown & Miller, Fatemi & Socie, Smith-Watson-Topper, Liu I and Liu II are used to estimate fatigue life and critical plane. These damage parameters are based on relations of stresses and strains. They are described below. A more detailed description can be found at [7]. They are programmed in Matlab software.

Findley

The Findley parameter relates maximum normal stress to a plane $\sigma_{n,max}$ and shear alternating stress τ_a by a constant k:

$$max\left(\tau_a + k\sigma_{n,max}\right) \quad (1)$$

The fatigue life or life cycles number N_f can be determined using:

$$max\left(\tau_a + k\sigma_{n,max}\right) = {\tau_f}^*\left(N_f\right)^b \quad (2)$$

Where ${\tau_f}^*$ is determined by: ${\tau_f}^* = \sqrt{1+k^2} * {\tau_f}'$

Brown & Miller

Since the loading cases are for combined axial and torsion loadings, Brown & Miller damage parameter can be expressed as a combination of shear strain range $\Delta\gamma$ and normal strain range to a plane $\Delta\varepsilon_n$:

$$max\left(\frac{\Delta\gamma}{2} + S\Delta\varepsilon_n\right) \quad (3)$$

where S is a constant. The respective fatigue life is given by the expression:

$$max\left(\frac{\Delta\gamma}{2} + S\Delta\varepsilon_n\right) = A\frac{\sigma_f'}{E}(2N_f)^b + B\varepsilon_f'(2N_f)^c \quad (4)$$

$$\begin{cases} A = 1.3 + 0.7S \\ B = 1.5 + 0.5S \end{cases} \quad (5)$$

The constant S can be determined using the equation below doing $N_f \rightarrow \infty$ and $\upsilon_e = \upsilon_p = \upsilon$:

$$S = \frac{\frac{\tau_f{}'}{G}\left(2N_f\right)^{b\gamma} + \gamma_f'\left(2N_f\right)^{c\gamma} - (1+\upsilon_e)\frac{\sigma_f'}{E}\left(2N_f\right)^{b} - \left(1+\upsilon_p\right)\varepsilon_f'\left(2N_f\right)^{c}}{(1+\upsilon_e)\frac{\sigma_f'}{E}\left(2N_f\right)^{b} + \left(1+\upsilon_p\right)\varepsilon_f'\left(2N_f\right)^{c}} \quad (6)$$

Fatemi & Socie

The Fatemi & Socie damage parameter is based on the Brown & Miller parameter but it counts the resistive effects of the irregular surface of the crack. The damage parameter can be expressed by:

$$max\left[\frac{\Delta\gamma}{2}\left(1 + k\frac{\sigma_{n,max}}{\sigma_{yield}}\right)\right] \quad (7)$$

Fatigue life is calculated using:

$$\frac{\Delta\gamma}{2}\left(1 + k\frac{\sigma_{n,max}}{\sigma_{yield}}\right) = \frac{\tau_f'}{G}\left(2N_f\right)^{b\gamma} + \gamma_f'\left(2N_f\right)^{c\gamma} \quad (8)$$

Where the constant k is determined using the equation 9 doing $N_f = 1000$:

$$k = \left[\frac{\frac{\tau_f{}'}{G}\left(2N_f\right)^{b\gamma} + \gamma_f'\left(2N_f\right)^{c\gamma}}{1.3\frac{\sigma_f'}{E}\left(2N_f\right)^{b} + 1.5\varepsilon_f'\left(2N_f\right)^{c}} - 1\right]\frac{K'(0.002)^{n'}}{\sigma_f'\left(2N_f\right)^{b}} \quad (9)$$

Smith-Watson-Topper

The Smith-Watson-Topper or SWT model is built for materials which the crack grows on planes of maximum tensile strain or stress. The damage parameter is based on the range of principal normal strain $\Delta\varepsilon_1$:

$$max\left(\sigma_n\frac{\Delta\varepsilon_1}{2}\right) \quad (10)$$

The respective fatigue life can be calculated using:

$$\sigma_{n,max}\frac{\Delta\varepsilon_1}{2} = \frac{\sigma_f'^2}{E}\left(2N_f\right)^{2b} + \sigma_f'\varepsilon_f'\left(2N_f\right)^{b+c} \quad (11)$$

Liu I & II

Liu built 2 damage parameters for combined critical plane and energy models. He made Liu I for tensile failure and Liu II for shear failure. The Liu I damage parameter can be expressed as:

$$max(\Delta\sigma_n\Delta\varepsilon_n) + \Delta\tau\Delta\gamma \quad (12)$$

The respective fatigue life is given by:

$$4\sigma_f'\varepsilon_f'\left(2N_f\right)^{b+c} + \frac{4\sigma_f'^2}{E}\left(2N_f\right)^{2b} = max(\Delta\sigma_n\Delta\varepsilon_n) + \Delta\tau\Delta\gamma \quad (13)$$

For Liu II or shear failure, the damage parameter is given by:

$$max(\Delta\tau\Delta\gamma) + \Delta\sigma_n\Delta\varepsilon_n \quad (14)$$

The respective fatigue life is calculated using:

$$4\tau_f'\gamma_f'\left(2N_f\right)^{b\gamma+c\gamma} + \frac{\left(4\tau_f'\right)^2}{G}\left(2N_f\right)^{2b\gamma} = max(\Delta\tau\Delta\gamma) + \Delta\sigma_n\Delta\varepsilon_n \quad (15)$$

Material & Software Analysis

ANSYS

To do the ANSYS simulations the data presented at table 1 are used. The monotonic material properties are based on reference [8] except the Young modulus. The Young modulus and density are obtained from Efunda Website [9] for the AZ31B-F magnesium alloy. The real stress vs real strain curve is determined using the nominal stress vs nominal strain curve of reference [8]. This curve is presented in figure 1.

Yield Strenght (Mpa)	Young´s Modulus (GPa)	Poisson Coefficient	Density (Kg/m^3)
201	44.8	0.15	1770

Table 1 – Material properties for ANSYS simulation

The considered geometric model is a typical specimen used for multiaxial loadings experiments in combined axial and torsion loading. The specimen is presented in figure 2. The element used to build the specimen is the Solid 186 of quadratic displacement behavior. A mesh of 8424 elements is used. The boundary conditions are applied at the bottom and at the top surface of the specimen. At the bottom surface all the displacements are made equal to zero. At the top surface the axial and shear loadings are applied as pressures.

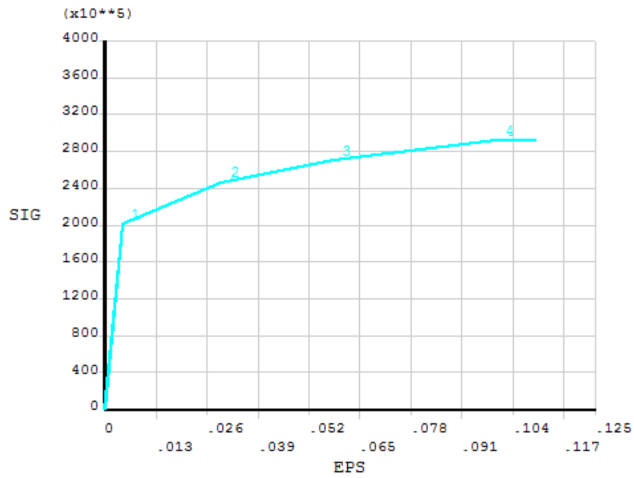

Figure 1 – Real stress vs strain curves for ANSYS simulation

Figure 3 illustrates the boundary conditions. The blue zone is the bottom, and the top is the opposite. Loads results are observed at node 3800 in the middle section of the specimen.

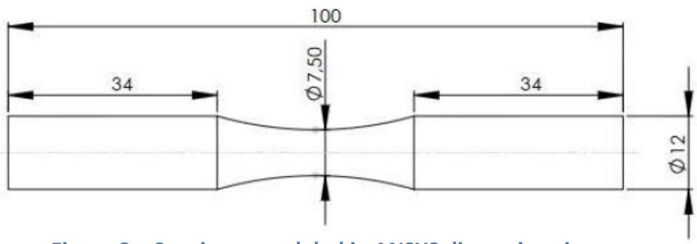

Figure 2 – Specimen modeled in ANSYS dimensions in mm

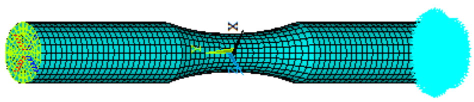

Figure 3 – Specimen modeled in ANSYS

Plasticity Program

The plasticity program has programmed the Jiang & Sehitoglu plasticity model adapted to nonproportional effects. The material properties used to simulate are presented in table 2. They are based on reference [8] data.

Description	Value
Young modulus (MPa)	44800
Proportional cyclic strength coefficient (MPa)	1976
Proportional cyclic hardening exponent	0.34
90 º Nonproportional cyclic strength coefficient (MPa)	2173.6
90 º Nonproportional cyclic hardening exponent	0.34
Poisson Coefficient	0.35
Shear modulus (MPa)	16592.5

Table 2 – Material properties for Plasticity program simulation

Load Cases and Stresses Results

The simulated loads are presented in table 3. The maximum von Mises applied stress is 204 MPa for both ANSYS and Plasticity program. However 1 MPa is considered to illustrate load paths. Only part of the stresses results of the loading cases 2 and 4 are presented in the next two pages.

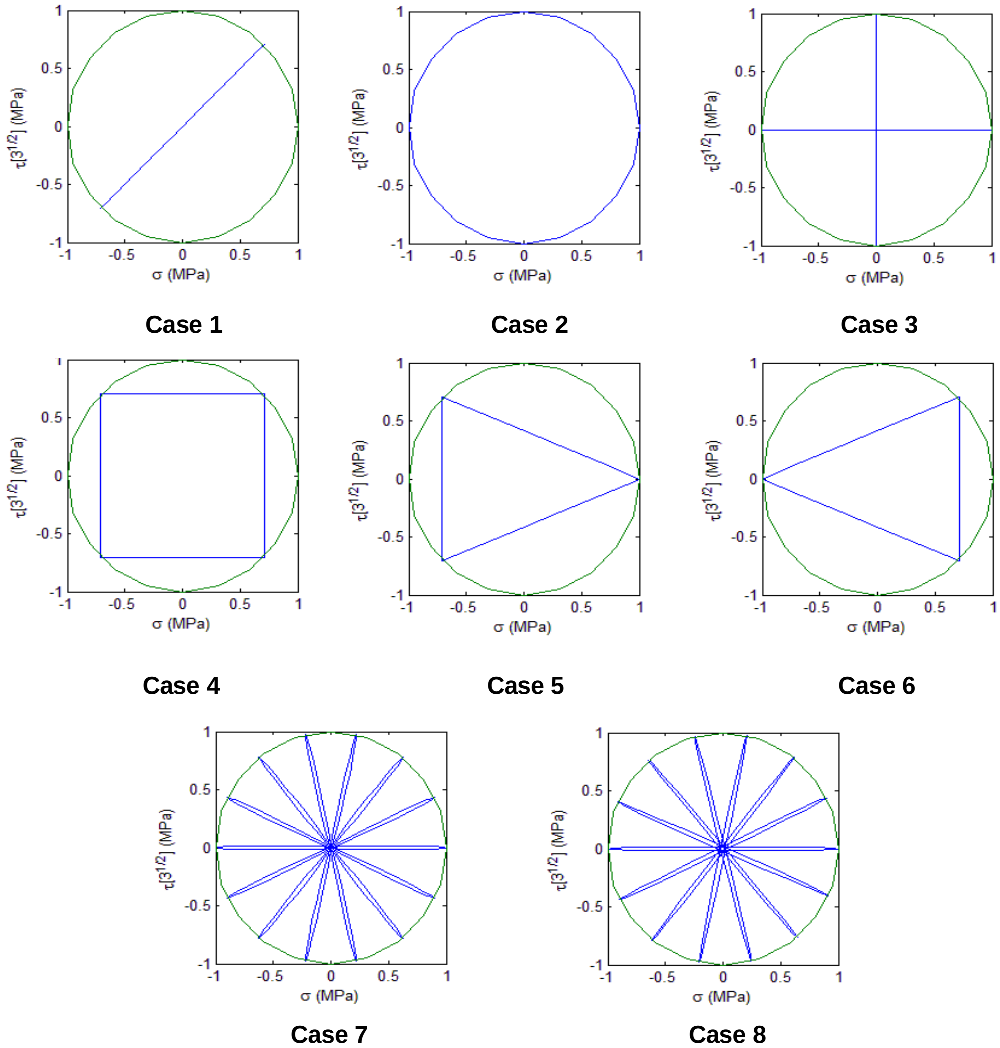

Table 3 – Stress controlled loadings in the $\sqrt{3} * \tau$ vs σ plane

In figures 4 and 5 the letters a), c) and e) correspond to ANSYS results. The letters b), d) and f) correspond to Plasticity program results.

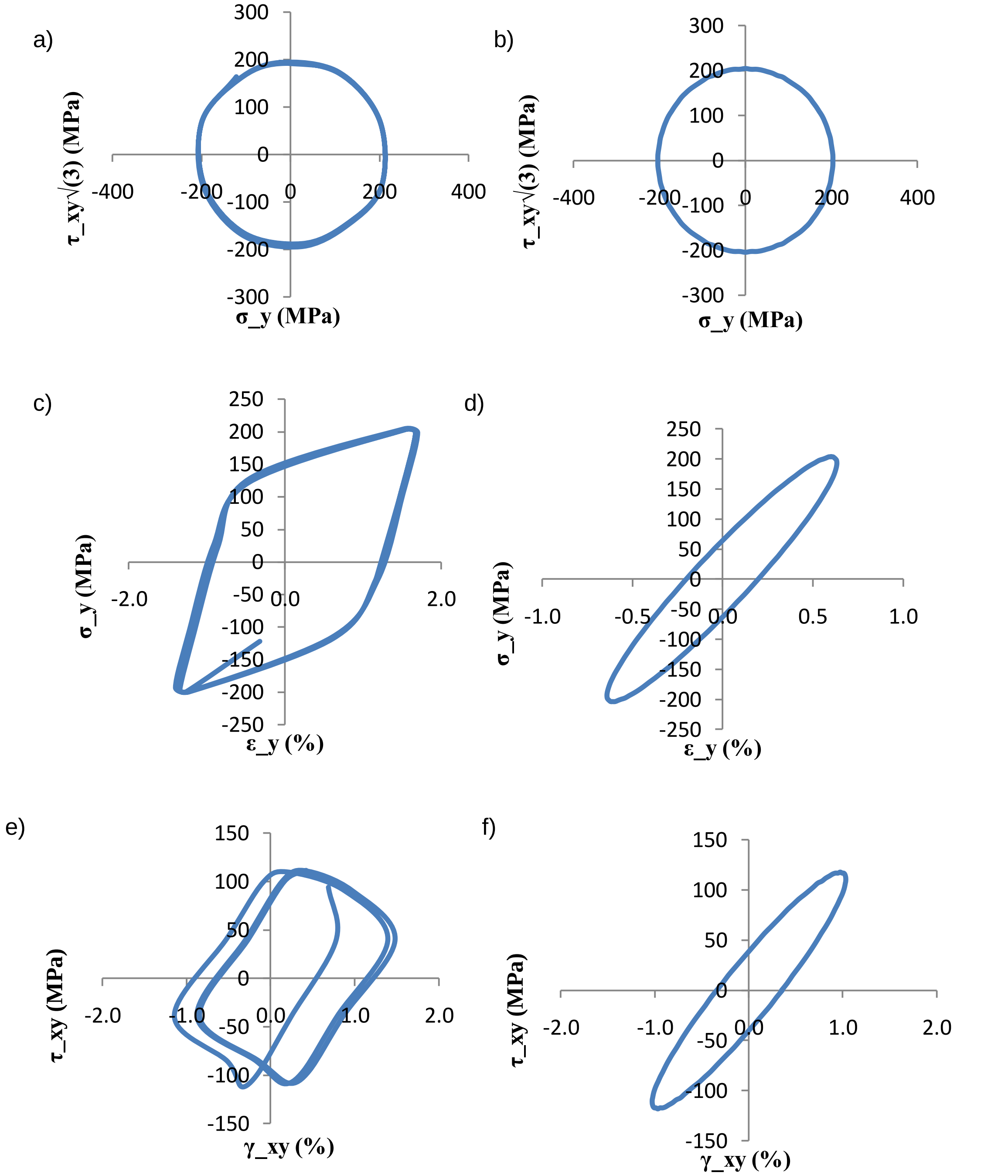

Figure 4 – Case 2 results: a) & b) shear stress*$\sqrt{3}$ vs axial stress, c) & d) axial stress vs axial strain, e) & f) shear stress vs shear strain

In figure 4 it can be observed that for the same loading path the material shows different hysteresis loops behavior. The work of the hysteresis loops of the ANSYS simulation is greater than the Plasticity program simulations.

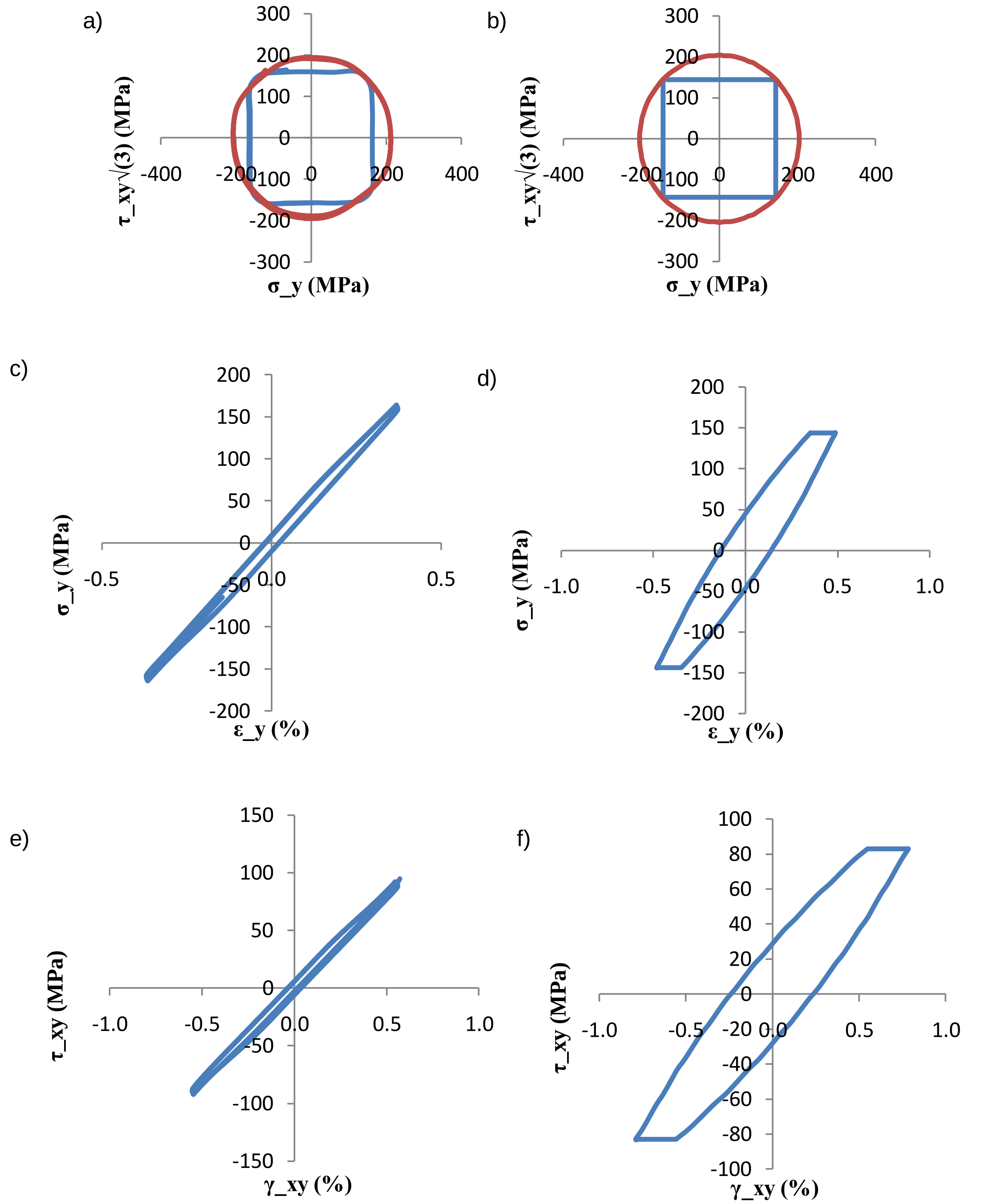

Figure 5 – Case 4 results: a) & b) shear stress*$\sqrt{3}$ vs axial stress, c) & d) axial stress vs axial strain, e) & f) shear stress vs shear strain

In figure 5 it can be seen that the hysteresis loops of ANSYS simulation do less work than Plasticity program simulations.

Fatigue Life Results

The damage parameters are calculated for each of the loading cases. The life cycles number results based on them are presented in table 4.

Fatigue Life	Findley	Brown & Miller	Fatemi & Socie	SWT	Liu I	Liu II	Minimum
Case 1	1332	1366	2084	2171	2171	2134	1332
Case 2	365	345	771	1370	1370	1439	345
Case 3	365	345	771	1370	1370	1439	345
Case 4	613	468	1215	2171	2171	2134	468
Case 5	1564	964	2869	1940	2440	4706	964
Case 6	1257	964	2473	2702	2440	4706	964
Case 7	383	358	804	1370	1370	1493	358
Case 8	383	358	804	1370	1370	1493	358

Table 4 – Fatigue life results

The case 2 is the case that has the minimum fatigue life. The case that has maximum fatigue life is not constant but changes between cases 1, 5 and 6.

Observing the life time results it can be noted that for cases 2 and 3 the life time is the same for all the damage parameters. This is caused because damage parameters don't count the time a loading is above yield value. To quantify this effect a expression of the type 16 should be investigated:

$$\frac{\overline{\tau_{von\ Mises}}}{\tau_{von\ Mises\ at\ yield}} \quad (16)$$

This von Mises expression change along the various planes as can be observed in figures 6 and 7.

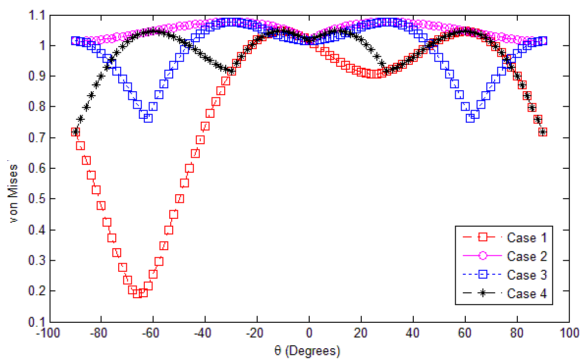

Figure 6 – von Mises expression for loading cases 1 to 4

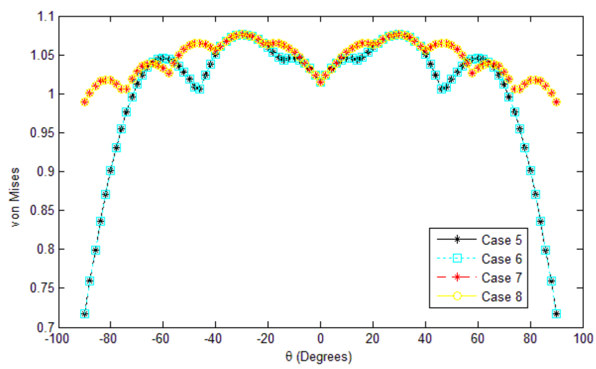

Figure 7 – von Mises expression for cases 5 to 8

However this von Mises expression 16 doesn't count nonproportional effects as the damage parameters. A simple method to insert this expression in the damage parameters is multiplying the damage parameters defined by the expression 16. The fatigue life results obtained are presented in table 5.

Fatigue Life	Findley	Brown & Miller	Fatemi & Socie	SWT	Liu I	Liu II	Minimum
Case 1	1023	1080	1714	2910	2910	2002	1023
Case 2	284	285	646	1235	1235	1324	284
Case 3	331	321	715	1311	1311	1378	321
Case 4	521	419	1074	2167	2167	2002	419
Case 5	961	664	1934	1708	2134	3780	664
Case 6	770	664	1678	2289	2134	3780	664
Case 7	292	294	656	1288	1288	1334	292
Case 8	292	294	656	1288	1288	1334	292

Table 5 – Fatigue life results for new damage parameters

As it can be seen in table 5, case 3 and case 2 loadings have always different fatigue lives. The minimum fatigue life has decreased.

Conclusion

The fatigue life theoretical results show that the new damage parameters differentiate the loading paths better. To determine how accurate they are, multiaxial fatigue experiments are needed to be done.

For the stresses results it is observed that for nonproportional loadings the material behavior results for ANSYS and Plasticity program are different. A method to include nonproportionality effects on ANSYS should be searched. Comparison of experimental results and the obtained data should be done.

The plastic work observed for case 2 in ANSYS simulation results is higher than Plasticity program results. The opposite happens for case 4. The reason why this happens should be investigated with experiments.

References

[1] B. L. Mordike, T. Ebert. Magnesium Properties – applications – potential. Material Science and Engineering 2001; A302, p. 37-45

[2] Internet Website Tagnite. http://www.tagnite.com/tagnite_coating/, 2010/09/01

[3] Sp. G. Pantelakis, N. D. Alexopoulos, A. N. Chamos. Mechanical Performance Evaluation of Cast Magnesium Alloys for Automotive and Aeronautical Applications. Journal of Engineering Materials and Technology 2007; Vol.129, p. 422-430

[4] Internet Website MagForming. http://www.palbam.co.il/magforming/magforming_objectives.htm, 2010/09/01

[5] Internet Website MagForge. http://www.magforge.eu/, 2010/09/01

[6] United States Automotive Materials Partnership. Magnesium Vision 2020, 2006

[7] D. F. Socie, G. B. Marquis. Multiaxial Fatigue. SAE International, 2001

[8] S. Begum et al. . Low cycle fatigue properties of an extruded AZ31 magnesium alloy. International Journal of Fatigue 2009; Vol. 31, p. 726-735