

Study on the Bauschinger Effect of Extruded Magnesium AZ31B During the Low-Cycle Fatigue Test of a Bone Implant Material Candidate

Original scientific paper

UDC:669.721.5:620.178.3
<https://doi.org/10.46793/adeletters.2026.5.3.2>

Irza Sukmana¹, Ahmad Yudi E. Risano¹, Mohammad Badaruddin¹, Zulhanif¹, Tarkono¹, Fauzi Ibrahim^{2*}

¹Department of Mechanical Engineering, Faculty of Engineering, Universitas Lampung, Indonesia

²Department of Automotive Engineering Technology, Politeknik Negeri Lampung, Indonesia

Abstract:

This study on the Bauschinger effect of extruded magnesium AZ31B during low-cycle fatigue (LCF) addresses the limited quantification of cyclic plasticity and tension–compression asymmetry in biodegradable Mg alloys for temporary orthopaedic fixation. Fully reversed ($R\epsilon = -1$), strain-controlled LCF tests were conducted at strain amplitudes of 0.006, 0.008, and 0.010 mm/mm ($n = 3$ per level) to characterize the Bauschinger response through stress-, strain-, and backstress-based indices. The Bauschinger effect factor decreased monotonically from 0.984 to 0.947, the normalized Bauschinger strain ratio fell from 0.843 to 0.680, and the backstress indicator rose more than threefold, from 0.93 to 3.18 MPa, with increasing strain amplitude. SEM fractography confirmed this trend, showing a transition from rough, serrated ridges at 0.006 mm/mm to facet-dominated, heavily torn surfaces at 0.010 mm/mm, consistent with intensifying slip–twinning heterogeneity and grain-boundary strain incompatibility underlying the Bauschinger effect. An empirical strain-life relation achieved a leave-one-out MAPE of 7.24%, closely matching the Coffin–Manson–Basquin fit (in-sample MAPE = 1.45%). Together, these results quantify how the Bauschinger effect in extruded AZ31B intensifies with strain amplitude and link this behaviour to fatigue-life prediction, offering a mechanistic basis for LCF-based screening of Mg-alloy implant candidates.

ARTICLE HISTORY

Received: 19 July 2026

Revised: 27 August 2026

Accepted: 9 September 2026

Published: 30 September 2026

KEYWORDS

Mg AZ31B, Low-cycle fatigue, Bauschinger effect, Kinematic hardening, Strain-life model

1. INTRODUCTION

Magnesium (Mg) alloys are promising candidates for temporary orthopaedic fixation because their density and elastic modulus are closer to those of cortical bone than those of conventional metallic implant materials, and because they can gradually degrade after temporary mechanical support is no longer required [1]. It possesses advantageous biodegradability, typically consisting of Al (2.71%), Zn (0.69%), Mn (0.32%), Fe (0.002%), Si (0.18%), Cu (0.001%), Ni (0.001%), and Ca (0.001%) [1, 2]. This remarkable property positions Mg as a promising alternative to conventional human bone screws, as biomaterial implants have the exceptional ability to fully degrade without the

need for external factors [3, 4]. The cost and associated risks of manufacturing traditional bone screws highlight the need for biodegradable alternatives [5, 6]. To ensure the suitability of Mg material for conventional bone conditions, extensive research and testing are essential to evaluate claims regarding hardness, tensile strength, and fatigue properties [7, 8].

Implants are used to correct deformations caused by diseases or accidents in human bones [9, 10]. However, significant plastic deformation occurs when the material's endurance against sustained pressure is exceeded, leading to fatigue and eventual failure of the biomaterial [11, 12]. Fatigue, a type of material failure, manifests in structures subjected to dynamic loads that exhibit fluctuations

*CONTACT: Fauzi Ibrahim, e-mail: fauziibrahim@polinela.ac.id

[13, 14]. Several previous studies have explored the low-cycle fatigue characteristics of extruded Mg-AZ31B alloys for bone implant applications [15, 16].

Low-cycle fatigue (LCF) is particularly relevant when local implant regions undergo repeated plastic strain. Previous investigations of wrought AZ31 alloys have identified cyclic softening, cyclic hardening, and asymmetric hysteresis; however, quantitative assessment of the Bauschinger effect together with strain-life modelling remains limited [17–19]. The present study therefore examines extruded AZ31B under fully reversed strain control at total strain amplitudes of 0.006–0.010 mm/mm. The study is designed as a controlled material-screening investigation and does not reproduce the complete physiological environment of an implanted device.

The objectives of this study are to: (i) quantify the Bauschinger effect during fully reversed LCF using stress- and strain-based indices; (ii) estimate a macroscopic backstress indicator from forward and reverse yield stresses; (iii) calibrate empirical and Coffin-Manson-Basquin strain-life relations from the mean half-life data; (iv) assess the empirical relation by leave-one-out cross-validation; and (v) define the limitations associated with the restricted strain-amplitude range, the absence of replicate-level dispersion data, laboratory-air testing, and the absence of direct electron backscatter diffraction evidence.

2. MATERIALS AND METHODS

2.1 Materials and specimens

The investigated material was a cold-extruded AZ31B magnesium alloy with the chemical composition listed in Table 1. Cylindrical stock with an initial diameter of 16 mm and a length of 130 mm was machined into tensile and fatigue specimens. Tensile specimens Mg1T–Mg3T were prepared in accordance with standard ASTM B557/B557M.

Table 1. Chemical composition of Mg AZ31B (wt.%)

Al	Zn	Mn	Fe	Si
2.71	0.69	0.32	0.002	0.18
Sn	Cu	Ni	Ca	Mg
<0.001	<0.001	<0.002	<0.001	Bal.

Fatigue specimen groups Mg8, Mg10, and Mg12 were prepared in accordance with standard ASTM E606/E606M and corresponded to total strain

amplitudes of 0.006, 0.008, and 0.010 mm/mm, respectively, as shown in Fig. 1. The longitudinal specimen axis was parallel to the extrusion direction. Three tensile specimens and three independently machined fatigue specimens per strain amplitude were tested; thus, the LCF program comprised nine tests.

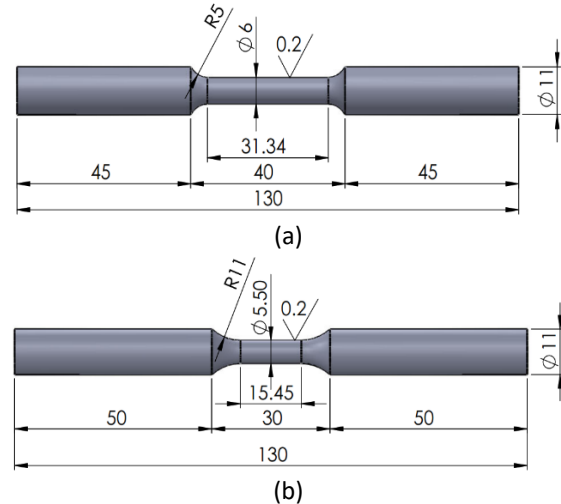


Fig. 1. Specimen shape and size: (a) tensile test and (b) low-cycle fatigue test (dimensions in mm)

2.2 Tensile and LCF tests

The experimental program comprised monotonic tensile testing, fully reversed strain-controlled LCF testing, optical metallography, and scanning electron microscopy (SEM) of selected fracture surfaces. Mechanical tests were performed using an MTS Landmark servo-hydraulic test system with a 100 kN load capacity and MTS Multipurpose Elite control software. An MTS axial extensometer with a 10 mm gauge length (model 632.13F-20) was attached to the specimen gauge section. Tensile tests were conducted at a crosshead speed of 0.15 mm/min. LCF tests were performed in laboratory air under a strain ratio $R\epsilon = \epsilon_{min}/\epsilon_{max} = -1$ at total strain amplitudes of 0.006, 0.008, and 0.010 mm/mm (dimensionless strain). The imposed strain rate was 0.00627 s^{-1} ; the corresponding frequencies are given in Table 3. Gauge surfaces were machined to an arithmetic mean roughness $Ra < 0.2 \text{ μm}$.

Elastic strain amplitude, plastic strain amplitude, stress amplitude, and elastic modulus were evaluated at half-life ($0.5N_f$), and fatigue life N_f was defined as the number of cycles to specimen fracture. Three independent specimens were tested at each strain amplitude. The values reported in Tables 2-6 and the summarized cyclic responses are arithmetic means of these replicate tests. The

processed dataset available for this revision contains the mean values but not the individual replicate values; therefore, standard deviations, confidence intervals, and error bars cannot be reconstructed without the original replicate records.

2.3 Fracture Analysis

Metallographic specimens were etched using an HNO₃-alcohol solution and examined with a Carl Zeiss Axio Vert A1 Mat optical microscope. Fracture surfaces were examined using a Zeiss EVO MA10 SEM in secondary-electron imaging mode. Electron backscatter diffraction (EBSD) and transmission electron microscopy were not performed; consequently, interpretations involving twinning, detwinning, dislocation accumulation, and grain orientation are based on the measured cyclic response and published mechanisms rather than direct orientation-resolved evidence [20, 21].

The test matrix used three strain-amplitude levels to capture the transition from lower to higher plastic-strain response while maintaining a feasible material and machine-time requirement. Triplicate testing at each level provides repeat observations and reduces reliance on a single specimen; however, three replicates and three amplitude levels remain insufficient for robust probabilistic fatigue-life modelling. Future work should preserve the individual replicate datasets and report standard deviation, confidence intervals, and error bars at each strain amplitude.

2.4 Analytical Framework and Predictive Models

The mean half-life ($0.5N_f$) elastic and plastic strain amplitudes were used to identify cyclic parameters and construct strain-life relations. Cyclic softening and hardening were quantified using Eqs. (1) and (2). Stress amplitude was estimated from elastic strain amplitude using Eq. (3), and the stabilized cyclic stress-strain response was represented by the Ramberg-Osgood relation in Eq. (4). The empirical total strain-life relation in Eq. (5) was fitted by ordinary least squares in logarithmic coordinates.

Its predictive stability within the measured range was examined by leave-one-out cross-validation (LOOCV), in which each mean point was predicted using a relation fitted to the other two mean points. For comparison with an established strain-life formulation, the elastic and plastic strain components were fitted separately using the Coffin-

Manson-Basquin (CMB) relation in Eq. (6). The backstress indicator in Eq. (7) was calculated from the forward maximum stress and the magnitude of the reverse yield stress.

The cycle softening ratio S is:

$$S = 1 - \frac{\sigma_{peakN_{f/2}}}{\sigma_{peakN=1}}. \quad (1)$$

Cycle hardening ratio H is:

$$H = \frac{\sigma_{peakN_{f/2}}}{\sigma_{peakN=1}} - 1. \quad (2)$$

The stress amplitude at half-life σ_a (MPa) was estimated from the elastic strain amplitude using Hooke's law:

$$\sigma_a = E\varepsilon_{e,a}. \quad (3)$$

The total strain amplitude ε_a in the stabilized cyclic stress-strain response was described using the Ramberg-Osgood form for stabilized cycling:

$$\varepsilon_a = \varepsilon_{e,a} + \varepsilon_{p,a} = \frac{\sigma_a}{E} + \left(\frac{\sigma_a}{K'}\right)^{\frac{1}{n'}}. \quad (4)$$

For fatigue-life prediction in the investigated regime, the total strain amplitude ε_a was fitted using an empirical strain-life relation in log-log space:

$$\varepsilon_a = C(2N_f)^m. \quad (5)$$

For comparison with an established strain-life model, the total strain amplitude ε_a was fitted using the Coffin-Manson-Basquin relation, in which the first term represents the elastic component $\varepsilon_{e,a}$ and the second term represents the plastic component $\varepsilon_{p,a}$:

$$\varepsilon_a = \frac{\sigma_{f'}}{E}(2N_f)^b + \varepsilon_{f'}(2N_f)^c. \quad (6)$$

To relate the macroscopic Bauschinger response to kinematic hardening, the backstress indicator X (MPa) was calculated from the forward maximum stress σ_F and the magnitude of the reverse yield stress σ_R after load reversal:

$$X = \frac{\sigma_F - \sigma_R}{2}. \quad (7)$$

In Eqs. (1)–(7), (σ_{peak}) $N=1$ and (σ_{peak}) $N_f/2$ are the first-cycle and half-life peak stresses, respectively; E is Young's modulus (MPa); $\varepsilon_{e,a}$, $\varepsilon_{p,a}$, and ε_a are the elastic, plastic, and total strain amplitudes, respectively; K' is the cyclic strength coefficient (MPa); n' is the cyclic strain-hardening exponent; C and m are empirical total strain-life constants; $\sigma_{f'}$ is the fatigue-strength coefficient (MPa); b is the fatigue-strength exponent; $\varepsilon_{f'}$ is the fatigue-ductility coefficient; c is the fatigue-ductility

exponent; N_f is the number of cycles to fracture; $2N_f$ is the number of reversals to fracture; X is the backstress indicator (MPa); σ_F is the forward maximum stress (MPa); and σ_R is the magnitude of the reverse yield stress (MPa).

3. RESULTS AND DISCUSSION

3.1 Mechanical Properties

Fig. 2 shows the engineering stress-strain response of the three extruded Mg AZ31B specimens in tension. The elastic modulus was calculated using a least-squares fit applied to the initial linear region (approximately the first 20% of

the curve). The yield strength was obtained using the standard 0.2% offset method, and the tensile results are summarized in Table 2.

The mean 0.2% offset yield strength from the three tensile tests was 186.01 ± 2.13 MPa, and the mean ultimate tensile strength was 269.62 ± 0.72 MPa (mean $\pm$ sample standard deviation, $n = 3$). The representative elastic modulus used in the strain-life calculations was 43.72 GPa. Fatigue results were also obtained from three specimens per strain amplitude, but the processed fatigue dataset available for this revision contains only the arithmetic means; therefore, fatigue standard deviations are not reported.

Table 2. Tensile properties and energy parameters of extruded Mg AZ31B

Specimen	Stress (MPa)		Plastic energy (kJ)	Elastic energy (kJ)	Reduction of area (%)	Total elongation (%)
	Yield (0.2%)	Ultimate				
Mg1T*	185.15	270.45	0.0130	0.0070	–	–
Mg2T*	188.44	269.29	0.0120	0.0080	25.38	16.44
Mg3T*	184.45	269.13	0.0133	0.0079	24.23	16.45
STDEV	2.13	0.72	0.00068	0.00055	0.81	0.007

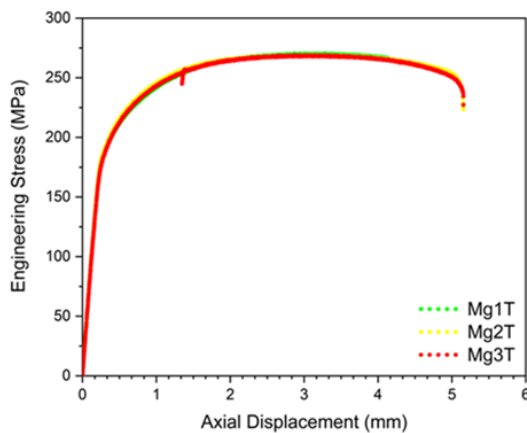


Fig. 2. Engineering stress-strain curves of extruded Mg AZ31B under tension

3.2 Strain-Life and Cyclic Plasticity Parameter Identification

Using the mean half-life elastic strain amplitudes in Table 3 and Eq. (3), the stress amplitude σ_a was estimated for each strain level. The empirical relation in Eq. (5) was calibrated over $2N_f = 624$ –1790 reversals, giving $C = 0.220$ and $m = -0.482$. The stabilized cyclic stress-strain relation in Eq. (4) yielded $K' = 999$ MPa and $n' = 0.252$ by fitting the paired σ_a – $\epsilon_{p,a}$ data, with the plastic strain amplitude calculated as the difference between the total and elastic strain amplitudes. The empirical relation

predicted fatigue lives of 885, 487, and 307 cycles, corresponding to an in-sample mean absolute percentage error (MAPE) of 1.89%. LOOCV predictions were 809, 494, and 288 cycles, with errors of –9.63%, +4.52%, and –7.56%, respectively, and a MAPE of 7.24%. The CMB fit in Eq. (6) gave $\sigma_F = 525.5$ MPa, $b = -0.1214$, $\epsilon_F = 18.37$, and $c = -1.2889$. It predicted 903, 463, and 316 cycles, corresponding to errors of +0.90%, –2.15%, and +1.30% and an in-sample MAPE of 1.45%. This comparison shows that both power-law forms describe the three mean data points within the tested range. Because the CMB relation contains four fitted parameters and was calibrated using the same three mean fatigue results, its small in-sample error does not constitute independent validation. A Morrow mean-stress correction was not applied because stabilized mean-stress histories and replicate-level mean-stress data were not available.

Table 3 lists the mean strain components, test frequency, elastic modulus, and fatigue life for each strain-amplitude group. Table 4 summarizes the mean half-life stress amplitudes and the predictions obtained from the empirical strain-life relation. Table 5 reports the LOOCV predictions and prediction errors for the empirical relation. Table 6 compares the experimental mean fatigue lives with the Coffin–Manson–Basquin predictions.

Table 3. Mean low-cycle fatigue results of extruded AZ31B ($n = 3$ per strain amplitude)

Specimen group	Strain amplitude (mm/mm)	Frequency (Hz)	Plastic strain (mm/mm)	Elastic strain (mm/mm)	Elastic modulus (GPa)	Fracture cycles, N_f
Mg8 ($n = 3$)	0.006	0.2613	0.001166	0.004834	36.76	895
Mg10 ($n = 3$)	0.008	0.1959	0.002753	0.005248	45.68	473
Mg12 ($n = 3$)	0.010	0.1568	0.004510	0.005490	44.80	312

Table 4. Mean half-life stress amplitudes and empirical strain-life predictions ($n = 3$ per strain amplitude)

Strain amplitude, ϵ_a (mm/mm)	Stress amplitude, σ_a (MPa)	Plastic strain, $\epsilon_{p,a}$	N_f (experimental)	N_f (predicted)
0.006	177.7	0.001166	895	885
0.008	239.7	0.002753	473	487
0.010	246.0	0.004510	312	307

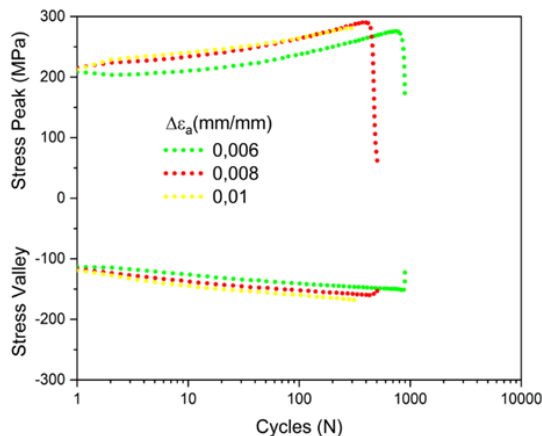
Table 5. Leave-one-out cross-validation of the empirical strain-life relation based on mean fatigue data

Strain amplitude (mm/mm)	N_f experimental	N_f LOOCV predicted	Prediction error (%)
0.006	895	809	-9.63
0.008	473	494	+4.52
0.010	312	288	-7.56

Table 6. Coffin-Manson-Basquin predictions based on mean fatigue data

Strain amplitude (mm/mm)	N_f experimental	N_f CMB predicted	Prediction error (%)
0.006	895	903	+0.90
0.008	473	463	-2.15
0.010	312	316	+1.30

Fig. 3 presents the mean maximum- and minimum-stress evolution with cycle number at the three strain amplitudes. The asymmetric tensile and compressive responses and the initial reduction followed by an increase in stress range support the identification of early cyclic softening and subsequent cyclic hardening.

**Fig. 3.** Maximum and minimum stress-cycle relationships at different strain amplitudes

3.3 Cyclic Stress-Strain Responses

Fig. 4(a–c) shows the evolution of the mean stress-strain hysteresis loops at each imposed strain amplitude. At 0.006 mm/mm, peak stress decreases slightly during the initial cycles and subsequently increases. The same sequence occurs at 0.008 and 0.010 mm/mm, while loop width and plastic strain increase with strain amplitude.

The tensile-compressive asymmetry is consistent with the texture-dependent activation of basal slip and [22, 23] extension twinning in extruded AZ31B. Load reversal may promote detwinning and reactivation of favourably oriented slip systems, thereby reducing the reverse yield stress.

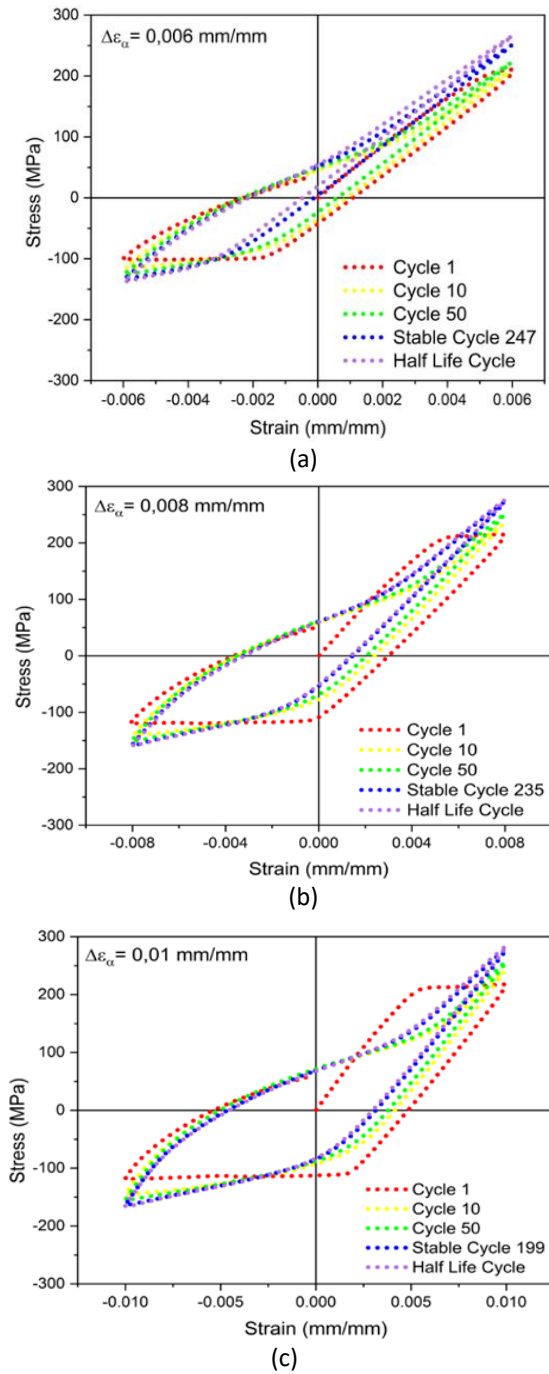


Fig. 4. Hysteresis stress-strain curves at strain amplitudes of (a) 0.006, (b) 0.008, and (c) 0.010 mm/mm

Continued cycling can increase dislocation density and internal backstress. These mechanisms are interpretations supported by the literature; they were not directly resolved in the present specimens because EBSD and transmission electron microscopy were not performed. The mean softening and hardening ratios calculated using Eqs. (1) and (2) are presented in Fig. 5.

Fig. 5 compares the calculated cyclic-softening and cyclic-hardening ratios as a function of total strain amplitude.

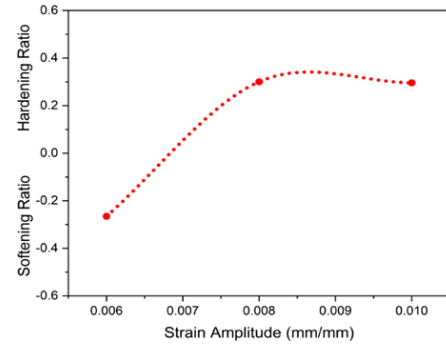


Fig. 5. Softening and hardening ratios of magnesium during the LCF test at a constant strain rate of 0.00627 s⁻¹

At total strain amplitudes of 0.006 and 0.008 mm/mm, the mean cyclic response changes from softening to hardening before fracture. At 0.010 mm/mm, the larger plastic-strain component is accompanied by a stronger increase in peak stress after the initial transient. This response is consistent with competition between reversible twinning/detwinning, which facilitates early reverse deformation, and progressive dislocation accumulation and twin-boundary interactions, which increase resistance to subsequent plastic flow [24–26]. Direct confirmation requires interrupted-cycle or post-fatigue orientation-resolved microscopy.

The wider hysteresis loops at higher strain amplitude indicate greater plastic-energy dissipation per cycle. Twin boundaries and dislocation pile-ups can produce heterogeneous internal stresses and impede slip, thereby contributing to cyclic hardening and the Bauschinger response [27–29]. Prismatic and pyramidal slip may also become increasingly active as plastic strain rises. The present macroscopic measurements do not resolve the relative contributions of these mechanisms.

Fig. 6 defines the forward loading, unloading, reverse yielding, and strain quantities used to calculate the Bauschinger-effect parameters.

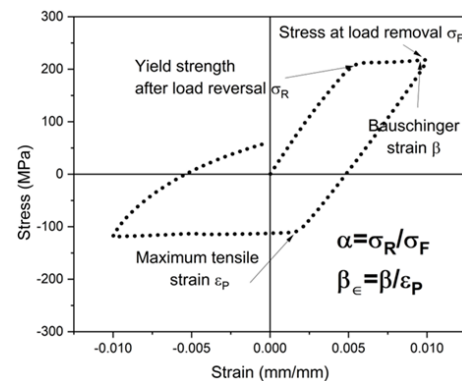


Fig. 6. Stress–strain curve under reverse loading showing backstress

Extruded AZ31B exhibits a measurable Bauschinger response, as indicated by non-linear unloading and a reduced yield stress after load reversal. The Bauschinger effect factor (BEF), defined in Fig. 6, is the ratio of the reverse yield-stress magnitude to the preceding forward maximum stress. A BEF of 1 denotes no reduction in reverse yield strength, whereas $BEF < 1$ indicates a Bauschinger response. The Bauschinger strain β is the additional strain required after reversal to recover the preceding maximum stress, and the normalized Bauschinger strain ratio $\beta\epsilon$ is β divided by the preceding maximum tensile strain [30–35]. These definitions are used for the mean Bauschinger-effect parameters reported in Table 7.

Fig. 7 illustrates the plastic pre-strain and reverse-loading path used to interpret the Bauschinger response.

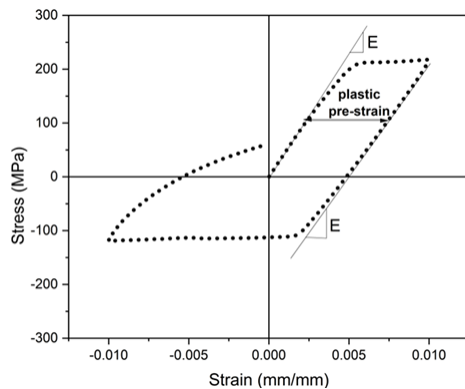


Fig. 7. Bauschinger cycle with plastic pre-strain

Fig. 8 distinguishes non-linear unloading, transient reverse yielding, and the reduction in reverse yield strength that characterizes the Bauschinger effect.

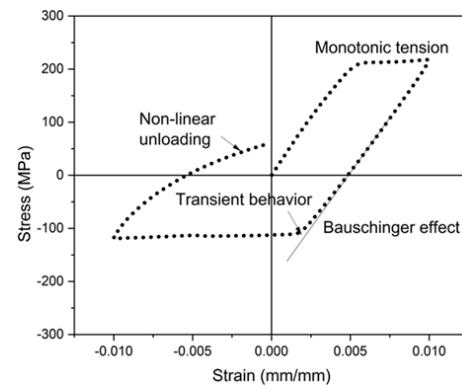


Fig. 8. Illustration of the Bauschinger effect under reverse loading

Table 7 shows that the mean BEF decreases from 0.98379 to 0.94667 as total strain amplitude increases from 0.006 to 0.010 mm/mm. Over the same range, the normalized Bauschinger strain ratio decreases from 0.84344 to 0.68023, whereas the backstress indicator increases from 0.93 to 3.18 MPa. These trends indicate a larger reduction in reverse yield strength and stronger internal-stress development at higher plastic strain. In wrought and other metallic systems, comparable Bauschinger behaviour has been associated with dislocation-slip reversibility, backstress strengthening, heterogeneous or gradient microstructures, and kinematic-hardening evolution [35–44]. The present study quantifies the macroscopic response; orientation-resolved microscopy is required to relate these indices directly to grain reorientation, as illustrated by the SEM observations in Fig. 9 and reported in other studies [45, 46].

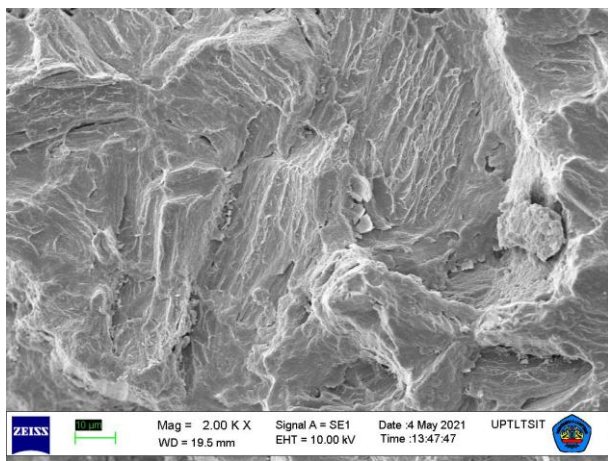
Table 7. Mean Bauschinger-effect parameters ($n = 3$ per strain amplitude)

Strain amplitude (mm/mm)	σ_F (MPa)	σ_R (MPa)	β	ϵ_p	α (BEF)	$\beta\epsilon$
0.006	114.45	112.60	0.00612	0.00726	0.98379	0.84344
0.008	117.28	113.53	0.00804	0.01096	0.96799	0.73289
0.010	118.94	112.59	0.01000	0.01470	0.94667	0.68023

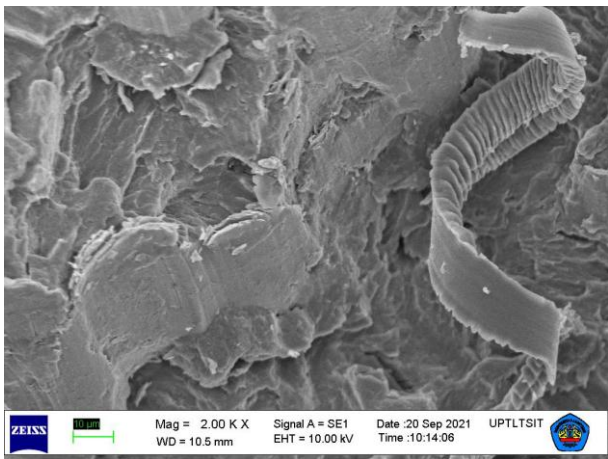
3.4. Fractographic Analysis

SEM fractographs of LCF specimens tested at strain amplitudes of 0.006, 0.008, and 0.01 mm/mm (Fig. 9a–c) consistently exhibit fracture morphologies dominated by tearing ridges, crystallographic facets, and localised plastic deformation, with the intensity of these features

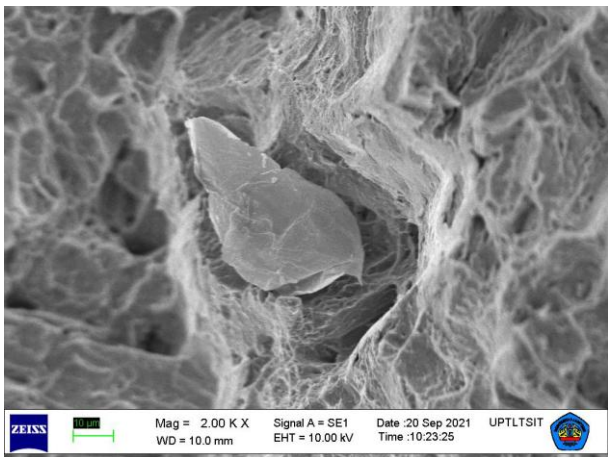
progressively increasing with strain amplitude. The fracture surface evolves from a relatively rough and serrated morphology at 0.006 mm/mm (Fig. 9a), to more widely distributed facets and tearing features at 0.008 mm/mm (Fig. 9b), and ultimately to a pronounced planar central facet surrounded by intensive tearing at 0.01 mm/mm (Fig. 9c).



(a)



(b)



(c)

Fig. 9. SEM images of the LCF specimen tested at different amplitudes (mm/mm): (a) 0.006, (b) 0.008, and (c) 0.010

The fracture's progressive evolution indicates that increasing strain amplitude promotes increasingly heterogeneous activation of crystallographic slip and deformation twinning among differently oriented grains in the Mg AZ31B alloy microstructure [47], thereby intensifying plastic strain incompatibility at grain boundaries. Such incompatibility promotes dislocation

accumulation and interactions with grain boundaries and twin boundaries, leading to the development of internal back stresses.

Furthermore, during load reversal, these internal back stresses facilitate reverse dislocation motion and reduce the resistance to plastic yielding in the opposite direction, providing a microstructural basis for the Bauschinger effect [40]. Accordingly, the increasing prominence of crystallographically controlled deformation features from the lower- to higher-strain-amplitude conditions provides fractographic evidence consistent with enhanced back-stress accumulation and a progressively stronger Bauschinger-type response associated with increasing cyclic plasticity. A direct quantitative correlation between the observed fracture morphology, grain-scale deformation, and the Bauschinger response will be further investigated through EBSD characterization and cyclic stress–strain analysis in a subsequent study.

4. CONCLUSION

This study quantified the Bauschinger effect in extruded Mg AZ31B alloy under fully reversed loading ($R\epsilon = -1$), strain-controlled LCF. During LCF testing, the material exhibited initial cyclic softening followed by cyclic hardening until fracture. As strain amplitude increased from 0.006 to 0.010 mm/mm, the mean Bauschinger Effect Factor decreased from 0.984 to 0.947, and the normalized Bauschinger strain ratio fell from 0.84 to 0.68, while the backstress indicator rose more than threefold, from 0.93 to 3.18 MPa. SEM fractography supported these trends, showing a progressive transition from rough, serrated surfaces at 0.006 mm/mm to facet-dominated, heavily torn surfaces at 0.010 mm/mm, reflecting increasingly heterogeneous slip–twinning activity and grain-boundary strain incompatibility that underlie the observed Bauschinger response.

The empirical strain–life relation, $\epsilon_a = 0.220 \cdot (2N_f)^{0.482}$, achieved a leave-one-out MAPE of 7.24%, indicating adequate predictive capability, though the in-sample Coffin–Manson–Basquin model performed better (MAPE = 1.45%). Collectively, these results establish a quantitative link among backstress evolution, reduced reverse-yield resistance, and strain-amplitude-dependent fracture morphology in extruded AZ31B, offering a mechanistic basis for preliminary screening of Mg-alloy implant candidates. Given the absence of replicate-level dispersion, direct EBSD evidence, and physiological corrosion-fatigue testing, the

findings represent an initial screening benchmark rather than a predictor of in vivo performance; further EBSD-based and corrosion-fatigue studies are needed for validation.

ACKNOWLEDGMENT

The authors gratefully acknowledge the financial support provided by Bantuan Publikasi Ditjen Risbang Kemdiktisaintek 2025 (Fauzi Ibrahim), under Contract No. 0488/C/DT.06.01/2025, and by BLU Unila through the Penelitian Guru Besar research grant scheme 2026 (Irza Sukmana), under Contract No. 1962/UN26.21/PN/2026.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

REFERENCES

- [1] L. Song, G. Duan, C. Han, J. Zhou, H. Liu, Y. Liu, B. Wu, Enhanced low-cycle fatigue life of an extruded AZ31B alloy after pre-ratcheting deformation. *Materialia*, 39, 2025: 102379. <https://doi.org/10.1016/j.mtla.2025.102379>
- [2] I. Sukmana, F. Ibrahim, M. Badaruddin, H. Nur, Low cycle fatigue properties of extruded magnesium AZ31B. *FME Transactions*, 50(3), 2022: 422–432. <https://doi.org/10.5937/fme2203422S>
- [3] P. Rider, Ž. Perić Kačarević, A. Elad, D. Rothamel, G. Sauer, F. Bornert, P. Windisch, D. Hangyási, B. Molnar, B. Hesse, M. Assad, F. Witte, Biodegradation of a magnesium alloy fixation screw used in a guided bone regeneration model in beagle dogs. *Materials*, 15(12), 2022: 4111. <https://doi.org/10.3390/ma15124111>
- [4] S. Söntgen, L. Keilig, K. Kabir, A. Weber, S. Reimann, K. Welle, C. Bourauel, Mechanical and numerical investigations of biodegradable magnesium alloy screws for fracture treatment. *Journal of Biomedical Materials Research Part B: Applied Biomaterials*, 111(1), 2022: 7–15. <https://doi.org/10.1002/jbm.b.35127>
- [5] Y. Luo, F. Liu, Z. Chen, Y. Luo, W. Li, J. Wang, A magnesium screw with optimized geometry exhibits improved corrosion resistance and favors bone fracture healing. *Acta Biomaterialia*, 178, 2024: 320–329. <https://doi.org/10.1016/j.actbio.2024.03.002>
- [6] J. Sun, Z. Li, S. Liu, T. Xia, J. Shen, Biodegradable magnesium screw, titanium screw and direct embedding fixation in pedicled vascularized iliac bone graft transfer for osteonecrosis of the femoral head: a randomized controlled study. *Journal of Orthopaedic Surgery and Research*, 18(1), 2023: 523. <https://doi.org/10.1186/s13018-023-04012-z>
- [7] Ž. Perić Kačarević, P. Rider, A. Elad, D. Tadic, D. Rothamel, G. Sauer, F. Bornert, P. Windisch, D. B. Hangyási, B. Molnar, T. Kämmerer, B. Hesse, E. Bortel, M. Bartosch, F. Witte, Biodegradable magnesium fixation screw for barrier membranes used in guided bone regeneration. *Bioactive Materials*, 14, 2022: 15–30. <https://doi.org/10.1016/j.bioactmat.2021.10.036>
- [8] M. Nasr Azadani, A. Zahedi, O.K. Bowoto, B.I. Oladapo, A review of current challenges and prospects of magnesium and its alloy for bone implant applications. *Progress in Biomaterials*, 11(1), 2022: 1–26. <https://doi.org/10.1007/s40204-022-00182-x>
- [9] Y. Zhou, A. Zhang, J. Wu, S. Guo, Q. Sun, Application and perspectives: Magnesium materials in bone regeneration. *ACS Biomaterials Science & Engineering*, 10(6), 2024: 3514–3527. <https://doi.org/10.1021/acsbiomaterials.3c01713>
- [10] Y. Gao, H. Huang, X. Jiang, T. Ha, Y. Li, K. Zhang, C. Wang, L. Wang, Y. Fan, Effect of mechanical loading on osseointegration combined with degradation behavior of magnesium bone screw in vivo. *Applied Materials Today*, 32, 2023: 101793. <https://doi.org/10.1016/j.apmt.2023.101793>
- [11] M. Ye, Y.K. Wu, Y.F. Lv, C. Xin, Q. Wang, Variation of low-cycle fatigue life in TA5 alloy as a function of different cyclic deformation mechanisms. *Journal of Materials Engineering and Performance*, 35, 2026: 6757–6767. <https://doi.org/10.1007/s11665-025-12043-2>
- [12] G. Liu, J. Han, Y. Li, Y. Guo, X. Yu, S. Yuan, Z. Nie, C. Tan, C. Guo, Effects of inorganic ions, organic particles, blood cells, and cyclic loading on in vitro corrosion of Mg–Al alloys. *Journal of Magnesium and Alloys*, 11(7), 2023: 2429–2441. <https://doi.org/10.1016/j.jma.2021.08.034>
- [13] H.-G. Nguyen, S.-J. Young, T.-D. Le, T.-N. Vu, T.-H. Fang, Bauschinger effect on high-entropy alloy under cyclic deformation. *Intermetallics*, 183, 2025: 108830. <https://doi.org/10.1016/j.intermet.2025.108830>

- [14] J. Chen, X. Xiao, S. Xiong, J. Wang, H. Huang, B. Yang, Low cycle fatigue behavior of Cu-Cr-Zr alloy with different cold deformation. *Fatigue & Fracture of Engineering Materials & Structures*, 46(1), 2023: 3–16.
<https://doi.org/10.1111/ffe.13842>
- [15] W. Wang, C. Fang, Y. Ji, Y. Lu, M. C. H. Yam, Experimental and numerical studies on Fe–Mn–Si alloy dampers for enhanced low-cycle fatigue resistance. *Journal of Structural Engineering*, 148(11), 2022: 04022170.
[https://doi.org/10.1061/\(ASCE\)ST.1943-541X.0003459](https://doi.org/10.1061/(ASCE)ST.1943-541X.0003459)
- [16] M.A. Bakkar, R. Saha, D. Das, Low-cycle fatigue performance and failure analysis of reinforcing bar. *Metals and Materials International*, 27(12), 2021: 4952–4966.
<https://doi.org/10.1007/s12540-020-00839-x>
- [17] X. Chen, J. Yue, X. Wu, J. Lei, X. Fang, A damage-coupled elasto-plastic constitutive model of marine high-strength steels under low-cycle fatigue loading. *International Journal of Pressure Vessels and Piping*, 205, 2023: 104982.
<https://doi.org/10.1016/j.ijpvp.2023.104982>
- [18] Z. Wang, S. Wu, Y. Lei, Q. Kan, G. Kang, Damage evolution of extruded magnesium alloy from deformation twinning and dislocation slipping in uniaxial stress-controlled low cycle fatigue. *International Journal of Fatigue*, 164, 2022: 107124.
<https://doi.org/10.1016/j.ijfatigue.2022.107124>
- [19] C.-H. Li, Z. Vidmar, B. Saxey, M. Reynolds, C.-M. Uang, A procedure for assessing low-cycle fatigue life of buckling-restrained braces. *Journal of Structural Engineering*, 148(2), 2022: 04021259.
[https://doi.org/10.1061/\(ASCE\)ST.1943-541X.0003237](https://doi.org/10.1061/(ASCE)ST.1943-541X.0003237)
- [20] A. Mandal, K.D. Sharma, S. Bagui, K. Barat, S. Patra, A. Karmakar, Tempering-microstructure reciprocity on low-cycle fatigue properties of Cu-modified quenched-and-tempered steel. *Materials Science and Engineering: A*, 950, 2026: 149474.
<https://doi.org/10.1016/j.msea.2025.149474>
- [21] H. Ban, X. Yang, L. Hai, Y. Shi, Low-cycle fatigue behaviour and fracture feature of stainless-clad bimetallic steel. *Journal of Constructional Steel Research*, 196, 2022: 107437.
<https://doi.org/10.1016/j.jcsr.2022.107437>
- [22] M. Li, S. Maskill, Z. Wen, Z. Yue, W. Sun, A miniaturized thin-plate low-cycle fatigue test method at elevated temperature. *Fatigue & Fracture of Engineering Materials & Structures*, 45(5), 2022: 1361–1378.
<https://doi.org/10.1111/ffe.13665>
- [23] L. Pagliari, R. Gerosa, D. Panzeri, F. Concli, High- and low-cycle fatigue of a 6060 aluminium alloy. *WIT Transactions on the Built Environment*, 216, 2025: 37–49.
<https://doi.org/10.2495/HPSM250041>
- [24] Z. Lyu, C. Liu, D. Xie, R. Feng, D. Yu, Y. Chen, K. An, Y. Gao, H. Wang, P.K. Liaw, Low cycle fatigue performances of Al_{0.3}CoCrFeNi high entropy alloys: In situ neutron diffraction studies on the precipitation effects. *Intermetallics*, 168, 2024: 108241.
<https://doi.org/10.1016/j.intermet.2024.108241>
- [25] Y. Gao, G. Shi, X. Wang, Mechanical properties of low-yield-point steels subjected to low-cycle structural damage. *Journal of Constructional Steel Research*, 183, 2021: 106733.
<https://doi.org/10.1016/j.jcsr.2021.106733>
- [26] H. Alwahsh, S. Salawdeh, Y. Jiang, J. Goggins, Extremely low-cycle fatigue testing of structural carbon steel for a novel self-centring system. In: *Civil Engineering Research in Ireland conference 2024 (CERI2024)*, 29-30 August 2024, Galway, Ireland, pp.500-505.
<https://doi.org/10.13025/29497>
- [27] Z. Zeng, G. Li, S.-W. Liu, D.-H. Huang, Y.-P. Liu, S.-L. Chan, Low-cycle fatigue of laser-arc hybrid-welded S960 high-strength steel joints. *Journal of Constructional Steel Research*, 236, 2026: 110040.
<https://doi.org/10.1016/j.jcsr.2025.110040>
- [28] C. Bai, L. Lan, R. Xin, S. Gao, B. He, Microstructure evolution and cyclic deformation behavior of Ti-6Al-4V alloy fabricated by electron-beam melting during low-cycle fatigue. *International Journal of Fatigue*, 159, 2022: 106784.
<https://doi.org/10.1016/j.ijfatigue.2022.106784>
- [29] L. Ávila de Oliveira Silva, G. Adinolfi Colpaert Sartori, D. Bondarchuk, I.M. Oliveira Anício Costa, C. Mesplont, J.-B. Vogt, Effect of interlamellar spacing on the low-cycle fatigue behavior of a fully pearlitic steel. *Metallography, Microstructure, and Analysis*, 10(5), 2021: 692–699.
<https://doi.org/10.1007/s13632-021-00775-1>
- [30] X. Liu, F. Yuan, Y. Zhu, X. Wu, Extraordinary Bauschinger effect in gradient-structured

- copper. *Heterostructured Materials*, 2021: 361–370.
<https://doi.org/10.1201/9781003153078-23>
- [31] T. Touch, S. Kishiki, S. Yamada, Low-cycle fatigue performances including large plastic strain of SUS821L1 lean duplex stainless steel. Proceedings of the 11th International Conference on Behaviour of Steel Structures in Seismic Areas. *Lecture Notes in Civil Engineering*, 519, 2024: 162–171.
https://doi.org/10.1007/978-3-031-62884-9_14
- [32] B. Xu, B. Huang, S. Tang, X. Xu, H. Peng, C. Wang, Q. Wang, Effects of temperature, loading frequency, stress amplitude, and stress ratio on the low-cycle fatigue behavior of FeMnSiCrNi shape-memory alloys. *Acta Mechanica Sinica*, 39, 2026: 133-151.
<https://doi.org/10.1007/s10338-025-00617-5>
- [33] M. Buttard, T. Lenoir, B. Chéhab, C. Josserond, A. Deschamps, J.-J. Blandin, G. Martin, Bauschinger effect in an aluminium alloy designed for laser powder-bed fusion. *Materialia*, 34, 2024: 102093.
<https://doi.org/10.1016/j.mtla.2024.102093>
- [34] P. Zhu, J. Lin, R. Xiao, H. Zhou, Unravelling the physical origin of the Bauschinger effect in glassy polymers. *Journal of the Mechanics and Physics of Solids*, 168, 2022: 105046.
<https://doi.org/10.1016/j.jmps.2022.105046>
- [35] O. Bouaziz, H.S. Kim, J. Lee, Y. Estrin, Bauschinger effect or kinematic hardening: Bridging microstructure and continuum mechanics. *Metals and Materials International*, 29(2), 2023: 280–292.
<https://doi.org/10.1007/s12540-022-01227-3>
- [36] X. Zhu, X. Yang, W. Huang, M. Liu, X. Wang, M. Li, Modeling the Bauschinger effect through the reversibility of dislocation slip in an Al–Cu–Li alloy. *Materials Science and Engineering: A*, 902, 2024: 146574.
<https://doi.org/10.1016/j.msea.2024.146574>
- [37] S. Gao, K. Yoshino, D. Terada, Y. Kaneko, N. Tsuji, Significant Bauschinger effect and backstress strengthening in ultrafine-grained pure aluminum fabricated by severe plastic deformation. *Scripta Materialia*, 211, 2022: 114503.
<https://doi.org/10.1016/j.scriptamat.2022.114503>
- [38] X. Du, S. Shuang, J. Zhao, Z. Fu, Q. Kan, X. Zhang, Extra strengthening and Bauschinger effect in a gradient high-entropy alloy: A molecular-dynamics study. *International Journal of Mechanical Sciences*, 264, 2024: 108829.
<https://doi.org/10.1016/j.ijmecsci.2023.108829>
- [39] P. Vourna, N.D. Papadopoulos, K. Argiris, P.P. Falara, E. Hristoforou, Magnetic evaluation of the Bauschinger effect in marine engineering steels. *NDT & E International*, 139, 2023: 102933.
<https://doi.org/10.1016/j.ndteint.2023.102933>
- [40] W. He, M. Wan, B. Meng, Size effect on nonlinear unloading behavior and the Bauschinger effect of a Ni-based superalloy ultrathin sheet. *International Journal of Mechanical Sciences*, 231, 2022: 107563.
<https://doi.org/10.1016/j.ijmecsci.2022.107563>
- [41] A. Ellermann, B. Scholtes, The Bauschinger effect in different heat-treatment conditions of 42CrMo4. *International Journal of Structural Changes in Solids – Mechanics and Applications*, 3(1), 2011: 1–13.
- [42] M. Kreins, K. Büßenschütt, S. Wesselmecking, U. Krupp, On the impact of nanoscale γ'' precipitates on the Bauschinger effect in single- and polycrystal Ni-base superalloy 718. *Materials Science and Engineering: A*, 856, 2022: 144008.
<https://doi.org/10.1016/j.msea.2022.144008>
- [43] R.R. Adigamov, V.A. Andreev, S.O. Rogachev, E.S. Fedotov, G.E. Khadeev, V.S. Yusupov, Bauschinger effect in alternating deformation. *Steel in Translation*, 52(7), 2022: 639–647.
<https://doi.org/10.3103/S0967091222070026>
- [44] Z. Hu, M.C. Gibson, A.P. Parker, Swage autofrettage finite-element analysis incorporating a user function to model the actual Bauschinger effect. *International Journal of Pressure Vessels and Piping*, 191, 2021: 104372.
<https://doi.org/10.1016/j.ijpvp.2021.104372>
- [45] A. Martinez-Pechero, E. Demir, C. Hardie, Y. Zayachuk, A. Widdowson, E. Tarleton, Modelling the Bauschinger effect in copper during preliminary load cycles. *Acta Materialia*, 289, 2025: 120886.
<https://doi.org/10.1016/j.actamat.2025.120886>
- [46] S. Lu, D. Huang, C. Liang, Y. Feng, Orientation-dependent yield and Bauschinger effects in two-dimensional Yukawa solids. *Physical Review Research*, 6(3), 2024: 033211.

<https://doi.org/10.1103/PhysRevResearch.6.033211>

- [47] C.J. Geng, B.L. Wu, X.H. Du, Y.D. Wang, Y.D. Zhang, F. Wagner, C. Esling, Low cycle fatigue behavior of the textured AZ31B magnesium alloy under the asymmetrical loading. *Materials Science and Engineering: A*, 560, 2013: 618–626.
<https://doi.org/10.1016/j.msea.2012.10.004>