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**AN OVERVIEW AND ANALYSIS OF MONOTONIC AND
CYCLIC EXPERIMENTS ON METAL SPECIMENS**

by

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Abstract

In the last decade, the human potential of the University of Thessaly had carried out a plenty of experiments on structural steel at the material level, in the context of various research programs, Thesis and Ph.D. The aim of this Thesis is firstly the creation of a database that contains all the experimental data from uniaxial tests, mainly were processed at UTH. The database, which will of course be updated when new experiments are carried out, contains stress-strain (or force-displacement) data from specimens subjected to uniaxial loading. Secondly, includes the classification of experiments based on their type in tensile, strain-controlled, stress controlled and compression tests and also the calculation primary properties and the export of important results for each occasion.

Certainly, in the first chapter a general overview of the database is made, giving basic information about the provenance and type of the samples, whether they have undergone any additional metallurgical process and whether they have special features such as, notches.

In the next chapter the fundamental theory is presented regarding the conclusions that can be obtained from the analysis of uniaxial tensile, strain controlled, stress controlled and compression test data. The information is utilized and the key details that can be derived in each case, ultimately contributing to the characterization of materials and the determination of their mechanical properties.

In chapter 3, the uniaxial tensile tests that are available for each metal are presented with the corresponding calculated mean values for the modulus of elasticity, the yield limit at 0.2% strain offset and at 0.5% full deformation, the maximum stress, the strain at this point, as well as the maximum deformation at the moment of fracture. The above properties, and additionally the plastic plateau phenomenon are used for the materials calibration.

Subsequently, Chapter 4 proceeds the analysis of strain-controlled tests and determine mean values for the modulus of elasticity, the yield limit at a 0.2% strain offset, and the yield point at 0.5% total deformation. Additionally, it was generated the diagrams of amplitude stress and mean stress versus the number of cycles to characterize the

cyclic behavior of the material. Finally, yield strength and modulus of elasticity calculations from the tensile and compressive curves in subsequent cycles, are provided to describe the presence of Bauschinger effect.

Chapter 5 reported to the stress-controlled test, calculating the average values for the modulus of elasticity, the yield strength at a 0.2% strain offset, and the yield point at 0.5% total deformation. Also, are presented the ratcheting strain curves, in order to define the behavior of metal coupons under constant stress amplitude. Furthermore, the elastic modulus has been measured for subsequent cycles, to explore how E change during the experiment.

Chapter 6 focuses on analyzing a small set of compression tests, determining the average values for the elastic modulus, the yield strength at 0.2% strain offset, and the yield point at 0.5% total deformation. This analysis is conducted for each material, considering different orientations, and comparing specimens that have undergone thermal processing with those that have not.

In the final chapter, the findings of this dissertation are discussed, along with some practical conclusions.

ΜΙΑ ΕΠΙΣΚΟΠΗΣΗ ΚΑΙ ΑΝΑΛΥΣΗ ΜΟΝΟΑΞΟΝΙΚΩΝ ΚΑΙ ΚΥΚΛΙΚΩΝ ΠΕΙΡΑΜΑΤΩΝ ΣΕ ΜΕΤΑΛΛΙΚΑ ΔΟΚΙΜΙΑ

ΙΩΑΝΝΗΣ ΝΑΤΣΙΟΣ

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Περίληψη

Την τελευταία δεκαετία, το ανθρώπινο δυναμικό του Πανεπιστημίου Θεσσαλίας είχε πραγματοποιήσει πληθώρα πειραμάτων σε δομικό χάλυβα σε επίπεδο υλικού, στο πλαίσιο διαφόρων ερευνητικών προγραμμάτων, διπλωματικών εργασιών και διδακτορικών διατριβών. Στόχος της παρούσας διπλωματικής εργασίας είναι καταρχάς, η δημιουργία μιας βάσης δεδομένων που θα περιέχει όλα τα πειραματικά δεδομένα από μονοαξονικές δοκιμές, που υποβλήθηκαν κυρίως σε επεξεργασία στο UTH. Η βάση δεδομένων, η οποία βέβαια θα ανανεώνεται όταν πραγματοποιούνται νέα πειράματα, περιέχει δεδομένα τάσης-παραμόρφωσης (ή δύναμης-μετατόπισης) από δοκίμια που υποβάλλονται σε μονοαξονική φόρτιση. Δεύτερον, περιλαμβάνει τη ταξινόμηση των πειραμάτων με βάση το τύπο τους σε δοκιμές εφελκυσμού, ελεγχόμενης παραμόρφωσης, ελεγχόμενης τάσης και συμπίεσης καθώς και τον υπολογισμό των πρωταρχικών ιδιοτήτων και την εξαγωγή σημαντικών αποτελεσμάτων για κάθε περίπτωση.

Βεβαίως, στο πρώτο κεφάλαιο γίνεται μια γενική επισκόπηση της βάσης δεδομένων, δίνοντας βασικές πληροφορίες για την προέλευση, το είδος των δειγμάτων, εάν έχουν υποστεί κάποια πρόσθετη μεταλλουργική διαδικασία και εάν έχουν ιδιαίτερα χαρακτηριστικά όπως, εγκοπές.

Στο επόμενο κεφάλαιο, παρουσιάζεται η θεμελιώδης θεωρία σχετικά με τα συμπεράσματα που μπορούν να εξαχθούν από την ανάλυση δεδομένων δοκιμών μονοαξονικού εφελκυσμού, ελεγχόμενης παραμόρφωσης, ελεγχόμενης τάσης και συμπίεσης. Οι πληροφορίες και οι βασικές λεπτομέρειες που μπορούν να εξαχθούν σε κάθε περίπτωση αξιοποιούνται, συμβάλλοντας τελικά στον χαρακτηρισμό των υλικών και στον προσδιορισμό των μηχανικών ιδιοτήτων τους.

Στο κεφάλαιο 3, οι μονοαξονικές δοκιμές εφελκυσμού που είναι διαθέσιμες για κάθε μέταλλο παρουσιάζονται με τις αντίστοιχες υπολογισμένες μέσες τιμές για το μέτρο ελαστικότητας, το όριο διαρροής για offset 0.2% και για 0.5% πλήρη παραμόρφωση, τη μέγιστη τάση, την καταπόνηση σε αυτό το σημείο καθώς και τη μέγιστη παραμόρφωση τη στιγμή της θραύσης. Οι παραπάνω ιδιότητες και επιπλέον

λαμβάνοντας υπόψη το φαινόμενο plateau, χρησιμοποιούνται για τη βαθμονόμηση των υλικών.

Στη συνέχεια, το Κεφάλαιο 4 προχωρά στην ανάλυση δοκιμών ελεγχόμενης παραμόρφωσης και προσδιορίζει τις μέσες τιμές για το μέτρο ελαστικότητας, το όριο διαρροής για offset 0.2% και το σημείο διαρροής για 0.5% συνολική παραμόρφωση. Επιπλέον, δημιουργήθηκαν τα διαγράμματα του πλάτους -τάσης και της μέσης τάσης έναντι του αριθμού των κύκλων για να χαρακτηριστεί η κυκλική συμπεριφορά του υλικού. Τέλος, οι υπολογισμοί της αντοχής διαρροής και του συντελεστή ελαστικότητας από τις καμπύλες εφελκυσμού και συμπίεσης σε μεταγενέστερους κύκλους, παρέχονται για να περιγράψουν την παρουσία του φαινομένου Bauschinger.

Το Κεφάλαιο 6 εστιάζει στην ανάλυση ενός μικρού συνόλου δοκιμών συμπίεσης, προσδιορίζοντας τις μέσες τιμές για το μέτρο ελαστικότητας, την αντοχή διαρροής για offset 0.2% και το σημείο διαρροής για 0.5% συνολική παραμόρφωση. Αυτή η ανάλυση πραγματοποιείται για κάθε υλικό, λαμβάνοντας υπόψη διαφορετικούς προσανατολισμούς και συγκρίνοντας δείγματα που έχουν υποστεί θερμική επεξεργασία με αυτά που δεν έχουν υποστεί.

Στο τελευταίο κεφάλαιο, συζητούνται τα ευρήματα της παρούσας διπλωματικής εργασίας, μαζί με ορισμένα πρακτικά συμπεράσματα.

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1. CHAPTER – INTRODUCTION

1.1 Introduction

The University of Thessaly has been actively involved in several research programs, such as ATTEL, MATCH, INDUSE, and ULCF, which focus on analyzing the behavior of structural mechanisms and metal components under loading conditions, particularly in response to physical phenomena like earthquakes. To support these studies, a significant number of specimens were either fabricated or extracted from specific sections of structural steel members, such as piping systems and lattice girders, for uniaxial testing. These small-scale experiments aim to assess the mechanical response of steel under both monotonic and cyclic loading within the plastic regime, providing key mechanical insights at the macroscopic level. These include phenomena such as cyclic ratcheting/softening, mean stress relaxation, and the plastic plateau.

By conducting these tests on small-scale specimens, researchers can efficiently gather data on various material properties, allowing them to extrapolate this information to predict the performance of larger structural components. This research is crucial for enhancing the safety and reliability of structures, as it generates essential data to inform the design and engineering of resilient systems capable of withstanding demanding physical phenomena like seismic events.

To accurately capture how a material's behavior evolves under loading, constitutive models are necessary. These models consist of mathematical equations, each defined by parameters that represent certain macroscopic properties, such as cyclic hardening or softening. In finite element analysis (FEA), a suitable constitutive model is applied based on the material properties of interest. For instance, the plastic plateau is not accounted for by the combined hardening model available in Abaqus. Through a trial-and-error process, researchers fine-tune the model's parameters to achieve the best possible prediction of the material's stress-strain behavior in simulations. This process, though effective, is both time-consuming and technically challenging.

So, the goal of this dissertation is to compile and organize raw data from uniaxial experiments, along with the corresponding reports, to establish a comprehensive database. This database will serve as a valuable resource, providing an overview of the available data on various metals and helping to identify areas for further experimentation. Ultimately, this can lead to more accurate predictions of constitutive model parameters and improvements in structural analysis.

1.2 Database summary

In the database, the experiments are categorized based on factors such as material grade, source type, specimen type, and associated research programs. **Table 1.1** and **Table 1.2** provide a general overview of the datasets. The first column classifies the materials according to the investigation reports they originate from, listed in chronological order, from the most recent to the oldest. Also, the last four columns demonstrate the number of available experiments on each occasion:
TENSION=Tensile test, C_STRAIN=Strain-controlled test, C_STRESS=Stress-controlled test, COMP=Compression test. The other three columns are analyzed next.

1.2.1 Grade column

The second column describes the material grade. Here, it is necessary to become some observations. In this way, the "S" in grade typically stands for "Structural" steel and therefore, the number after S signifies the minimum yield strength of the steel in MPa (Megapascals). Also, in the context of TS590 steel, "TS" typically stands for "Tensile Strength." The number following "TS," in this case, 590, indicates the minimum tensile strength of the steel in megapascals (MPa). According to S355J2+N steel and S275J2, "J2" indicates that the material can withstand longitudinal Charpy V-notch impacts of 27 Joules at -20°C. The "+N" signifies that the material has undergone normalized rolling, which involves heating to 910°C for 1.5 minutes per millimeter of thickness, followed by cooling in still air. In the context of X-Number steel, the "X" denotes that the steel is intended for pipeline applications, particularly those specified by the American Petroleum Institute (API) under the API 5L standard. The number indicates the minimum yield strength of the steel in ksi (kilopounds per square inch). Furthermore, for consistency, all specimens are made from P355N material, in accordance with the EN 10216-3 standard, which is equivalent to API 5L Grade X52 and the "P" stands for "Pressure." This designation indicates that the steel is intended for use in pressure vessels and boilers. According to 625 stainless steels, the "625" designation refers to the specific alloy composition, which typically includes a combination of nickel, chromium, molybdenum, and niobium, among other elements and "Stainless" refers to the alloy's characteristic resistance to rust and corrosion. The 'MC' in context of S355MC and S460MC, the symbol 'M' characterizes that the steels have been subjected to thermo-mechanical rolling and 'C' means that the steel have been subjected to cold drawing. In the context of 43A-BS4360 -steel, the designation "43A" in BS4360 refers to a specific grade of carbon steel, defined by the British Standard BS4360. The BS4360 standard specifies requirements for weldable structural steels. The "43A" grade indicates that the steel has a minimum yield strength of 275 MPa and a minimum tensile strength of 410 MPa.

1.2.2 Specimen Cross-Section column

The type of specimen's cross-section and if they have submitted to an extra process are described in the third column of **Table 1.1 & Table 1.2**. The coupons utilized in experiments of this database have a rectangular cross-section or a circular cross-section. Additionally, in this column it is described whether the specimen has undergone any further processing after extraction. In X52 grade, the "SP" means smooth plane specimens.

1.2.3 Specimen Type column

Moreover, in the fourth columns, is defined the source of specimens, if are from plate or specific profiles pipe, hollow section, or flange, and if they had subjected to a mechanical process such as quenching or pre-strain. Certainly:

- **SCH20 Seamless Elbow**
 - **SCH20**: This stands for "Schedule 20," which is a classification used to denote the wall thickness of pipes and fittings.[2]
 - **Seamless**: This indicates that the elbow is made from a seamless pipe, meaning it does not have any welded seams.
 - **Elbow**: This is a type of pipe fitting used to change the direction of flow in a piping system.[3]
- **HEA 140**
 - **HEA 140** refers to a specific type of steel beam or column section according to the European standard EN 10365. 'HEA' are characterized by their H-shaped cross-section.
 - **'140'**: This number refers to the nominal height of the beam's cross-section in millimeter.[4]

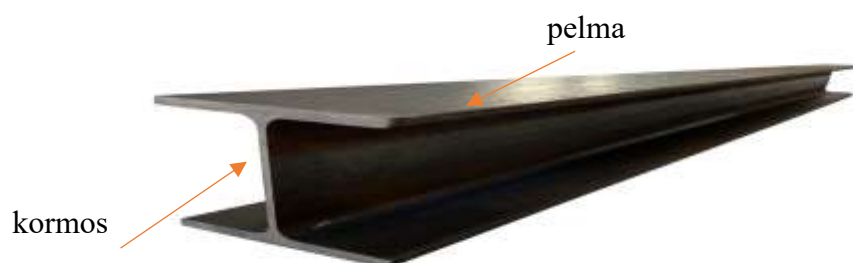


Fig 1.1 HEA 140 Beam [32].

- **CHS- 323.7x10mm**
 - **CHS** stands for Circular Hollow Section.
 - **323.7x10mm**, the first number (323.7) refer to the diameter and the second to thickness in millimeters [5].
- **HFW Pipe** stands for High-Frequency Welded Pipe, if contains the term line this indicate that these pipes are part of the infrastructure for conveying substances like oil and water, often over long distances.[6]
- **MLP pipe** typically refers to Multi-Layer Pipe. These pipes consist of multiple layers of materials,[7].
- **Tee-joint piping connection-elbow** typically refers to a configuration in a piping system where a tee fitting, and an elbow fitting are used in conjunction.[8]

Additionally, the numbers following plate and pipe specifications indicate the thickness and diameter, respectively, and are measured in either millimeters or inches. If a percentage value is included, it signifies that the material has undergone a pre-straining process.

Table 1.1 a) General summary of database experiments.

REFERENCE	GRADE	SPECIMEN CROSS-SECTION	SPECIMEN TYPE	TENSION	C_STRAIN	C_STRESS	COMP
Fracture and fatigue of S355 and S700 steel for floating wind energy structures_ (2024) [28]	S700	RECTANGULAR	COLD ROLL-FORMING PLATE (VETA S.A)	13	2	2	-
Collapse testing and analysis of high frequency welded (HFW) pipes_ (2024) [38]	X65	RECTANGULAR	HFW PIPE-16in	6	-	-	14
Heat treatment effects on collapse of JCO-E steel pipes under external pressure: Experiments and numerical predictions_ (2024) [37]	X60	RECTANGULAR	PIPE-30in	14	-	-	13
Heat treatment effects on collapse of JCO-E steel pipes under external pressure: Experiments and numerical predictions_ (2024) [37]	X65	RECTANGULAR	PIPE-26in	12	-	-	12
Fracture and fatigue of S355 and S700 steel for floating wind energy structures_ (2024) [28]	S355J2+N	RECTANGULAR	COLD ROLL-FORMING PLATE (VETA S.A)	6	2	2	-
Collapse testing and analysis of high frequency welded (HFW) pipes_ (2024) [38]	X65	RECTANGULAR	HFW LINE PIPE 160mm	-	4	-	-
Finite element analysis of JCO-E fabrication process and its influence on the collapse capacity of offshore pipelines_ (2024) [40]	X60	RECTANGULAR	PLATE 38.7 mm	-	20	-	-
Hartloper_Lignos-et-al-JStrEng_ (2023) [1]	ASME-S234	RECTANGULAR	SCH20 SEAMLESS ELBOW	4	6	3	-
Corinth Pipeworks S.A. project_ (2023)	X65	RECTANGULAR	PLATE-1(26in_t37)-39 mm	-	10	-	-
Finite element modeling of the JCO-E line pipe fabrication process; material properties and collapse pressure prediction (2023) [39]	X65	RECTANGULAR	PLATE-2(26in_t19_44) 37mm	-	16	-	-
EPRG 234 Project_ (2022)	X65	RECTANGULAR	MPL PIPE 200mm	3	4	-	-
EPRG 234 Project_ (2022)	625 STAINLESS STEEL	RECTANGULAR	MPL PIPE	3	6	2	-
Low-cycle fatigue of fillet-welded steel plate connections_ (2021) [32]	S275J2	RECTANGULAR	PLATE 8mm	4	2	-	-
Christos Prosgolitis-Experimental report_ (2021)	43A-BS 4360	RECTANGULAR	PIPE-0%	4	4	-	-
Christos Prosgolitis-Experimental report_ (2021)	43A-BS 4360	RECTANGULAR	PIPE-9%	2	7	-	-
Material Choice for Seismic Resistant Structures (MATCH)_ (2017) [33]	S500	RECTANGULAR	THERMO-MECHANICAL LY ROLLED PLATE	-	4	6	-
Material Choice for Seismic Resistant Structures (MATCH)_ (2017) [33]	S700	RECTANGULAR	QUENCHED HOLLOW SECTION	2	7	2	-

Table 1.2 b) General summary of database experiments.

REFERENCE	GRADE	SPECIMEN CROSS-SECTION	SPECIMEN TYPE	TENSION	C_STRAIN	C_STRESS	COMP
Material Choice for Seismic Resistant Structures (MATCH)_ (2017) [33]	S355	RECTANGULAR	HEA140(T1)	2	8	3	-
Material Choice for Seismic Resistant Structures (MATCH)_ (2017) [33]	S355	RECTANGULAR	HEA140(T2)	2	6	2	-
Experimental investigation and analytical modeling of fatigue crack in HSLA steels with pre-existing plastic deformation_ (2017) [34]	S355MC	RECTANGULAR	THERMO-MECHANICALLY ROLLED AND CALL DRAWING PLATE 0%	2	9	-	-
Experimental investigation and analytical modeling of fatigue crack in HSLA steels with pre-existing plastic deformation_ (2017) [34]	S355MC	RECTANGULAR	THERMO-MECHANICALLY ROLLED AND CALL DRAWING PLATE 8-9%	3	10	-	-
Experimental investigation and analytical modeling of fatigue crack in HSLA steels with pre-existing plastic deformation_ (2017) [34]	S460MC	RECTANGULAR	THERMO-MECHANICALLY ROLLED AND CALL DRAWING PLATE 8-9%	-	10	-	-
Experimental investigation and analytical modeling of fatigue crack in HSLA steels with pre-existing plastic deformation_ (2017) [34]	S460MC	RECTANGULAR	THERMO-MECHANICALLY ROLLED AND CALL DRAWING PLATE 9-10%	2	-	-	-
Experimental investigation and analytical modeling of fatigue crack in HSLA steels with pre-existing plastic deformation_ (2017) [34]	S460MC	RECTANGULAR	THERMO-MECHANICALLY ROLLED AND CALL DRAWING PLATE 12-13%	1	13	-	-
Experimental investigation and analytical modeling of fatigue crack in HSLA steels with pre-existing plastic deformation_ (2017) [34]	S355MC	RECTANGULAR	THERMO-MECHANICALLY ROLLED AND CALL DRAWING PLATE 12-13%	3	11	-	-
Experimental investigation and analytical modeling of fatigue crack in HSLA steels with pre-existing plastic deformation_ (2017) [34]	S355MC	RECTANGULAR	THERMO-MECHANICALLY ROLLED AND CALL DRAWING PLATE 15-16%	3	-	-	-
Experimental investigation and analytical modeling of fatigue crack in HSLA steels with pre-existing plastic deformation_ (2017) [34]	S460MC	RECTANGULAR	THERMO-MECHANICALLY ROLLED AND CALL DRAWING PLATE 0%	2	9	-	-
Ultra-low cycle fatigue of steel under cyclic high-strain loading conditions (ULCF)_ (2014) [35]	X52	RECTANGULAR-SP	PIPE	3	30	-	-
Performance-based approaches for high strength tubular columns and connections under earthquake and fire loadings(ATTEL) (2013) [5]	TS590	CYLINDRICAL	CHS- 323,7x10mm	2	2	4	-
Performance-based approaches for high strength tubular columns and connections under earthquake and fire loadings (ATTEL) (2013) [5]	TS590	CYLINDRICAL	CHS- 355x12mm	2	2	3	-
Structural safety of industrial steel tanks, pressure vessels and piping systems under seismic loading (INDUSE)_ (2013) [36]	P355	RECTANGULAR	TEE-JOINT PIPING CONNECTION-ELBOW	4	6	-	-

1.3 Tensile tests

Tensile testing is a fundamental mechanical test that provides essential information about the mechanical properties of materials, such as tensile strength, yield strength, Young's modulus, ductility, and toughness. According to certain testing equipment and standard test methods, experiments involve subjecting a material specimen to a controlled tensile force often until failure, measuring various parameters throughout the process. Tensile tests are essential for determining how materials respond to uniaxial tensile stress, assessing their suitability for different applications, and are applicable in both strain-controlled and stress-controlled testing scenarios.

The tensile specimens utilized in experiments of this database have mainly a rectangular cross section, **Fig1.2**. However, also a few have a circular cross section. These specimens have a narrow central section with enlarged ends, to enhance gripping stability and prevent sample breakage at the gripping points.[9]

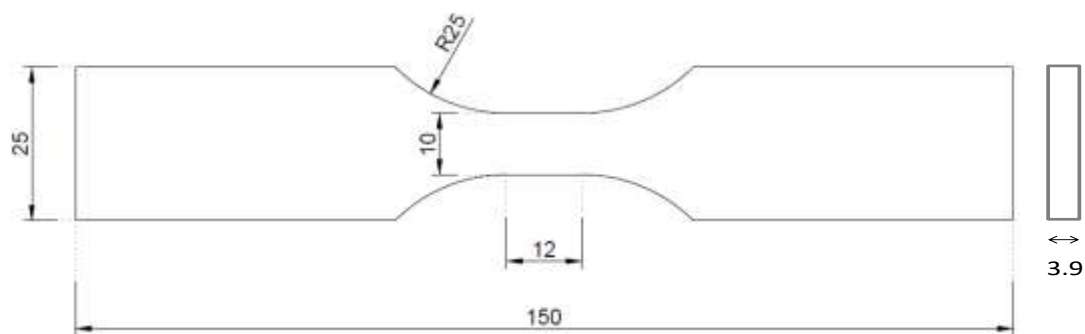


Fig 1.2 Regular rectangular specimen of 625 stainless steel.

1.3.1 Engineering stress-strain tension curve

In the following figures (**Fig 1.3 & 1.4**) are illustrated the stress-strain curve of a typical tension test. Afterward are presented the significant points, regions and are determined the mechanical properties, that obtained from this experiment.

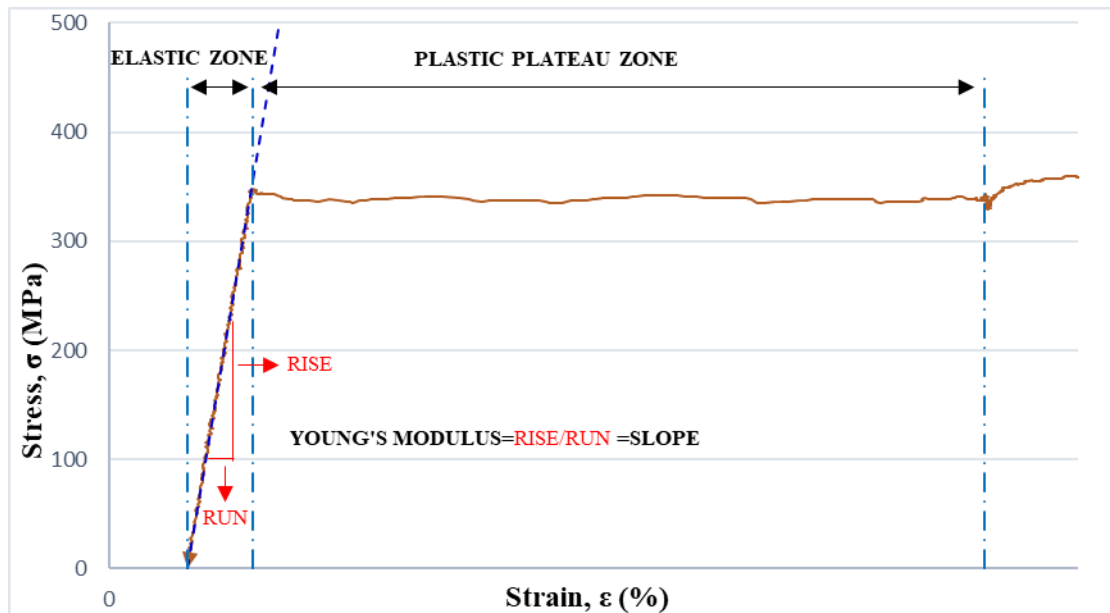


Fig 1.3 Tensile stress-strain curve of S355_T1 specimen until plastic plateau zone.

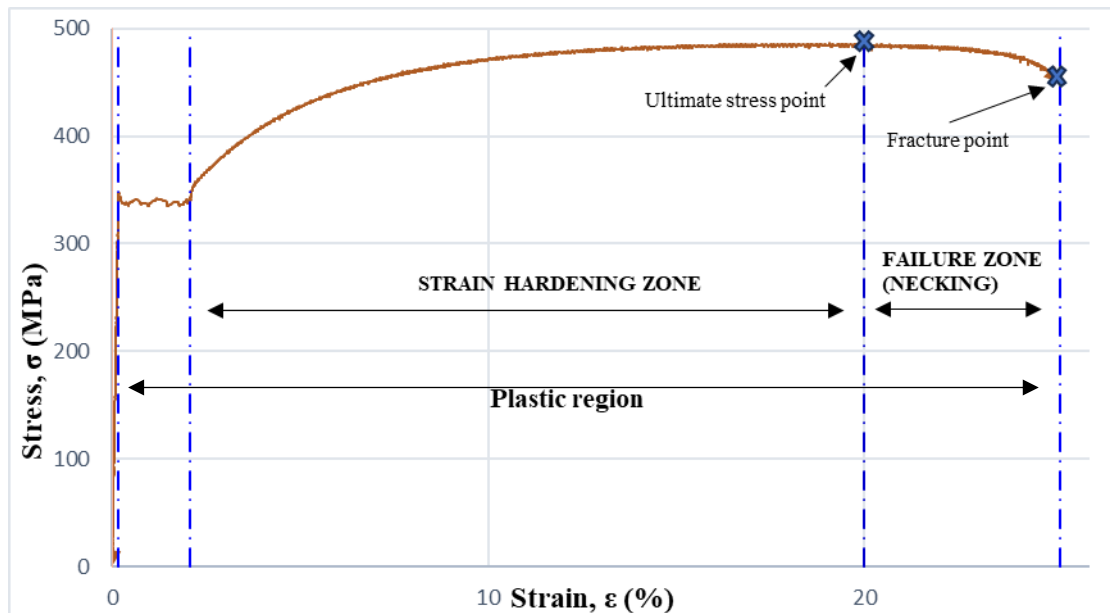


Fig 1.4 Tensile stress-strain curve of S355_T1 specimen.

The axial direction represents the engineering strain (ϵ) which calculated by the change in the gage length $L-L_0$, divided by L_0 (L_0 the initial gage length of the coupon and L the gage length over the time) [10]:

- $\epsilon = (L - L_0) / L_0$

The other direction shows the engineering stress (σ) measured by the axial applied force (F) divided by the initial cross section area (A) of the specimen [10]:

- $\sigma = F / A$

The stress-strain curve can be divided into two main regions. The first region, known as the elastic region (zone), is the initial linear segment where Hooke's law applies. So, the material deforms elastically, meaning it returns to its original shape upon unloading. The second region, called the plastic region, begins after the yield strength point and corresponds to the nonlinear portion of the curve, indicating inelastic and permanent deformation. The plastic region can be further subdivided into three zones:

1. **Plastic Plateau Zone:** In this zone (Fig 1.5), after the elastic region, the stress reaches a maximum value σ_A (upper yield point), then drop to minimum one σ_B (lower yield point) and the plastic strain increases from point B to C while the stress remains almost constant $\sigma_B = \sigma_C$, resulting in a zero slope, in general. This phenomenon does not appear to high strength steels.[11]

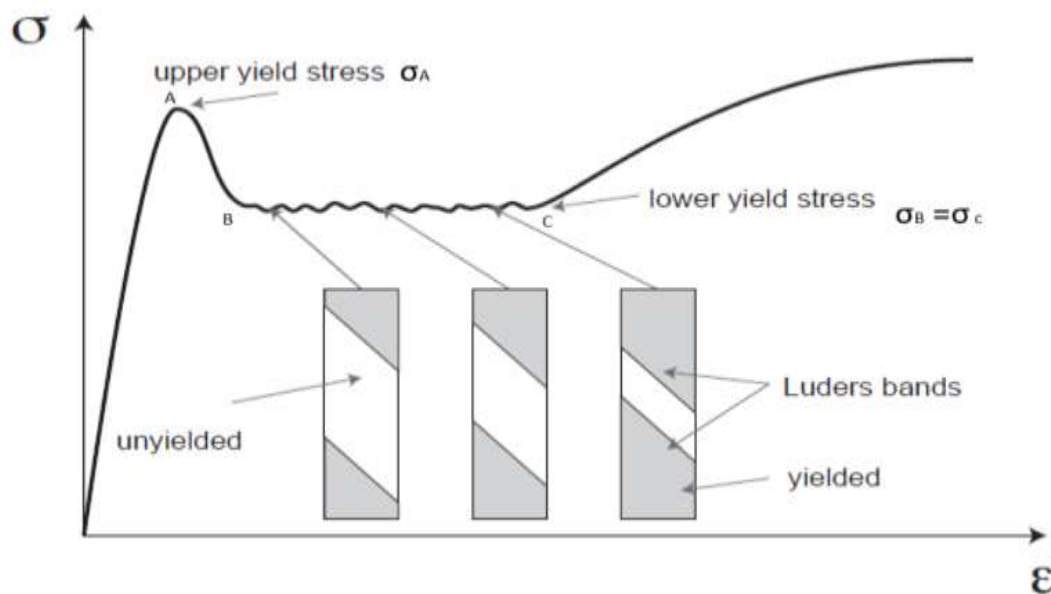


Fig 1.5 Stress-strain curve of tensile test [12].

2. **Strain Hardening Zone:** Here, the material increases its strength at a decreasing rate, as indicated by the positive slope, until it reaches ultimate strength.[9]
3. **Necking Zone:** This zone characterizes by necking phenomenon that appears in ductile material. After the material reaches its peak strength, the cross-sectional area of the tensile specimen rapidly narrows in the middle portion as the applied force reduces, ultimately leading to fracture (marked by a negative slope in the stress-strain curve). The reason why there is no necking in brittle materials is that the maximum stress point identifies with fracture point.[13]

1.3.2 Mechanical properties

Afterward are determined the mechanical properties, that obtained from this diagram:

- **Elastic or Young's modulus (E)**, indicates the material's stiffness and represents the slope of the linear part:
 - $E = \epsilon / \sigma$ (Hooke's Law)

In this Thesis, the modulus values identified as part of the linear region can be fitted to a least-squares line to determine the slope E. [9],[10]

- **Ultimate Tensile Strength (σ_{UTS})**: The maximum stress a material can endure while being elongated before fracturing, represented by the highest point on the stress-strain curve.[9]
- **Yield strength limit ($\sigma_{y0.2\%}$, $R_{t0.5\%}$)**: This point marks the boundary between the elastic and plastic regions. It represents the maximum stress that does not cause permanent deformation, which is crucial for improving the overall durability of materials. In this Thesis, for the calculation is applied the 0.2% offset method - $\sigma_{y0.2\%}$ (when yielding is ideally considered to occur when 0.2% elastic strain has been reached.), but also the yield point is measured for 0.5% overall strain- $R_{t0.5\%}$ (elastic + plastic).[9]
- **Elongation at the onset of necking (Euts)**: It refer to the percentage strain that succeed the material reaching the ultimate strength and is one measure of ductility. A higher value indicates greater ductility in the material.[9],[10]
- **Maximum Elongation (Efr)**: It is the highest amount of percentage strain that a material undergoes before fracturing during a tensile test. It represents the maximum increase in gage length of the specimen compared to its original length. It also enhances ductility, as greater maximum elongation indicates higher ductility.[9]
- **Toughness**. It is expressed by the capacity of a material to absorb energy and undergo plastic deformation without breaking. Toughness is represented by the area beneath the stress-strain curve [14]. Materials, which possess high strength, but low ductility (brittle behavior) or the opposite i.e. low strength and high ductility, also display low tensile toughness. So, to achieve toughness, a material must possess both strength and ductility. [9],[10]

1.3.3 Microstructure of plastic plateau phenomenon

In metals under tensile stress, such as low-carbon steels and certain Al-Mg alloys, a phenomenon known as the plastic plateau commonly occurs due to the formation of Lüders bands. Lüders bands are localized regions of plastic deformation that form after the material reaches a yield point, known as the Lüders peak or upper yield stress,[15]. This peak arises from the overstress needed to dislodge dislocations initially pinned by solute atoms. Once the unpinning stress is reached, a sudden drop in flow stress occurs, leading to an avalanche of dislocations and strain localization. The Lüders bands propagate along the specimen, causing a plateau in the stress-strain curve at a nearly constant stress, referred to as the lower yield stress.[16],[11]

The formation of Lüders bands is often initiated by geometric imperfections, such as sample fillets, or material imperfections, such as inclusions or large grains, which create local stress concentrations. [16]. Notably, once a sample has been stretched beyond the Lüder strain range, further deformation does not produce Lüders bands, as the dislocations have already been dislodged from their interstitial atoms.[15] This is why pre-straining a material can prevent the formation of a plastic plateau.

1.3.4 True stress-strain tension curve

Next, the actual stress and strain diagram is briefly presented. The difference is that the true stress and strain take into consideration the changes in area and length.

- True stress is calculated by dividing the applied load (F) by the current cross-sectional area (A):
 - $\tilde{\sigma} = F/A$
- Also, the expression that relates true stress with engineering one is:
 - $\tilde{\sigma} = \sigma \cdot (1 + \epsilon)$
- True strain is calculated by the logarithm of the ratio of the current length to the original length
 - $\epsilon_{\text{true}} = \ln(L/L_0)$
- Also, the expression that relates true strain with engineering one is:
 - $\epsilon_{\text{true}} = \ln(1 + \epsilon)$

As illustrated in the **Fig 1.6**, the true and engineering stress-strain curves coincide for small strains because the changes in specimen dimensions and cross-sectional area are minimal. However, once necking begins, the area (A) reduces rapidly, causing the true stress to increase significantly compared to the engineering stress. This increase continues until fracture, where the true stress reaches its maximum value.

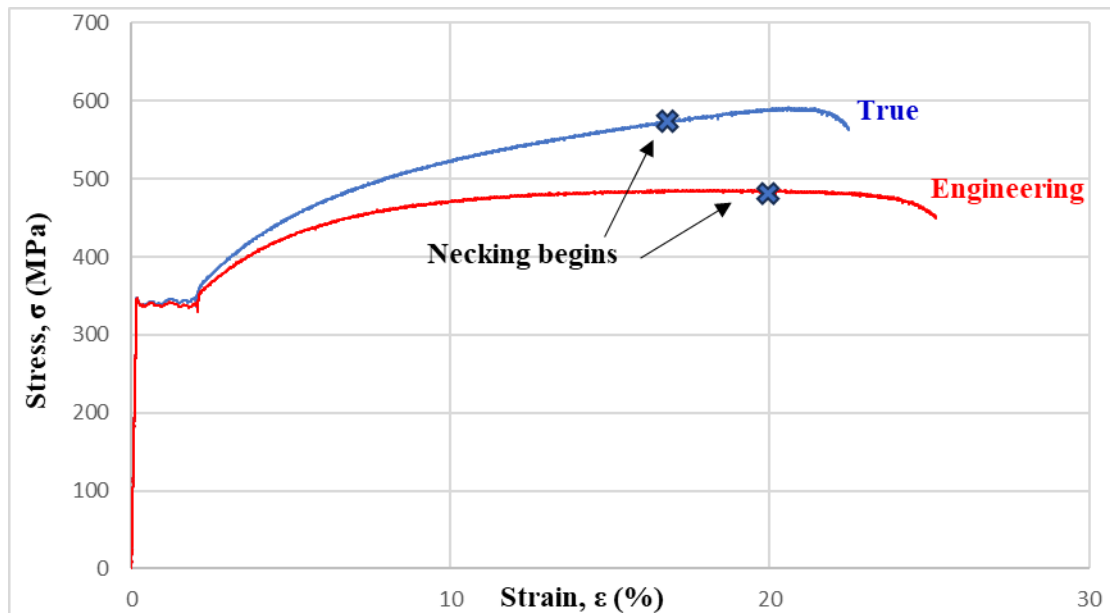


Fig 1.6 True and Engineering tensile stress-strain curve of S355_T1 specimen.

1.4 Strain controlled tests

In strain-controlled tests, a material specimen is exposed to a specified strain rate, enabling researchers to precisely regulate and monitor the deformation process. This type of experiments is essential for examining phenomena like strain hardening, softening, and the Bauschinger effect, which are key to understanding the material's ductility, toughness, and overall durability. Strain-controlled testing is also key in characterizing materials' behavior under cyclic loading conditions, which is important for evaluating fatigue properties and predicting the lifespan of components subjected to repetitive stress cycles. The aforementioned phenomena inclusive of mean stress relaxation one, are analyzed in the following paragraphs.

1.4.1 Bauschinger effect

Bauschinger phenomenon undeniably contributes to the rapid progress of cyclic plasticity models, as it takes into consideration the materials anisotropy and requires a more complex concept to described, depending on a combination of isotropic and kinematics hardening. The determination of Bauschinger effect is archived by manifestation of certain characteristics in cyclic test, which are analyzed beyond.

i. Early reverse yielding

Bauschinger effect take its name by J. Bauschinger in 1881 who observed, that making a compression test after a tensile test in plastic region, the yield stress reduced [17]. Certainly, according to this phenomenon, the inflection of plastic strain in various metals and alloys in forward direction, leads to cold working in this direction and so increase the yield strength, but in the reverse loading the compressive yield strength actually decrease. As greater is the yield strength in a direction, so smaller is in the opposite one, that illustrated at **Fig 1.7**, in which, $\sigma_{y,a}$ is the yield strength at the tension and $\sigma_{y,b}$ is the reduced yield in compression, [18]. It must $|\sigma_{y,a}| > |\sigma_{y,b}|$. Also, the increase of pre-strain or the decrease of the film thickness, causes usually qualitatively larger Bauschinger phenomenon i.e. the distance between two in a raw yield strengths became bigger, ($|\sigma_{y,a}| + |\sigma_{y,b}|$). [19]

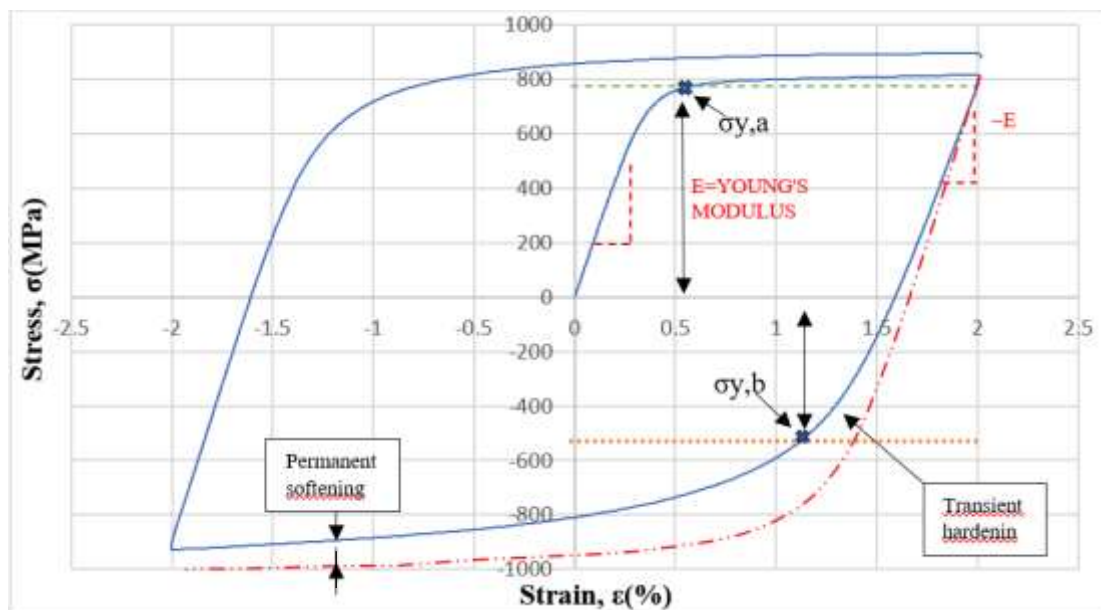


Fig 1.7 1st cycle of S700(L-N)_L3_cy specimen on strain controlled test.

ii. Transient hardening and permanent softening

Transient hardening is another important property of Bauschinger phenomenon that take place immediately after the reverse yielding strength. Specifically, at it seems at the **Fig 1.7**, the compression curve of stress-strain relationship become sharper, its slope increase, so the elastic modulus become higher and the work hardening rate rises compared to that of the tension curve, [22]. At medium prestrain, i.e. about 10% of the maximum strain, it is created a difference between the forward and the reverse flow curve, in which they are nearly parallel until a important plastic strain value. This phenomenon is well known as Permanent softening, [20].

iii. Work hardening stagnation

Work hardening Stagnation is the next aspect of the Bauschinger effect that occurs after premature yielding [23] phenomenon mainly in single phase alloy, and low carbon 'steels. Observing the **Fig 1.8**, it seems that the curve become almost straight, with its slope to become lower and maybe takes no positive values. That means the creation of a hardening plateau with a decreasing and may negative rate under reverse deformation, which significantly influenced by the values of prestrain, temperature and the surface's quality, [20].

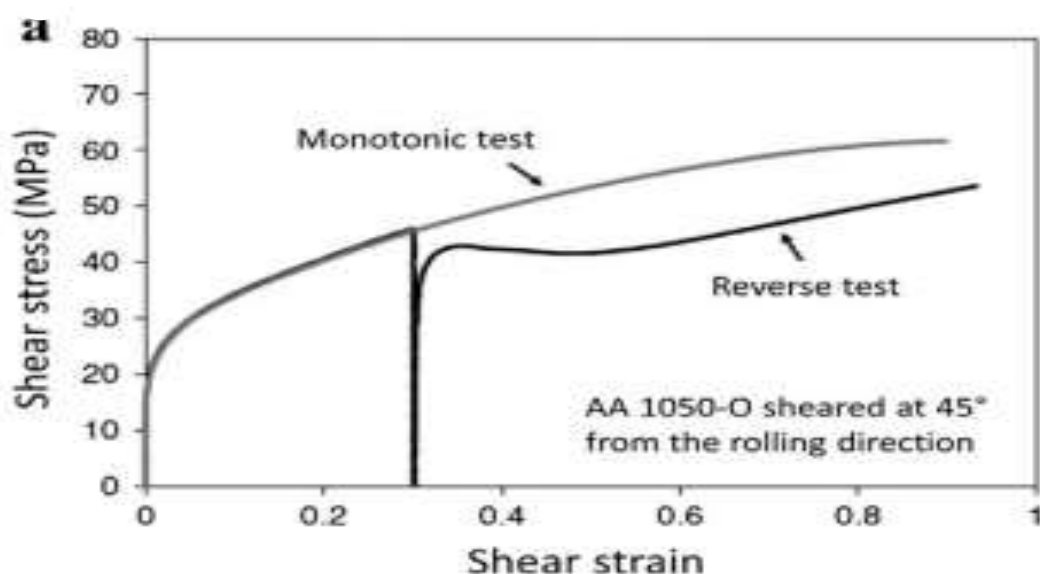


Fig 1.8 Experimental curves of an aluminum alloy illustrating the work hardening stagnation of the Bauschinger phenomenon [20].

- **Microstructure analysis of Bauschinger effect**

The Orowan and back stress are the main theories for the description of the Bauschinger mechanism. When dislocations move during plastic deformation in tensile direction, they encounter various obstacles, such as other dislocations, particles, grain boundaries, and precipitates that impede their progress. This interaction creates localized stress, which acts in opposition to the applied stress, termed back stress at the points of contact, which resists the continued motion of similarly oriented dislocations, **Fig 1.9**. In compression step, this back stress pushes the dislocations away from the obstacles in the opposite direction, which corresponds to the direction of the reverse strain. Finally, the stress field assists in moving the dislocation in the direction of the reverse strain, resulting in a reduction of the reverse yield stress by the magnitude of the back stress. Also, it is worth noting that as dislocation density rises, the frequency of dislocation interaction sites also increases, leading to higher back stress levels. Therefore, the Bauschinger effect is expected to be more pronounced in a material with greater dislocation density, [24]. The plateau observed in single-phase alloys was ascribed to variations in dislocation density rather

than changes in their distribution. It was thought that the plateau arose from a balance between the creation of new dislocations during reverse loading and the annihilation of dislocations that had been previously stored, [20].

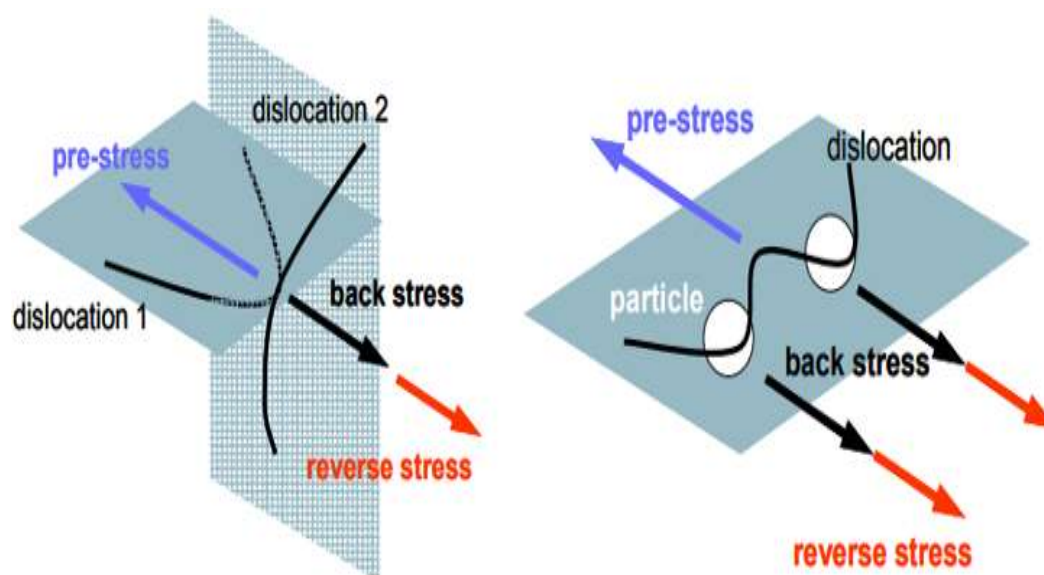


Fig 1.9 Schematic representation of a) dislocation-dislocation and b) dislocation-particle interaction [10].

1.4.2 Cycling hardening/Softening behavior

Cyclic hardening and softening describe the alterations in a material's properties, particularly its strength or hardness when it is submitted to strain-controlled test. These phenomena are identified based on the behavior of the maximum stress once a stable state is reached, i.e. the cyclic stress-strain response no longer changes significantly with additional cycling. As illustrated in **Fig 1.10**, If the peak stress increases under repeated cyclic loading, the material becomes stronger and more resistant to deformation, so that indicates cyclic hardening. Otherwise, if the maximum stress reduces with more cycles that mean a weaker material and its attribute characterized as cycling softening. Finally, there is one more occasion, in which the material does not show neither softening nor hardening behavior, so it maintains the peak stress at constant magnitude.[20],[21].

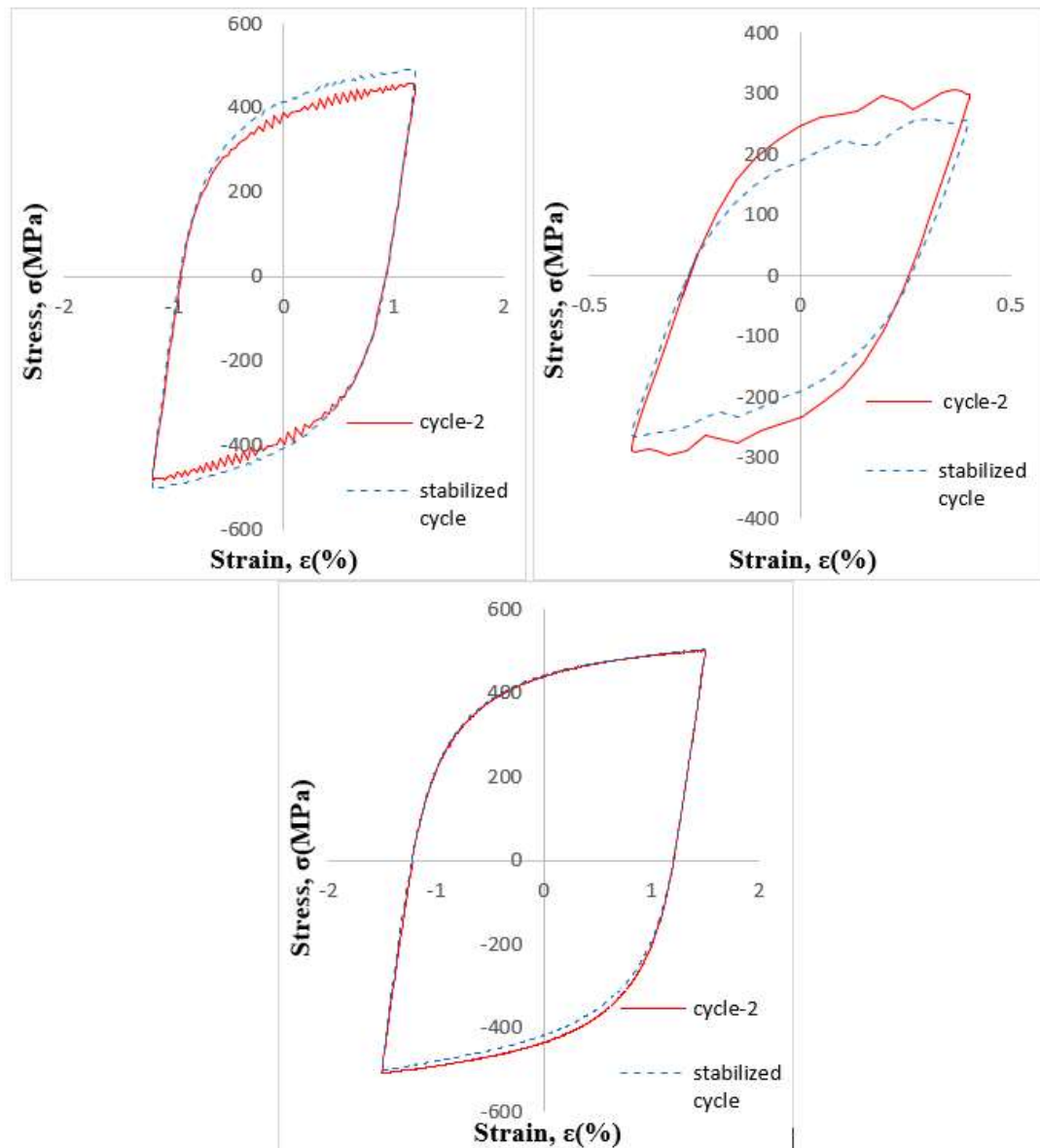


Fig 1.10 Schematic representation of the types of cyclic behavior: a) cyclic hardening(S355_T1_Pelma-1.2%), b) cyclic softening (43A-steel_IDF4-0.4%), c) no cyclic hardening or softening(S700(L-N)_T3_cy).

- **Amplitude stress- cycle diagram**

To utilize the data from the strain-controlled tests, amplitude stress versus number of cycles diagrams were created for each test. These diagrams are used to characterize the materials' behavior under cyclic loading, determining whether the metallic specimens exhibit cyclic hardening, softening, or neither. **Fig 1.11** provides an example that clearly demonstrates this process: Initially, the increase in amplitude stress with each cycle from 1 to 100 cycles indicates cyclic hardening. Afterward, from 100 to 250 cycles, the change is minimal, suggesting that the material has reached a stable state. Finally, in the last cycles, the curve shows a significant drop, indicating a softening behavior. For general characterization purposes of coupons cyclic behavior, the comparison is typically made between the first cycle and the

stabilized cycles. Analyzing the behavior in the final cycles is not particularly useful, as the material reaches a point of failure, becoming very unstable and potentially exhibiting rapid hardening or softening. The amplitude stress defines as $AS = (\sigma_{max} - \sigma_{min})/2$ where σ_{max} and σ_{min} are the maximum and minimum stress in each cycle.

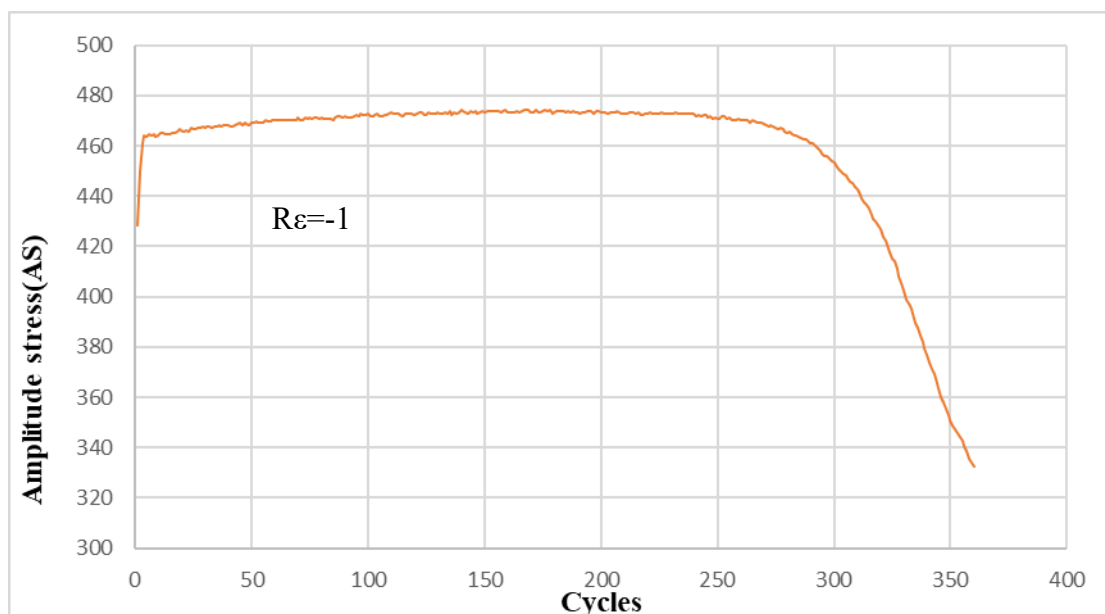


Fig 1.11 Amplitude stress versus number of cycles diagram of S355_T2_Pelma-1.2%.

- **Microstructure analysis of Cycling hardening/Softening behavior**

Cyclic hardening or softening behavior is determined by the movement and arrangement of dislocations, which form specific structures under cyclic loading conditions. This arrangement depends on the degree of cross slip in the material. Cross slip enables dislocations to move between slip planes, increasing interactions and multiplying dislocation in terms of forests and pileups. Higher dislocation density results in greater resistance to deformation as dislocations obstruct each other's movement, leading to cyclic hardening. Conversely, if cross slip facilitates dislocation annihilation and rearrangement into more stable, lower-energy configurations like cell structures, it reduces the dislocation density, making it easier for dislocations to move and resulting in cyclic softening, [20],[21].

1.4.3 Mean stress relaxation

According to mean stress relaxation phenomenon some materials, when subjected to asymmetrical strain-controlled test, (i.e. the experiment characterized by a strain offset) appear a reduction in the hysteresis loop's mean stress magnitude with each cycle before reaching stabilization. The existence of this phenomenon is influenced by the geometry of the structure and the presence of plastic deformation, [25]. Consequently, the rate or extent of stress relaxation is directly related to the

magnitude of the plastic strain amplitude. Larger strain amplitudes lead to greater stress relaxation, [20].

- **Mean stress-cycle diagram**

The mean stress-cycle curve calculated by strain-controlled experiments data as $S_{mean} = (\sigma_{max} - \sigma_{min})/2$ where σ_{max} and σ_{min} is the maximum and minimum stress in each cycle. As observed in **Fig. 1.12**, which presents a mean stress versus cycles diagram, the mean stress initially increases or decreases during the first few cycles, indicating an unstable condition. Eventually, the mean stress stabilizes around a constant value, which may be slightly positive, negative, or close to zero. In last cycles, the mean stress presents an abrupt drop or increase which keeps up with the complication phenomena that follow failure. A zero mean stress value signifies that the hysteresis loop is symmetric along the horizontal axis, while negative values indicate a downward shift and positive values an upward shift.

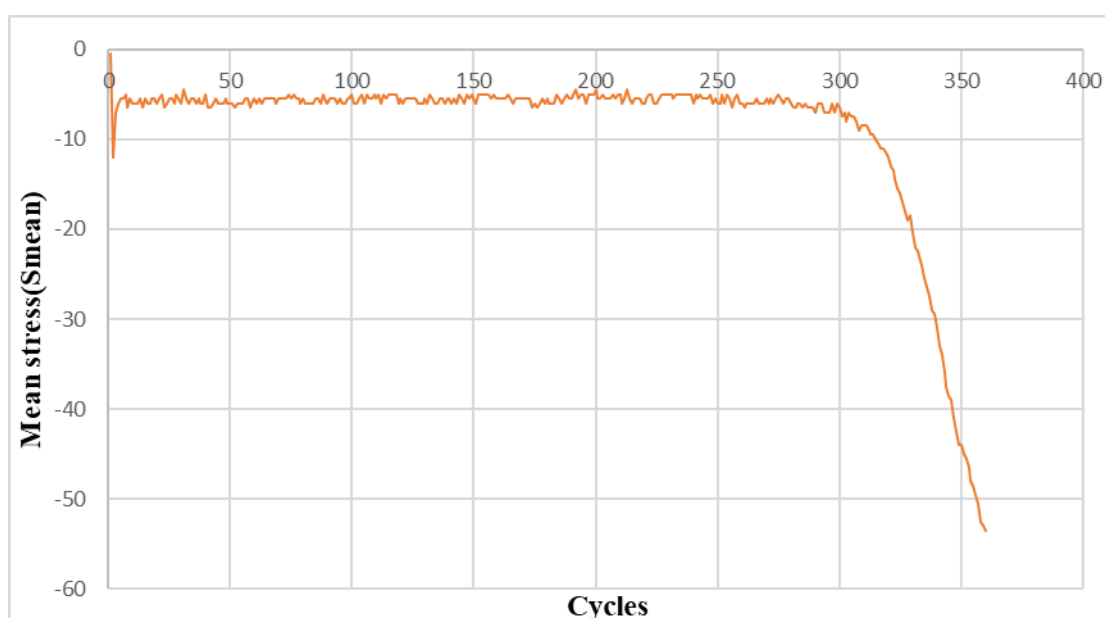


Fig 1.12 Smean stress versus number of cycles diagram of S355_T2_Pelma-1.2%.

1.5 Stress-controlled tests

In stress-controlled tests, a specified stress amplitude is applied to the material, and the resulting strain response is recorded. This method enables the analysis of material behavior under consistent or fluctuating stress conditions. It is particularly valuable for studying the effects of cyclic loading, such as ratcheting phenomenon which analyzed, next.

1.5.1 Ratcheting

Ratcheting is a cyclic plasticity phenomenon that appears when a material is submitted to stress-controlled test with negative or positive mean stress value. In other words, the stress ratio, i.e. maximum to minimum stress must be different from -1, [9]. Quantitatively, ratcheting is defined as the plastic strain accumulation that follows mean stress, [20], [26]. So, the existence of ratcheting requires applied stress beyond the yield strength limit, to ensure plastic deformation.

Schematically, as illustrated in **Fig 1.13, 1.14, 1.15**, ratcheting is perceived by the continuing shift of each hysteresis loop changing strain, while the stress limits stay constant. The way that each stress-controlled cycle translates, leads in distinguishing three types of ratcheting, [9].

- **Constant ratcheting (Fig 1.13).** Under certain stress loading conditions some materials indicate a linear increase of cyclic plastic strain. The distance between peak and valley strain points of each hysteresis loop maintain a steady state with the number of cycles and the shape of loops have not a reliable change. So, the material undergoes negligible cyclic hardening or softening, until failure occurs due to microstructural damage, crack initiation, and propagation. [27]

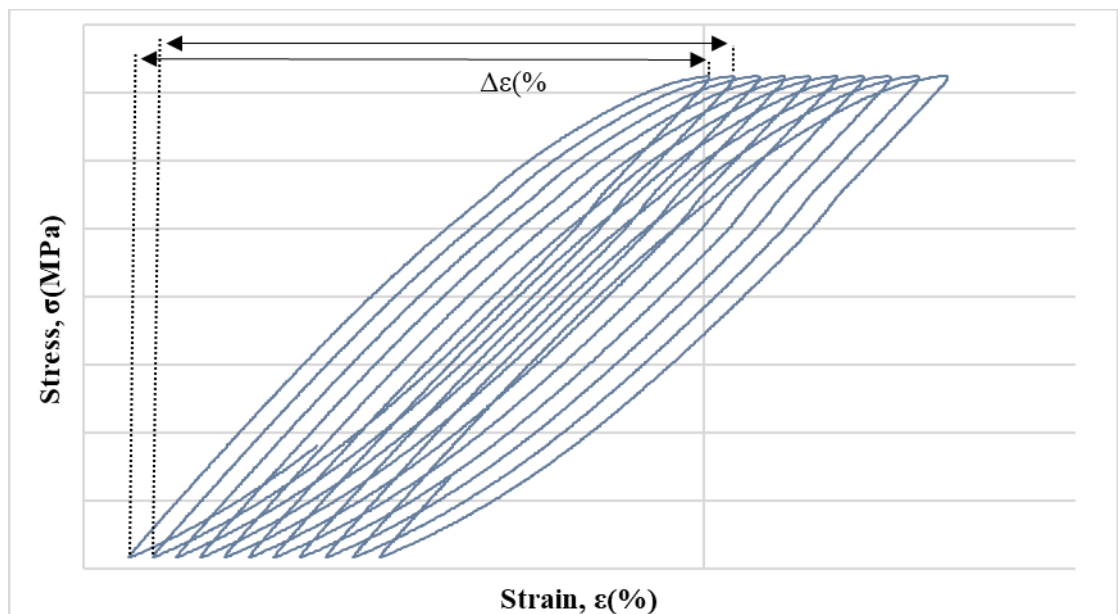


Fig 1.13 Constant ratcheting behavior of S700(L-N) coupon.

- **Increasing ratcheting rate, (Fig 1.14).** A ratcheting strain rate with upward character means a more and more increasing ratcheting strain accumulation from cycle to cycle, leading to unsteadiness plastic flow and localized necking. As is indicated by some stress-controlled experiments of this database, the material which is characterized primarily by softening behavior or have higher mean stress and amplitude stress obtain increasing ratcheting rate.

Life span of the material moves down substantially, as the cross-sectional area reduce because of the rapid elongation, ending in overload failure. The mechanism of this failure can be ductile so there it is significant plastic deformation or brittle i.e. sudden break with little plastic deformation.[27]

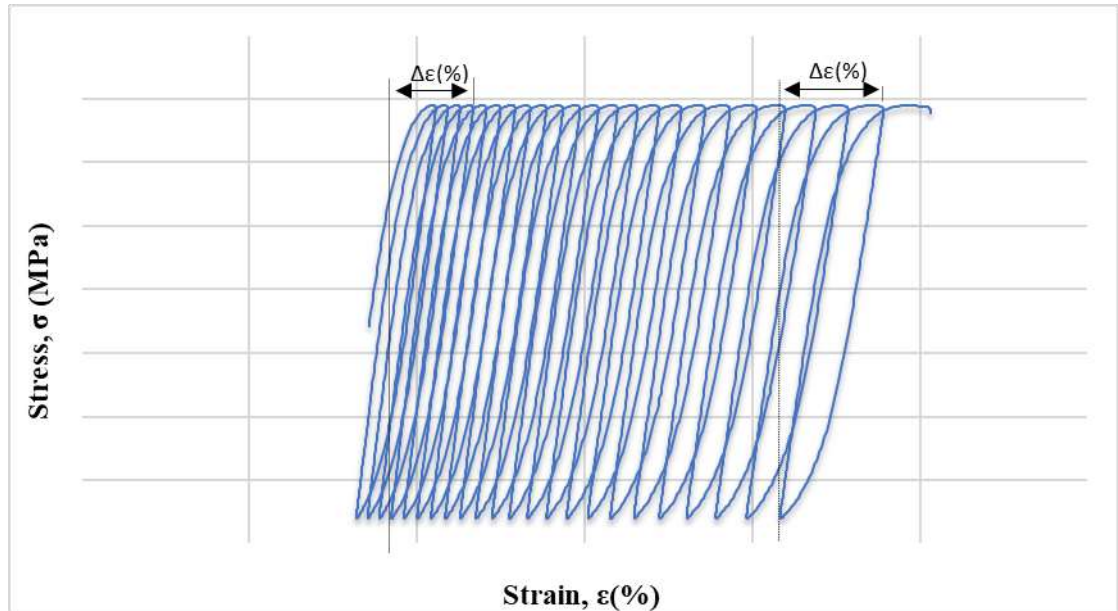


Fig 1.14 Increasing ratcheting behavior of S700(MATCH) coupon.

Decreasing ratcheting rate, (Fig 1.15). Negative ratcheting, continuous reduction in the rate of ratcheting ending up to shakedown (plastic or elastic) i.e. from one cycle onwards the hysteresis loops identify. The material resists further plastic deformation under the submitted cycling condition and as a result the accumulation of ratcheting strain stop in steady value for a finite number of cycles. This situation mainly appears at materials with cyclic hardening behavior. The mechanism of failure can be high-cycle fatigue, if the decreasing ratcheting rate led to elastic shakedown or low cycling fatigue, in occasion of plastic shakedown. [9],[27]

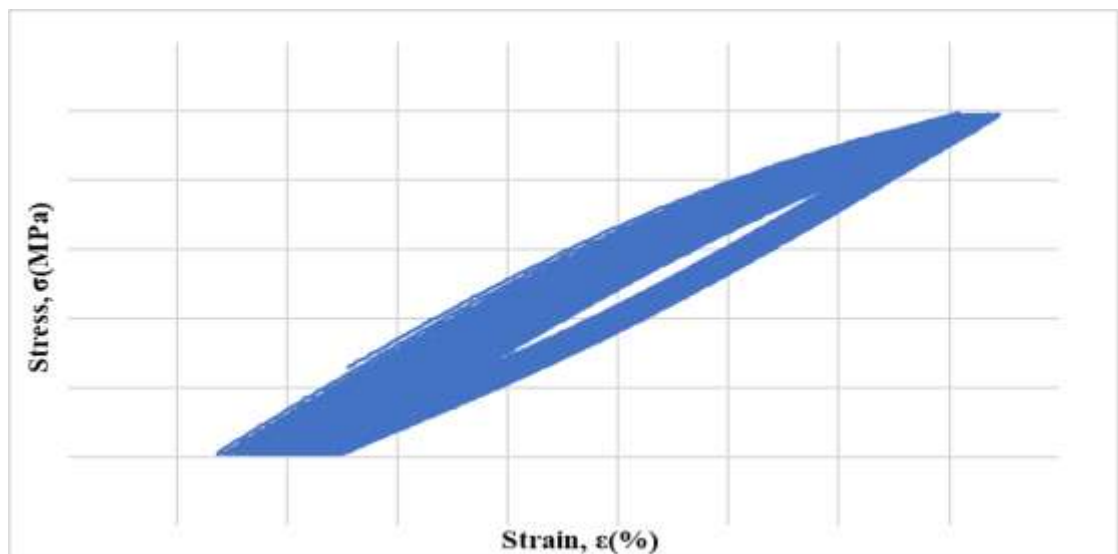


Fig 1.15 Negative ratcheting behavior of 625 stainless steel coupon.

- **Stress-controlled tests diagrams**

In the context of the analysis of the stress control tests, the following diagrams were calculated:

- **Debar_max (%) - Ni:** The gap between consecutive peak strain values in function with the intervals which determined by the number of cycles i.e. $N_i = N - 1$. This diagram indicates one way to express how each hysteresis loop translates according to the previous one over time. If Debar_max is positive the stress-strain curve of the test shift forward, so there is additional ratcheting strain accumulation with increasing or decreasing rate, that depends on how change the magnitude of Debar_max . If Debar is negative the loops translate to the opposite direction, which mean negative phenomenon of plastic shakedown, as the hysteresis loops identify. [$\text{Debar_max} = \text{emax}(N+1) - \text{emax}(N)$]
- **Er (%) - N:** The average value of maximum and minimum strain per cycle, which represent the ratcheting rate versus the number of cycles. [$\text{Er} = (\text{emax} + \text{emin})/2$]

- **Relation of cyclic hardening/softening and ratcheting.**

The asymmetry conditions of stress-controlled cyclic test make ratcheting a vital studying. Ratcheting phenomenon involves two types of cumulative damage: fatigue damage due to: 1) the repeated formation of stress-strain hysteresis loops adding small incremental damage with each cycle and 2) the buildup of ratcheting strain. These effects can greatly reduce a material's performance. Also, the upcoming elongation in direction of mean stress caused by the accumulation of ratcheting strain implies with the thinning of the component's cross-sectional area, leading to the early failure of the specimen. The ratcheting strain versus the number of cycles is a representative curve of how the ratcheting behavior evolve over time, connecting with the hardening and softening mechanisms. Certainly, a standard ratcheting curve consists of three zones: primary, secondary, and tertiary. In the primary zone (**Fig 1.16-I**), the increase of accumulation ratcheting strain with a decreasing rate (as indicated by the slope of curve $d\text{Er}/dN$), combined with no major reduction of cross-sectional area result in ascendancy of cyclic hardening. Afterward some cycles, the slope of curve $d\text{Er}/dN$ obtain a constant value (second zone, **Fig 1.16-II**), as the strain hardening is balanced by the lowering of the cross-sectional area. In last zone (**Fig 1.16-III**), the decrease of cross-sectional area become determinative because of the large strain accumulation and so the material obtains softening character. As a result of this continuous decreasing of cross-sectional area, the maximum true stress reaches a higher value and the failure are responded to necking.[20],[28],[9],[29]

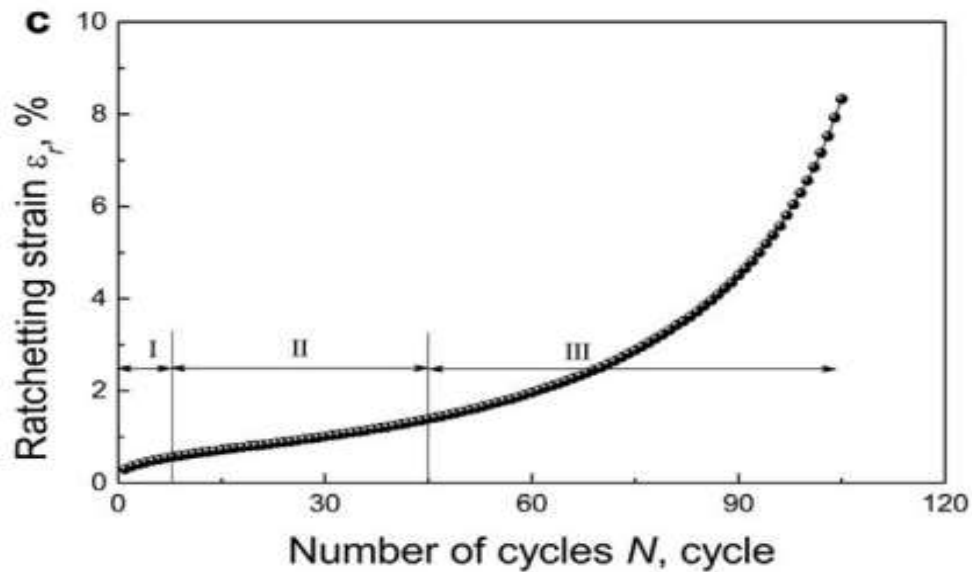


Fig 1.16 Ratcheting strain curve [8].

- **Microstructure analysis of ratcheting**

The existence of ratcheting phenomenon depends on dislocation displacements, their interactions and cell formation, [9]. The obstacles like grain boundaries, precipitates and inclusions, block the dislocation movement as the maximum shear stress in direction of the mean stress is not enough to beat them. The asymmetry of cyclic loading, in which subjected a material led dislocations to move more in mean stress direction, oscillating between obstacles. Because the deformation initially occurs elastically upon load reversal before dislocation motion is initiated, a hysteresis appears in the stress-strain diagram, [28],[30]. Therefore, depending on the nature of the obstacles and stress condition, the appropriate mechanisms are deployed in order to overcome the obstacles. These can respond in annihilation, in generation of new dislocations, maybe in a thermally activated processes and pile-up. Considering positive mean stress, the absolute value of maximum stress exceeds minimum one, so the shear stress on the dislocations is significantly more likely to overcome the obstacles, causing the hysteresis loop to shift and subsequently adding ratcheting strain. [28]

1.6 Compression tests

Compression tests are vital for assessing the behavior of materials when subjected to compressive forces. They offer key insights that allow engineers and material scientists to select appropriate materials for various applications, ensuring the safety and performance of structures and products. Some materials exhibit markedly different characteristics under compression compared to tension, and in specific scenarios, they are predominantly used to endure compressive loads. These tests yield

essential mechanical properties, including compressive yield strength, compressive ultimate strength, and compressive modulus of elasticity.[9]

Some materials break when they reach their compressive strength limit, while others undergo irreversible deformation. As a result, a certain level of deformation can be treated as the maximum compressive load. Compressive strength is a crucial factor in structural design. [31] The specimen typically used is a simple cylinder with a length-to-diameter ratio (L/d) ranging from 1 to 3. However, for cases where precise determination of the elastic modulus in compression is required, L/d ratios up to 10 may be utilized. Additionally, specimens with square or rectangular cross sections can also be tested. [9]

1.6.1 Mechanical properties

The early stages of compressive stress–strain curves exhibit a similar overall behavior to those observed in tension, **Fig 1.17**. Consequently, various material properties, including the elastic modulus (E), the proportional limit (σ_p), and the yield strength (σ_y 0.2%), can be determined from this initial portion in the same way as they are for tension.

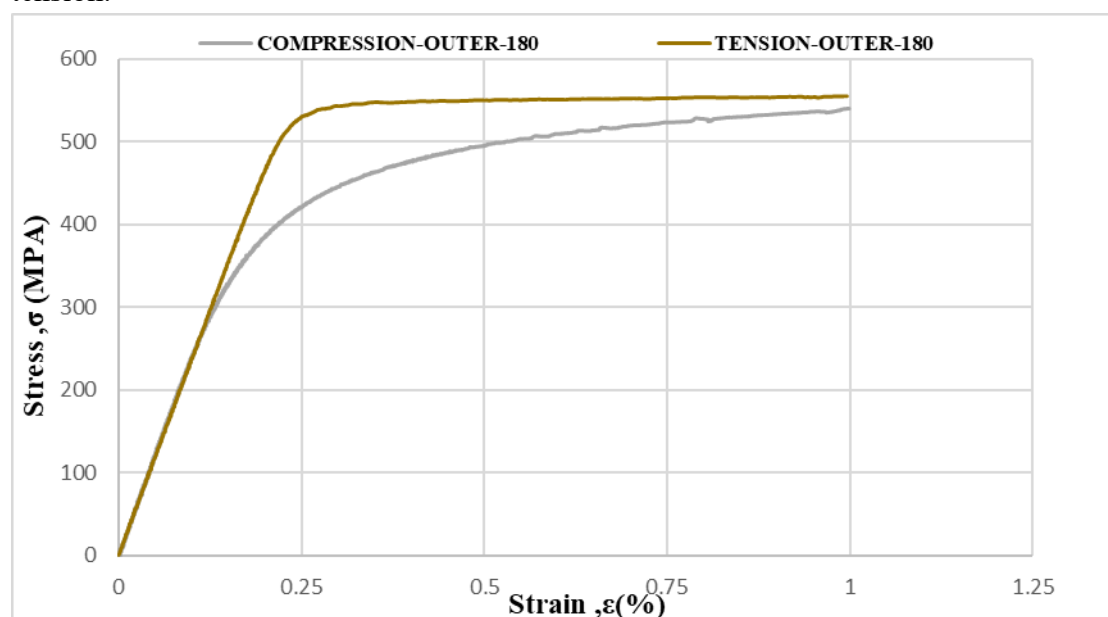


Fig 1.17 Stress-strain curve of outer 180 specimen for compression and tension test.

The proportional limit marks the point on a stress-strain curve where stress remains directly proportional to strain. Within this linear range, the material undergoes elastic deformation, meaning it will revert to its original shape when the stress is removed. Beyond this point, the material may still exhibit elastic behavior, but the stress-strain relationship ceases to be linear. If the stress continues to increase beyond this limit, the material may experience permanent deformation, meaning it will not fully return to its original shape.

The behavior of materials under compression differs qualitatively from their behavior under tension. Notably, while tension leads to a reduction in force before final fracture due to necking, this phenomenon does not occur in compression. Instead, the cross-sectional area increases, causing the stress-strain curve to rise sharply, with no peak before fracture. Consequently, in compression, the engineering ultimate strength and fracture strength are identical. [9]

2. CHAPTER - TENSILE TEST ANALYSIS

2.1 Tensile test summary

For the tensile experiments of this database are measured and documented the mechanical properties of various materials. These properties, detailed in the subsequent tables, provide a comprehensive overview of each material's behavior under tensile stress. And by examining them, the materials can be classified and analyzed based on their specific characteristics, allowing for a deeper understanding of their performance under different conditions and drawing conclusions about the suitability of these materials for various applications.

In **Table 2.1**, the mean values of E, $\sigma_{y0.2\%}$, and $R_{t0.5\%}$ from tensile experiments are shown, along with the respective divergences for each value. The divergences for $\sigma_{y0.2\%}$ and $R_{t0.5\%}$ range from 0.09% to 10.73% and 0.05% to 10.96% respectively, which are acceptable percentages. The higher values near 10% calculated by specimens taken from different directions and that also explains why the $R_{t0.5\%}$ and $\sigma_{y0.2\%}$ have almost similar diverges on the same material. The elastic modulus for the materials starts from 175823 MPa and ends at 226875 Mpa which are logical values for steels. Moreover, the diverges of Elastic modulus reaches until 12.80%, except the X60_30in has the higher diverge equal to 17.95%.

Table 2.1 Summary of database tensile tests with measured yield strength at 0.2% offset ($\sigma_{y0.2\%}$) and at 0.5% total plastic strain ($R_{t0.5\%}$) and Elastic modulus (E).

GRADE	TENSION	$\sigma_{y0.2\%}$ (MPa)	Div(%) - $\sigma_{y0.2\%}$	$R_{t0.5\%}$ (MPa)	Div(%) - $R_{t0.5\%}$	E (MPa)	Div(%) - E
S700(L-N)	7	793.85	7.414%	787.42	8.817%	226857	10.07%
S355(L-N)	6	339.5	1.03%	339	1.77%	208333	1.60%
ASME-S234	4	277.5	5.23%	296.75	10.19%	195284	2.57%
S275J2	4	325.25	2.69%	333.75	2.92%	204363	6.24%
X65 16in	6	546.66	10.73%	550.33	10.96%	207346	5.61%
X60 30in	14	541.92	10.13%	544.35	7.46%	214683	17.95%
X65 26 in	12	521.58	5.07%	528.09	5.47%	220083	11.06%
X65(MPL)	3	509	3.73%	510.33	3.79%	226248	0.83%
625 stainless steel	3	457	10.72%	468.3	9.96%	175823	12.80%
43A-steel	4	275.75	4.99%	286.5	4.36%	193189	2.59%
S355MC_0%	2	385.5	0.13%	388.5	0.39%	202185	0.18%
S355MC_9%	2	496.5	0.30%	496.5	0.30%	187464	1.66%
S355MC_12-13%	3	520	0.77%	520	0.77%	184433	0.83%
S355MC_15-16%	2	534	0.19%	534	0.19%	191390	1.32%
S460MC_0%	2	532.5	0.09%	528.5	0.66%	214090	0.50%
S460MC_9-10%	2	634.5	0.08%	634.5	0.08%	209015	1.59%
S460MC_12-13%	1	659	-	659	-	210300	-
S700(MATCH)	1	740	-	708	-	200784	-
S355 T1	2	439	4.33%	439.5	4.44%	206565	0.07%
S355 T2	2	379	8.18%	392.5	5.48%	192734	0.00%
X52 SP	3	355.33	2.626	369	0.54%	191354	7.16%
TS590(323,7*10)	2	729	0.82%	724	0.55%	212219	0.75%
TS590(355*12)	2	739.5	0.88%	737.5	6.10%	208342	3.71%
P355	4	409	3.91%	409.25	3.84%	211618	8.21%

***Note:**

- $\sigma_{y0.2\%}$ = yield strength at 0.2% offset
- $R_{t0.5\%}$ = yield strength at 0.5% total plastic strain
- E=Elastic modulus
- $Div (\%)-\sigma_{y0.2\%}$ = (mean value of $\sigma_{y0.2\%}$ -max specimen value of $\sigma_{y0.2\%}$)/mean value of $\sigma_{y0.2\%}$, respectively for $R_{t0.5\%}$ and E.
- EUTS=strain at ultimate stress
- σ_{UTS} =ultimate stress
- EFR=strain at fracture point
- The S355J2+N symbolized as S355(L-N) and the S700 from the same reference as S700(L-N), in order to distinguished from the same grade from 'MATCH' research. L and N represent the names of writers of the corresponding Thesis (L from 'Laxanidis' and N from 'Ntakhs').
- The T1 and T2 in front of HEA indicate the different chemical compositions of two S355 –steel HEA. The specimens are extracted from the kormos and pelma position of the HEA.
- The TS590(323.7*10) and TS590(355*12) specimens may be symbolized TEST(4-) and TEST(5-) or just (4-) and (5-), respectively.

2.2 Experimental results

In **Table 2.2**, are demonstrated the mean value of each tensile tests' properties, while the materials were sorted from smallest to largest yield limit with offset 0.2%. If the classification was based on $R_{t0.5\%}$, the results will be almost the same (S355MC_0% and S700(MATCH)). The experiments of X60-steel for 30in and X65-steel for 16in and 26in were not conducted until failure but until 1% strain, so the values with the star are the higher available and not the real one.

Table 2.2 Properties of tensile tests.

GRADE	$\sigma_{y0.2\%}$ (MPa)	$R_{t0.5\%}$ (MPa)	σ_{UTS} (MPa)	EUTS (%)	EFR (%)	PLATEAU RANGE(%)
43A-steel	275.5	286.5	404.37	23.1%	31.1%	-
ASME-S234	277.5	296.75	444.95	17.66%	33.21%	0.16%-1.58%(L)
275J2	325.25	333.75	479.6	16.47%	29.45%	0.2%-2.01%
S355(L-N)	339.5	339	488.76	18.22%	31.08%	0.22%-1.93%
X52 SP	355.33	369	532.7	16.71%	25.4%	0.26%-1.25%
S355 T2	379	392.5	485.1	14.71%	23.7%	0.435%-2.63%
S355MC_0%	385.5	388.5	460.91	18.15%	40.75%	0.72%-2.49%
P355	409	409.25	576	16.62%	51.33%	0.27%-0.725%(L)
S355 T1	439	439.5	610.5	13.14%	27.79%	0.23%-2.1%
625 stainless	457	468.3	830.4	50.63%	72.36%	-

S355MC_9%	496.5	496.5	512.4	6.62%	22.92%	-
X65(MLP)	509	510.33	589.5	11.05%	73.45%	-
S355MC_12-13%	520	520	526.57	6.069%	20.07%	-
X65_26in	521.58	528.09	573.11*	4.99%*	-	-
S460MC_0%	532.5	528.5	592.39	13.008%	29.67%	0.52%-2.72%
S355MC_15-16%	534	534	537.29	0.81%	23.97%	-
X60_30in	541.92	544.35	560.82*	0.99%*	-	-
X65_16in	546.66	550.33	586.25*	1.03%*	-	-
S460MC_9-10%	634.5	634.5	637.9	0.43%	16.53%	-
S460MC_12-13%	659	659	679.6	0.41%	10.47%	-
TS590(323.7*10)	729	724	809.125	7.71%	15.93%	-
TS590(355*12)	739.5	737.5	815.5	7.34%	15.76%	-
S700(MATCH)	740	708	835.8	4.04%	14.86%	-
S700(L-N)	793.85	787.42	847.45	7.47%	8.61%	-

***Note:**

- (L)=All specimens are extracted from longitudinal direction

2.2.1 Fracture elongation classification

- First region

Firstly, the materials are separated based on their ductility in three parts according to elongation until fracture. In first one, are placed the materials with E_f (%) less than about 17%. Certainly, the S700, the TS590, the S460MC_12-13%, and the S460_15%, metal specimens have E_f (%) from 8.61% until 16.53% as shown in **Fig 2.1**.

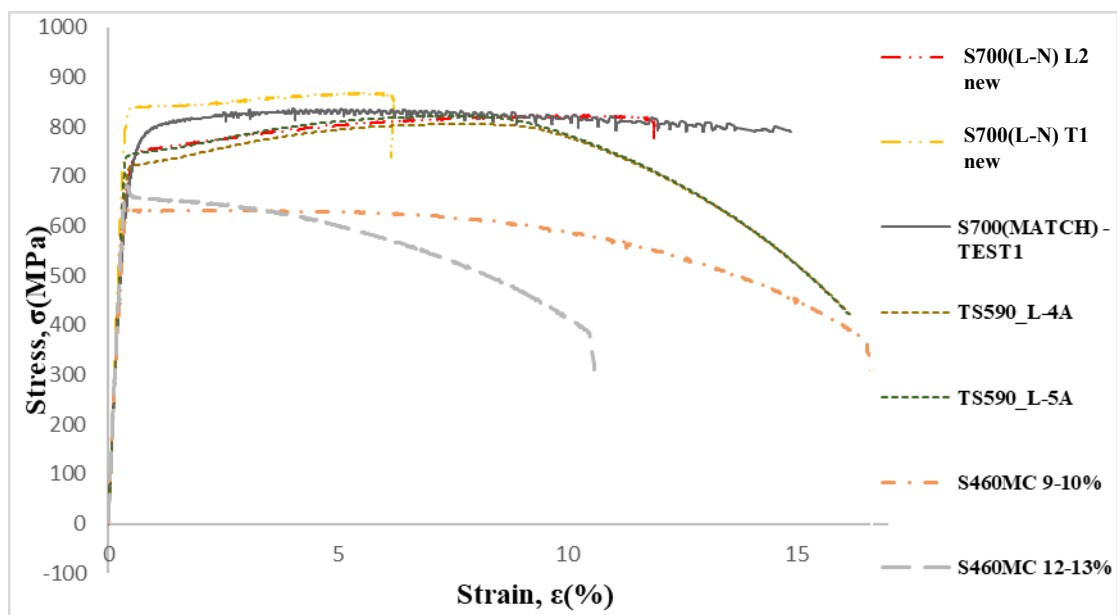


Fig 2.1 Steel specimens with E_{fr} (%) smaller than 17%.

However, these behavior for S460MC is not normal, it caused by the pre-strain process 9-10% and 12-13%, as the S460MC with 0% prestrain, have 3 times higher E_f (%) ($S460MC_0\%_E_f$ (%) - $S460MC_12-13\%_E_f$ (%) = 19.19%), and 12.75% higher ultimate stress which appear at about 0.4% strain, as presented in **Fig 2.2**.

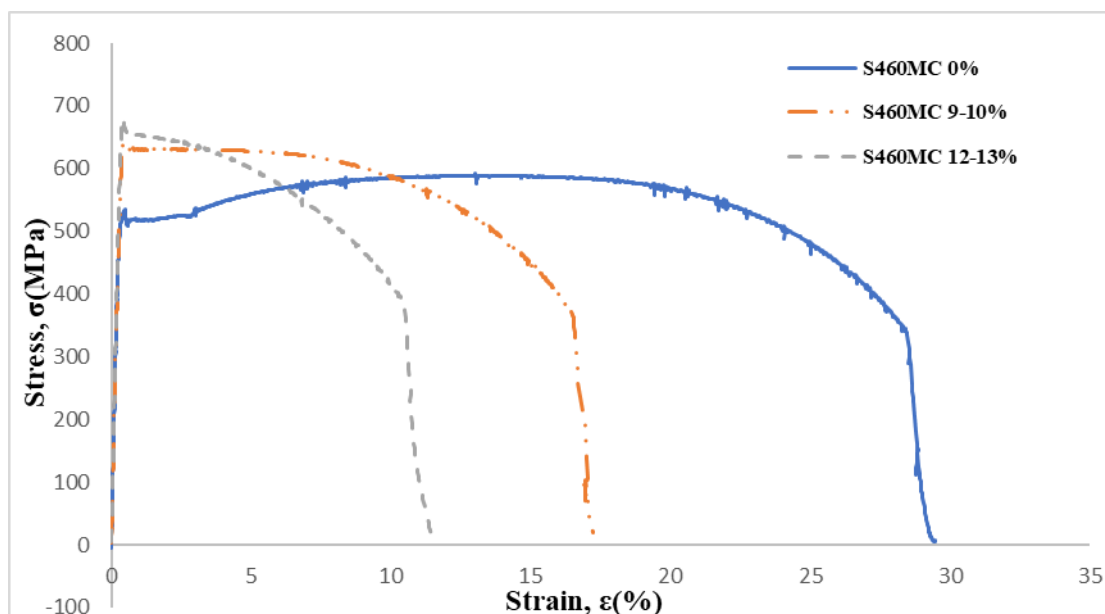


Fig 2.2 Stress-strain curves for S460MC with 0%,9-10%,12-13% prestrain.

The S700 steel exhibits the highest yield strength ($\sigma_{0.2\%}$) and ultimate tensile strength (σ_{uts}), particularly in the S700(L-N), which is produced through cold roll forming. Following this, the TS590 steel has lower yield strength and ultimate tensile strength compared to S700 steel.

- **Second region**

In **Fig 2.3** is illustrated that the second range of E_f (%) is from 20.07% to 33.21%, and apart from ASME-S234, 43A, 275J2, S355(L-N), X52_SP, S355_T1, S355_T2, S355MC_9%, S355MC_12-13%, S355MC_15-16% and S460MC_0% steel specimens.

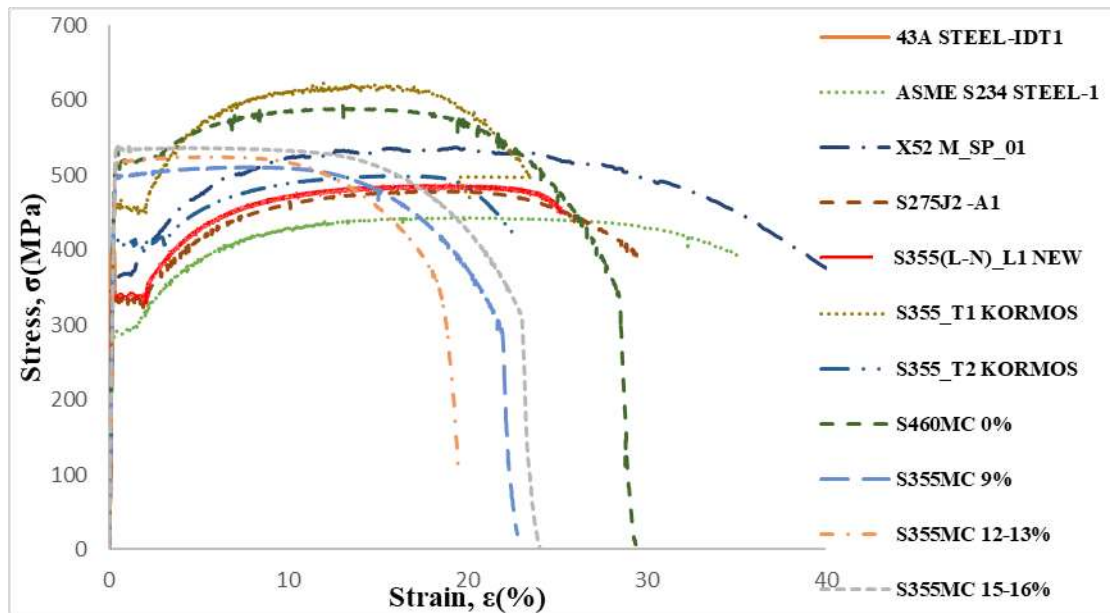


Fig 2.3 Stress-strain curves for specimens of region 2.

Like the S460MC, the S355MC with pre-strain present almost 50% lower Efr (%), $((S355MC_0\%_Efr(\%) - S355MC_12-13\%_Efr(\%))/S355MC_0\%_Efr(\%))$ while the $\sigma_{0.2\%}$ and σ_{uts} increase, as the pre-strain magnitude increases. It is observed that neck elongation (Euts) begins at approximately 6% strain for S355MC with 9% and 12-13% pre-strain levels, while it starts at just 0.81% strain for those with 15-16% pre-strain, **Fig 2.4**.

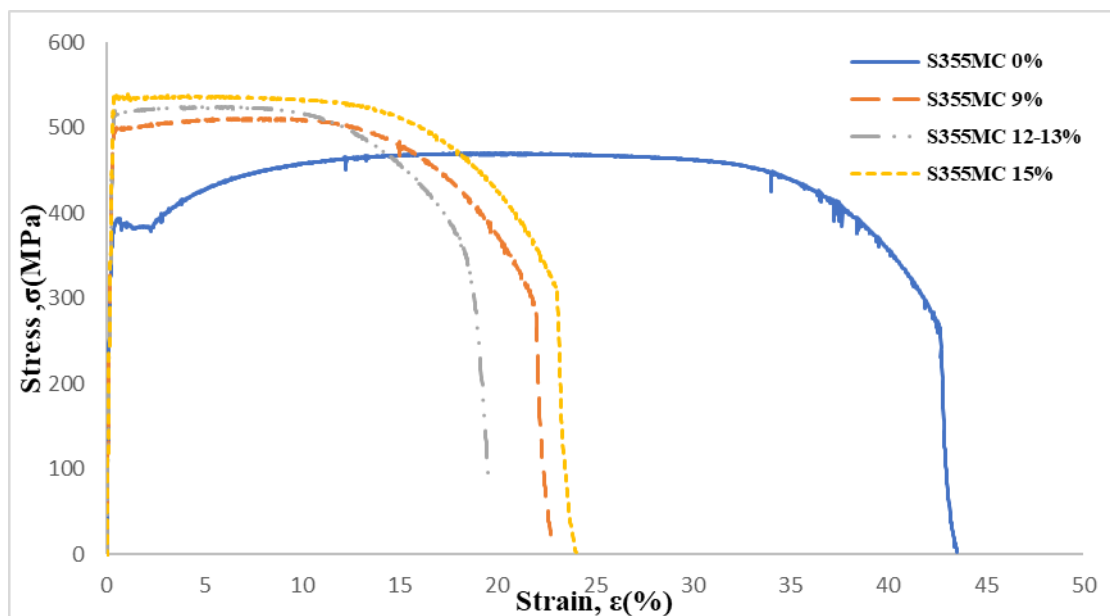


Fig 2.4 Stress-strain curves for S355MC with 0%, 9%, 12-13%, 15% prestrain

In contrast, all other materials exhibit neck initiation points ranging from 13% to 18.69% strain. Furthermore, from **Table 2.2**, the materials in this region of Efr (%), have the smaller values of $\sigma_{y0.2\%}$ and σ_{uts} , compared to the other two.

- **Third region**

In **Fig 2.5** are depicted, the S355MC_0%, P355, 625-stainless-steel and X65(MLP) - steel which indicate max elongation until fracture from 37.51%-73.45%. It is remarkable that the 625-stainless-steel appears Efr at 72.36%, which is extremely high according to the other metals, while at the same time reach its maximum strength at 830 MPa. This value is 45% higher than its yield limit and 17 MPa lower than the largest maximum strength of S700(L-N), and also appears at 50.63% strain (31.94% higher than the highest Euts percentage of 43-A steel). The X65(MLP) -steel has Efr =73.45 % and ultimate strength 13.6% higher than its yield limit which it is achieved at 11.05%. So, that means a neck elongation interval (from Euts to Efr) at about 62% strain, while the second higher value is 34.71% and appears at P355N. These materials have a larger area under the stress-strain curve, and so indicate greater toughness.

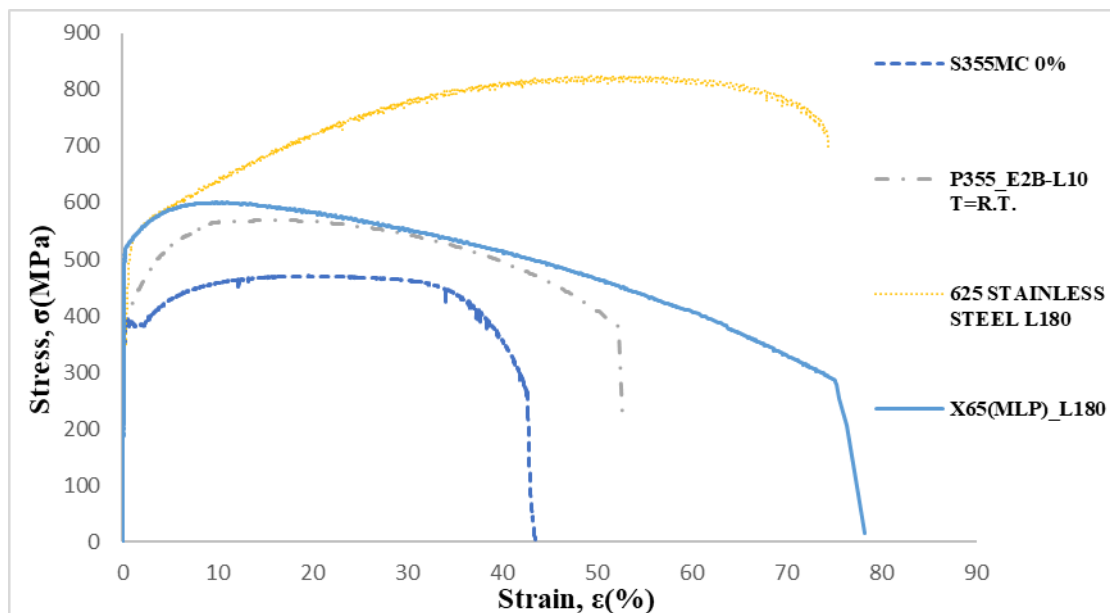


Fig 2.5 Stress-strain curves for specimens of region 3.

2.2.2 Yield limit and ultimate strength comparison

It has been observed that materials with lower yield limits exhibit a greater increase in ultimate strength. In **Table 2.2**, for materials ranging from 43A steel with a yield strength of $\sigma_{y0.2\%}=275.5$ MPa to 625 stainless steel with $\sigma_{y0.2\%}=457$ MPa, the yield-to-ultimate strength ratio ($\sigma_{y0.2\%}/\sigma_{uts}$, or y/T) fluctuates between 0.55 and 0.84. These values are significantly lower than the theoretical maximum of $y/T = 1$, indicating that these materials are more ductile, with a wider gap between the yield point and the onset of necking. In contrast, for materials with yield strengths between $\sigma_{y0.2\%}=496.5$ and 793.85 MPa, the ratio varies between 0.86 and 0.99(close to 1), as shown in **Fig 2.6**, suggesting that these materials are less ductile.

Furthermore, the 625 stainless steel, highlighted in red, stands out because it is distinct from the other specimens, being stainless steel, unlike the structural steels or pipe materials. This explains its very low y/T ratio of 0.55, and consequently, its higher ductility. Additionally, the steels that underwent prestrain are also marked in red, as this process influences the values of $\sigma_{y0.2\%}$ and σ_{uts} . Moreover, for pipes, the y/T ratio is required to be less than 0.92. All pipe materials in this dataset (S700(MATCH), TS590, X65(MLP), 625 stainless steel, P355, X52_SP, 43A, ASME S234) fall below this limit.

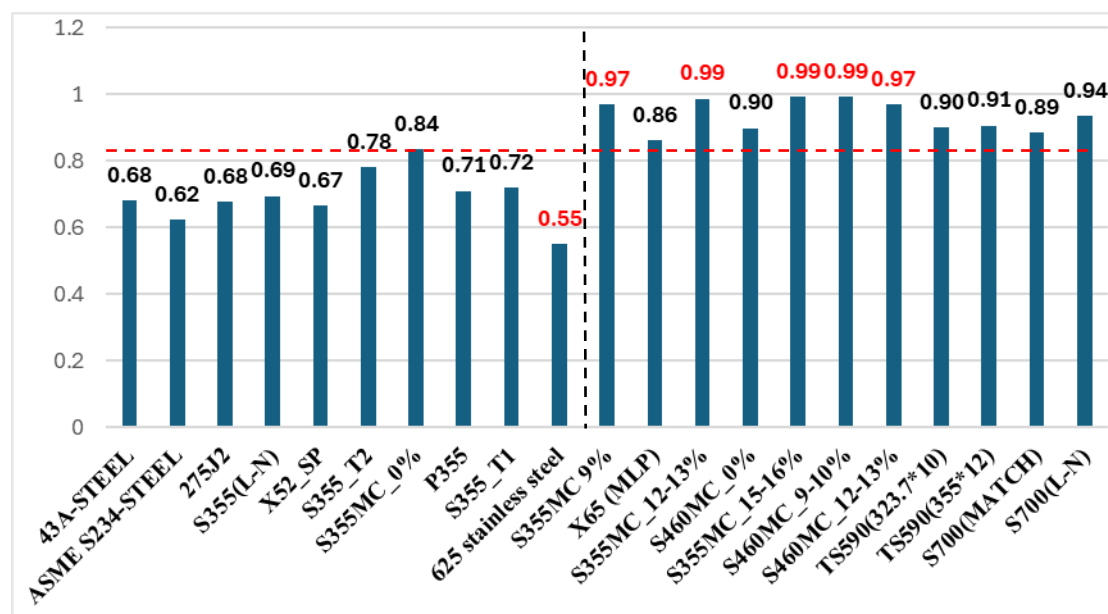


Fig 2.6 Ratio $\sigma_{y0.2\%}/\sigma_{uts}$ (y/T) for each material.

This phenomenon can be attributed to the fact that materials with lower yield limits tend to start with fewer dislocations, and during plastic deformation, the number of dislocations increases, leading to significant strain hardening.

2.2.3 Plastic plateau

In **Table 2.2**, the materials from ASME-S234 steel ($\sigma_y=277,5\text{MPa}$) until S355_T1($\sigma_y=439\text{MPa}$) and additionally the S460MC_% appears plateau, with the last one to demonstrate a very small plateau range compared to the others. Firstly, it is noted that specimens extracted from pipes, generally do not exhibit a plastic plateau, due to manufacturing processes like cold working, which increase dislocation density and result in a more gradual yield point rather than a distinct plateau. For ASME-S234 and P355N steels, only specimens extracted longitudinally from the pipe demonstrate a plastic plateau, while those from the hoop direction do not. However, the 43A-steel samples which characterized by the lower yield limit ($\sigma_{y0.2\%}=275.5\%$) and all extracted from longitudinal direction don't present any plateau. Also, X52_SP coupons extracted all from longitudinal direction of the pipe present plateau phenomenon - for the other direction there is no information, **Fig 2.7**.

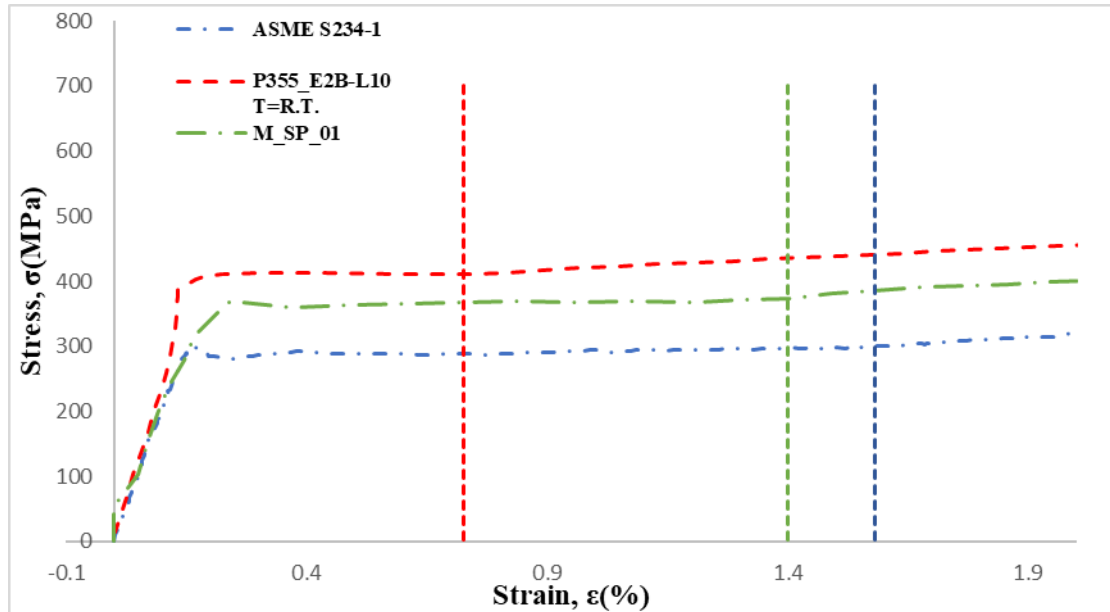


Fig 2.7 Plateau region for pipe specimens.

The S275J2, S355(L-N), S355_T1, S355_T2, S355MC_0%, and S460MC_0% specimens, which are extracted from plate and rectangular hollow sections, exhibit a plastic plateau up to 1.93% strain. This behavior is notably different from that of pipe specimens, as shown in **Fig 2.8**.

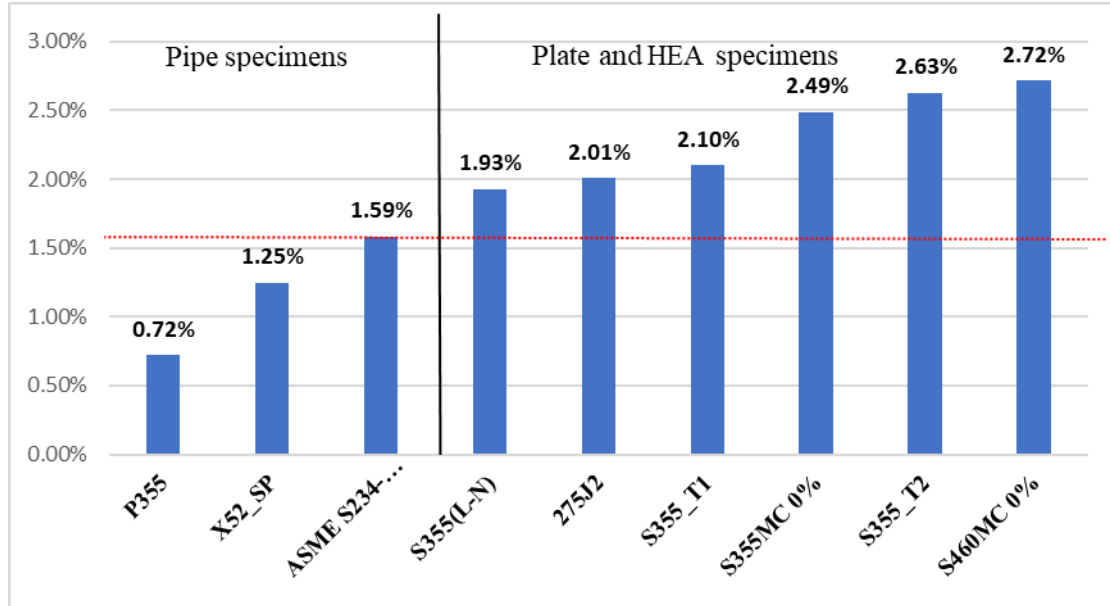


Fig 2.8 Specimens plateau (upper limit).

The S355MC and S460MC specimens, produced through thermomechanical rolling and cold drawing, show higher plastic plateau intervals equal to 0.72%-2.49% and 0.52%-2.72%, respectively. Notably, the S355_T2 specimen from the kormo of HEA has a plateau ranging from 0.32%-3.2%, as seen in **Fig 2.9**. While the corresponding

specimen from pelma presents plateau up to 2.07%, ending up in a mean plateau value of S355_T2 equal to 2.63%.

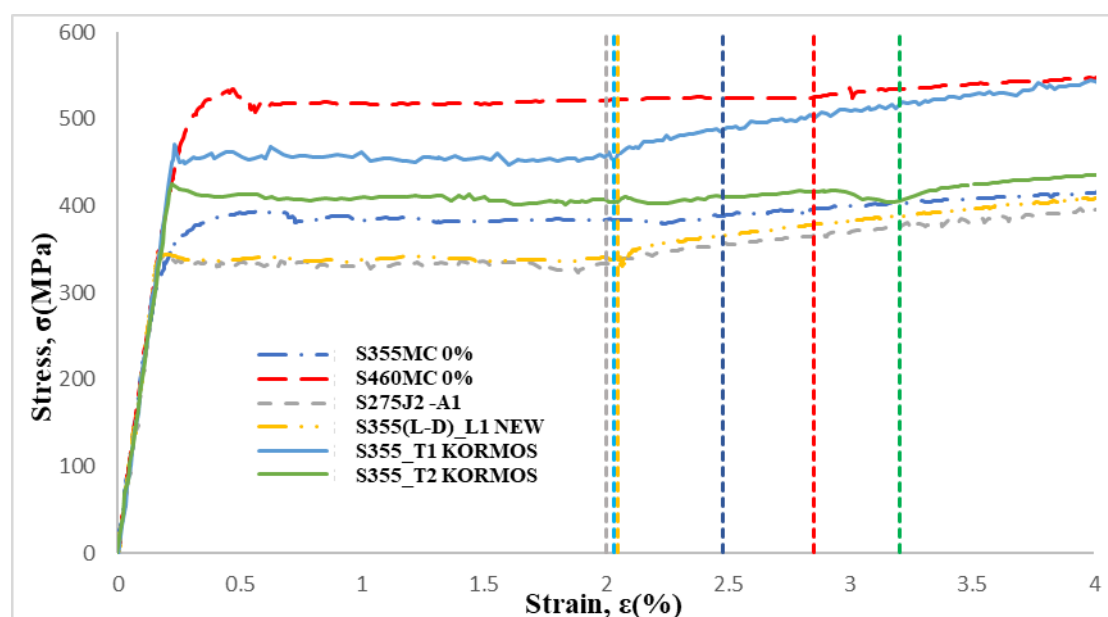


Fig 2.9 Plateau region for plate specimens.

Furthermore, the S355_T1 and S355_T2 specimens, which are distinguished by the different chemical composition, have no significant differences in plateau phenomenon. Furthermore, it is noticeable from **Fig 2.2** and **Fig 2.4**, that there is no plateau in S355MC and S460MC specimens that extracted from plates with prestrain process, while the un-strained ones present the higher plateau in relation to the other materials. Pre-strained causes dislocations to move and multiply within the material, thereby increasing dislocation density so the material frequently display work hardening. This leads to a smoother transition from elastic to plastic deformation, eliminating the flat plateau typically seen in the stress-strain curve.

3. CHAPTER – STRAIN CONTROLLED TEST ANALYSIS

3.1 Strain controlled test summary

In **Table 3.1**, as in the tensile tests, are calculated the mean values of E , $\sigma_{y0.2\%}$, and $R_{t0.5\%}$ for the tension curve of the first cycle with the respective divergences for each value, in order to decide on the correctness of the experiments. Also, the material has categorized in the prementioned table based on the yield limit, starting in ascending order. The divergences for $\sigma_{y0.2\%}$ range from 0.08% to 9.56% with the exception X60-steel ($\text{div-}\sigma_{y0.2\%}=19.06\%$). The $R_{t0.5\%}$ fluctuate between 0.0% to 10.7% with the same exception (X60 steel $\text{div-}R_{t0.2\%}=20.8\%$) and also X52_SP ($\text{div-}R_{t0.5\%}=17\%$). It is remarkable and desirable that like in tension tests, such as in strain controlled experiments the $\sigma_{y0.2\%}$ and $R_{t0.5\%}$ have nearby diverges for the same material grade, if not included X52_SP which has $\text{div-}\sigma_{y0.2\%}=4.59\%$. All materials have reasonable values. The highest deviation is seen in X60-steel, reaching 29.5%, while all others are below 17.68%. It is evident that X60-steel exhibits the greatest variability in calculated properties, which can be attributed to the specimens being extracted from three different regions of the plate (transverse, longitudinal, and middle). The 43A-BS4360 specimens with 0% prestrain, extracted from the inner surface of the pipe, exhibit a significantly lower yield limit compared to those taken from the outer surface, which are characterized by 9% prestrain. In contrast, the elastic modulus of the inner surface specimens is notably higher by 40000 MPa. Moreover, the S355MC and S460MC show obviously an increase in yield limit, as the magnitude of pre-strain increases, and the elastic modulus decreases (as happen at prementioned 43A-steel). This reduction is more noticeable compared to 0% with 8-9% process and much more lower comparing 8-9% with 12-13%. Except X65(MLP) steel, the classification from the lower to the higher value is the same for $R_{t0.5\%}$ and $\sigma_{y0.2\%}$.

Table 3.1 Summary of database strain-controlled tests with measured yield strength at 0.2% offset ($\sigma_{y0.2\%}$) and at 0.5% total plastic strain ($R_{t0.5\%}$) and Elastic modulus (E).

GRADE	C_STRAIN	$\sigma_{y0.2\%}$ (MPa)	Div- $\sigma_{y0.2\%}$	$R_{t0.5\%}$ (MPa)	Div- $R_{t0.5\%}$ (MPa)	E (MPa)	Div-E
BS4360 43A_0%	4	302.5	0.82%	308	0.00%	226856	5.22%
ASME-S234	6	303.67	5.4%	310.17	5.70%	210621	2.93%
S355(L-N)	2	354.5	1.55%	352.5	1.56%	204530	4.53%
S275J2	2	357.5	0.69%	352.5	2.90%	188910	9.46%
X52_SP	30	361.6	4.59%	355.3	17.00%	202349	9.69%
P355	6	383.17	6.80%	386.33	10.70%	203920	9.79%
S355 T2	6	406.33	0.08%	404.16	3.91%	210422	9.23%
S355MC_0%	9	410	2.43%	410	2.43%	214180	2.95%
BS4360 43A_9%	7	418.5	0.35%	421	0.23%	191901	6.29%
X60	20	430.85	19.06%	428.65	20.80%	231400	29.5%
S355 T1	8	434.4	7.23%	435.8	4.79%	207139	6.23%
S500	4	478.5	3.44%	475.5	0.73%	200750	4.38%
S355MC_8-9%	10	496.5	3.72%	496.6	3.34%	182772	3.76%
625 stainless	6	501.5	4.08%	504.8	3.33%	186909	4.32%
X65(MLP)	4	517	2.70%	518	2.50%	216988	7.81%
X65_PLATE-1	10	517.4	7.61%	514.76	7.64%	229336	13.45%
S355MC_12-13%	11	518	4.24%	518.8	4.08%	180726	4.03%
S460MC_0%	9	532.8	2.84%	535.6	3.62%	208118	3.54%
X65_PLATE-2	16	534.9	4.29%	533.06	4.14%	218482	16.85%
X65(HFW)	4	589.5	7.40%	591	6.9%	195850	6.47%
S460MC_8-9%	10	600.5	3.41%	608.1	2.65%	189258	7.25%
S460MC_12-13%	13	629.5	2.14%	629.6	1.21%	182778	10.83
S700(MATCH)	7	685.6	9.56%	681.5	7.24%	214701	6.93%
TS590(355*12)	2	726	1.93%	726	0.0193	196413	6.91%
TS590(323.7*10)	2	750	0.67%	745	0.67%	212492	0.07%
S700(L-N)	2	810.5	4.62%	795	4.65%	220000	2.27%

***Note:**

- X65(26in_t37) = X65_PLATE-1
- X65(26in_t19_44) = X65_PLATE-2

The yield limit and elastic modulus determined from strain-controlled tests shows significant differences compared to the $\sigma_{y0.2\%}$ and E from tensile tests, primarily due to the use of different specimen dimensions. This entails some reordering in terms of their placement based on the yield limit.

3.2 General Observations

3.2.1 Strain range and Cycles

A general observation about the strain-controlled test is that as the percentage of applied $\Delta\epsilon$ (%) increases, so the number of cycles for fatigue decreases, while the slope of the amplitude stress-cycles curve increases, as the moment of fatigue failure

approaches. An instance of that behavior is illustrated in **Fig 3.1**, the specimen with applied strain range 0.4%(ODF1_0.2_1) demonstrates failure at about 14500 cycles. On the other hand, for $\Delta\epsilon=0.8\%$ (ODF4_0.4_2) and $\Delta\epsilon=1.6\%$ (ODF6_0.8_2) at about 3900 and 1094 cycles correspondingly. **Fig 3.2** clearly illustrates that beyond the stabilization region, the amplitude stress vs. cycles curves becomes markedly steeper for $\Delta\epsilon=0.8\%$, with an even more pronounced effect observed for $\Delta\epsilon=1.6\%$, where the stabilization region is absent.

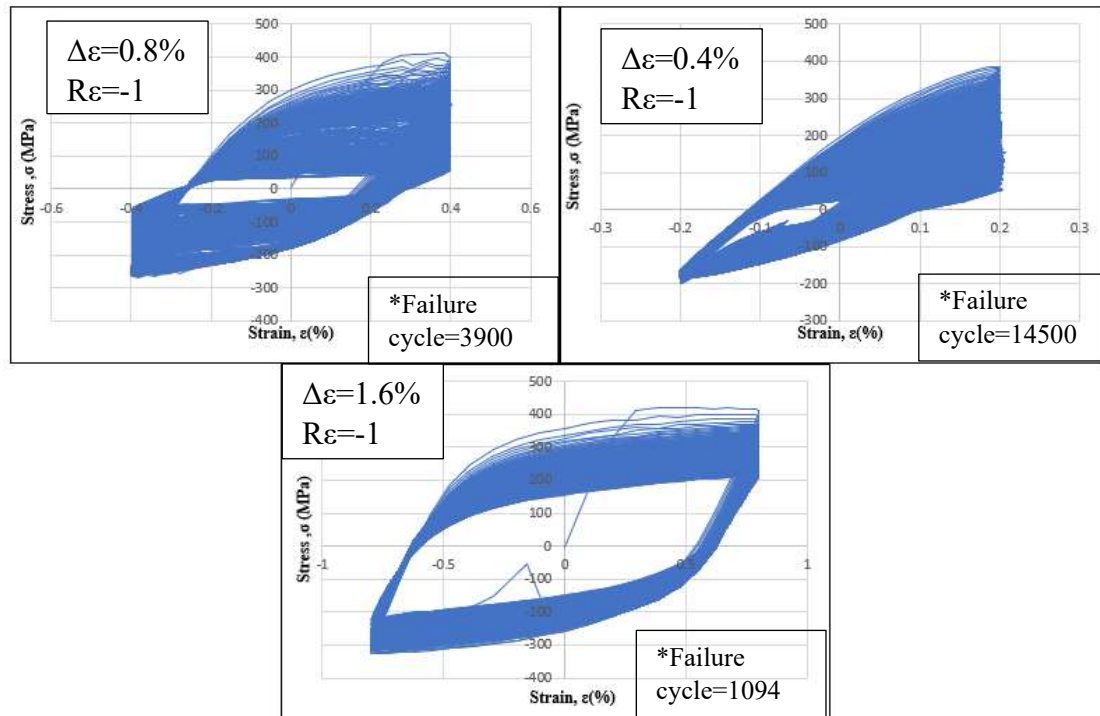


Fig 3.1 Strain control hysteresis loops for BS4360-43A steel coupons for $\Delta\epsilon=0.2\%, 0.4\%, 0.8\%$.

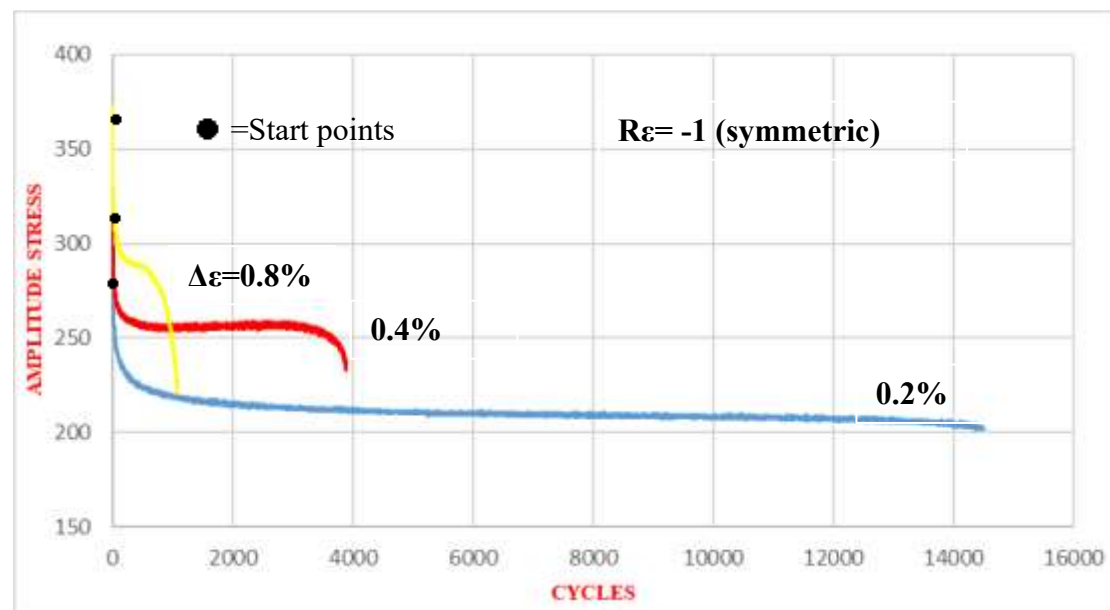


Fig 3.2 Amplitude stress versus cycles curves of BS4360 43A-steel.

3.2.2 Strain range and cyclic response

Another important notice is the effect of the amplitude strain on the cyclic or hardening behavior of metal. In this way, the ASME-S234 and 625 stainless steels specimens present higher cyclic hardening going from $\Delta\epsilon=1.5\%$ to $\Delta\epsilon=3\%$ and from $\Delta\epsilon=3\%$ to $\Delta\epsilon=6\%$, respectively. **Fig 3.3** shows the strain-controlled tests conducted on ASME-S234 steel coupons. The slope of the corresponding stress-amplitude vs. cycles curves (**Fig. 3.4**) highlights the observed cyclic behavior, which is attributed to the increase in applied $\Delta\epsilon$ (%).

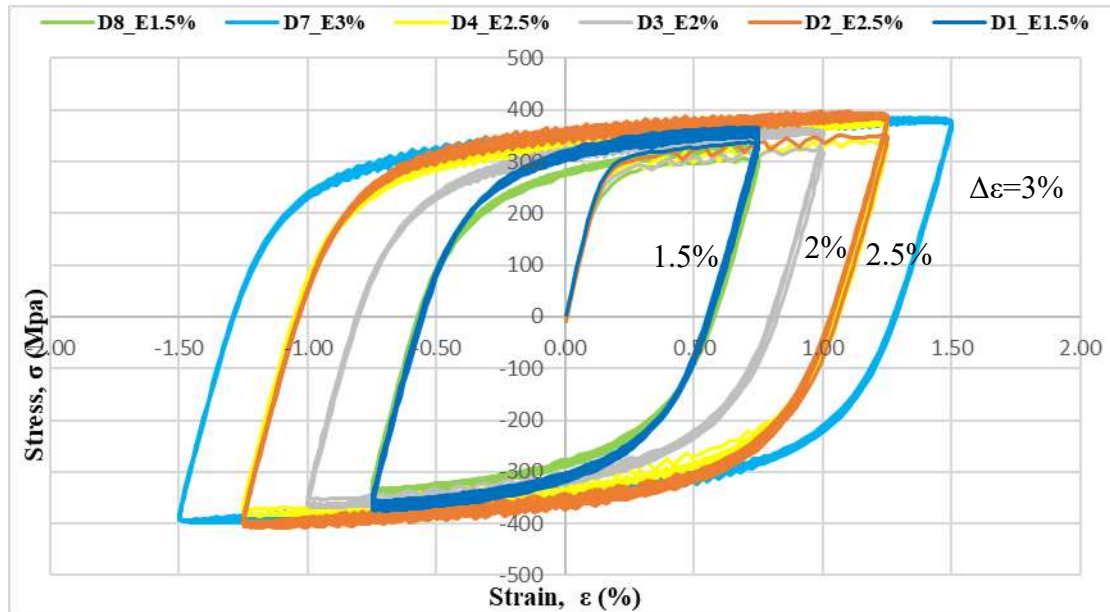


Fig 3.3 Strain control hysteresis loops for ASME S234 steel coupons for $\Delta\epsilon=1.5\%, 2\%, 2.5\%, 3\%$.

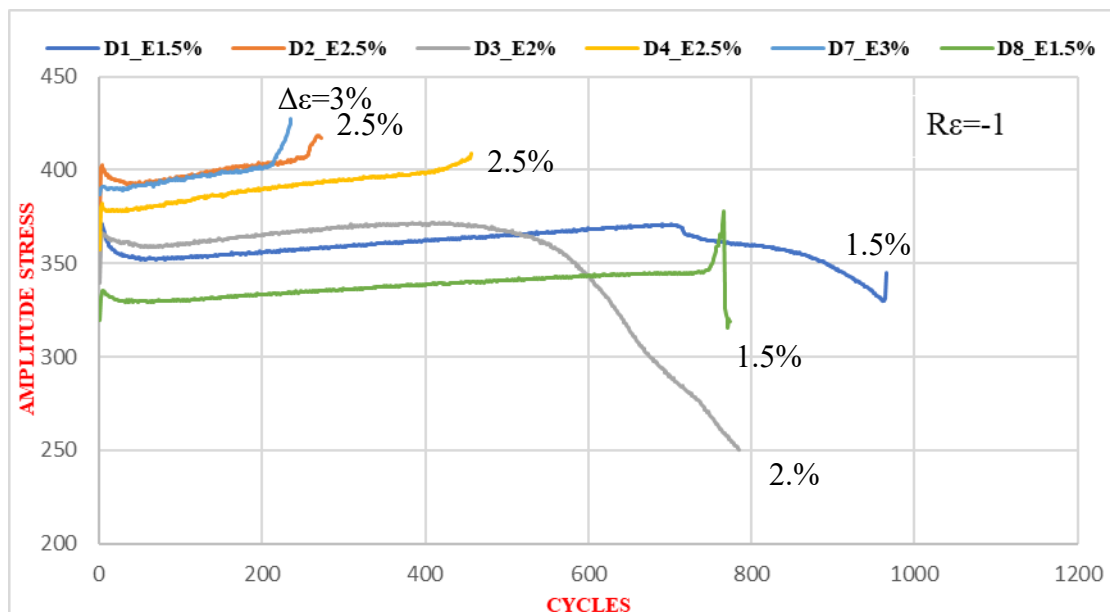


Fig 3.4 Amplitude stress versus cycles curves of ASME-S234 steel.

Furthermore, the X52_SP_L-1, X52_SP_L0, P355N and S275J2 steel specimens present transition from the cyclic softening to hardening behavior from lower towards higher $\Delta\epsilon$ (%). **Fig 3.5** shows the strain-controlled experiments for P355 and in **Fig 3.6** illustrated the respective amplitude stress versus cycles curves. It seems that, both in transverse and in longitudinal direction (specimens that characterized by T and L respectively), going from 1.5% to 4.5% strain range the curve obtain increasing features.

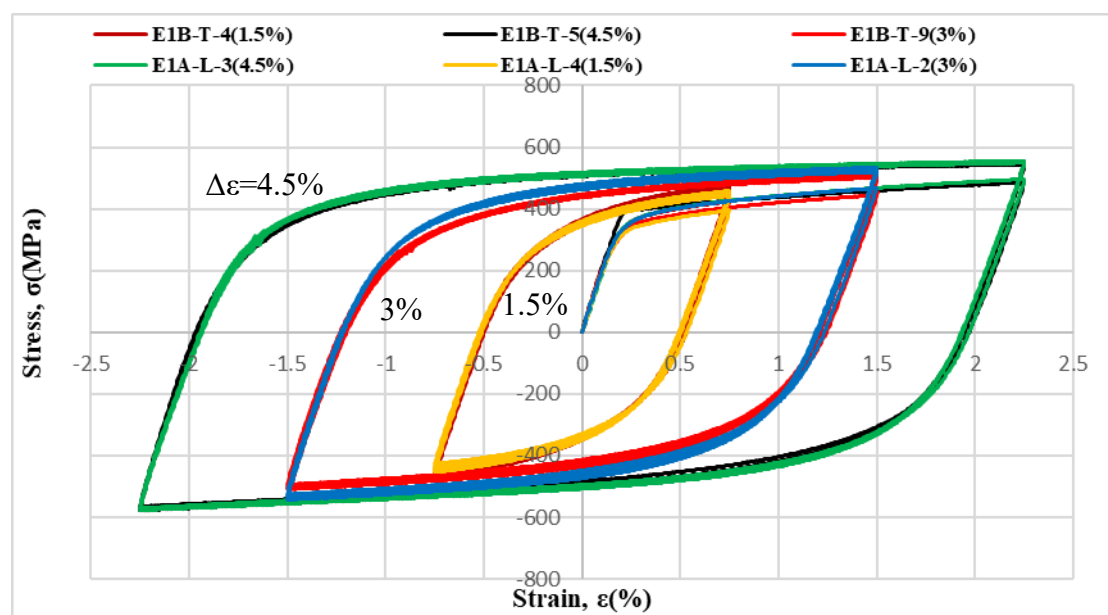


Fig 3.5 Strain control hysteresis loops for P355N-steel coupons for $\Delta\epsilon=1.5\%, 3\%, 4\%$.

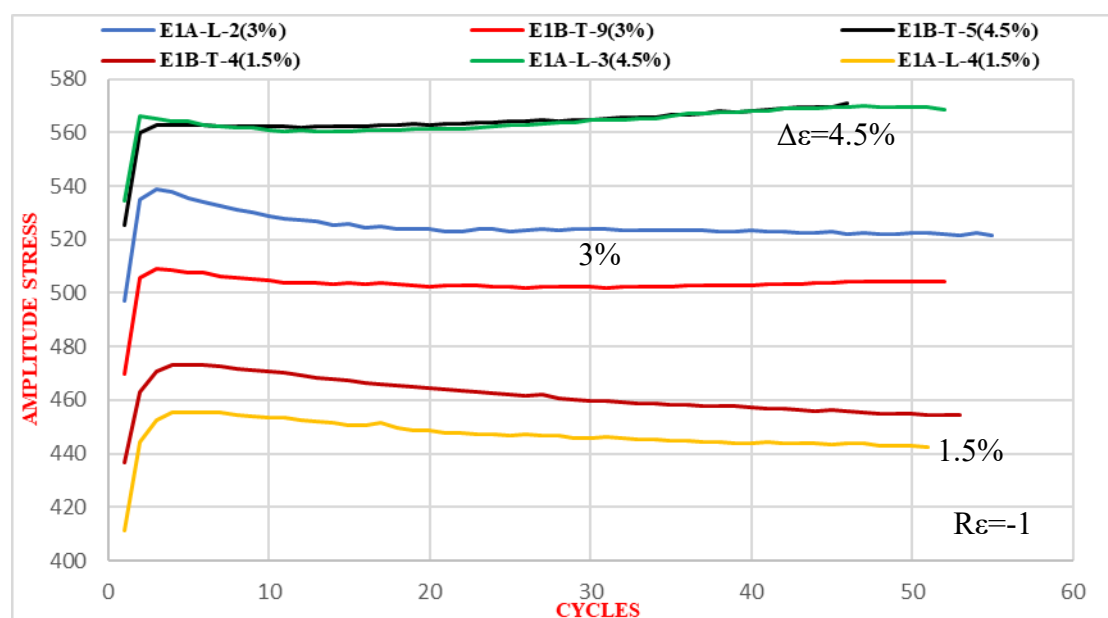


Fig 3.6 Amplitude stress versus cycles curves of P355N-steel.

Another example of this behavior is observed in X52_SP steel (**Fig 3.7**). As the applied strain amplitude increases from 0.5%, the tendency for softening diminishes

progressively until it reaches a primarily stable behavior at 1.5%. Beyond this point, from 2% to 3%, the material clearly exhibits hardening, as depicted in **Fig 3.8**.

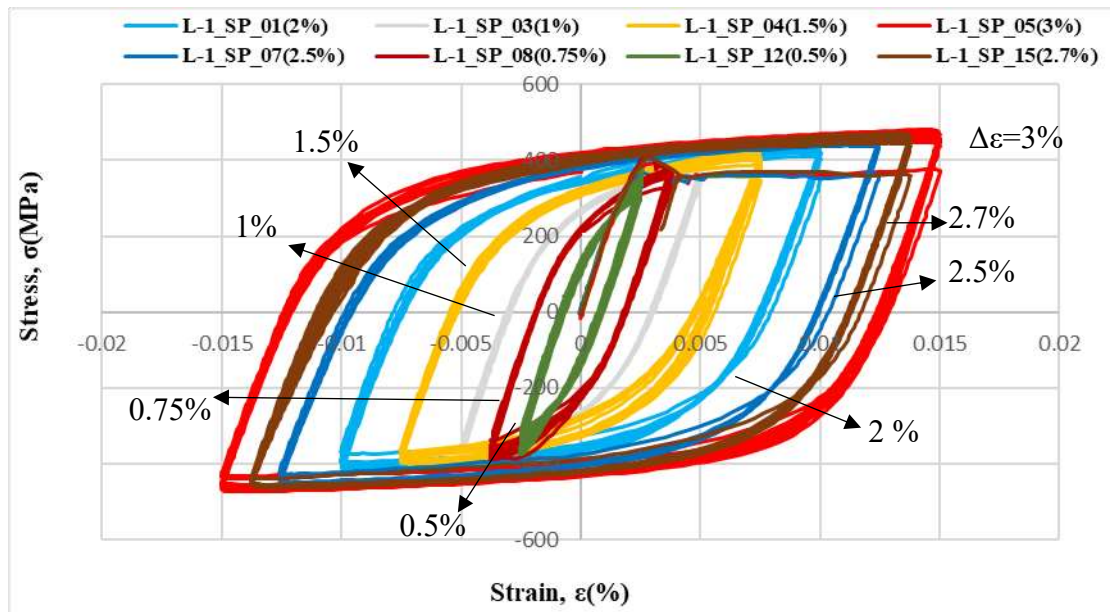


Fig 3.7 Strain control hysteresis loops for X52_SP steel coupons for $\Delta\epsilon=0.5\%, 0.75\%, 1\%, 1.5\%, 2\%, 2.5\%, 2.7\%, 3\%$.

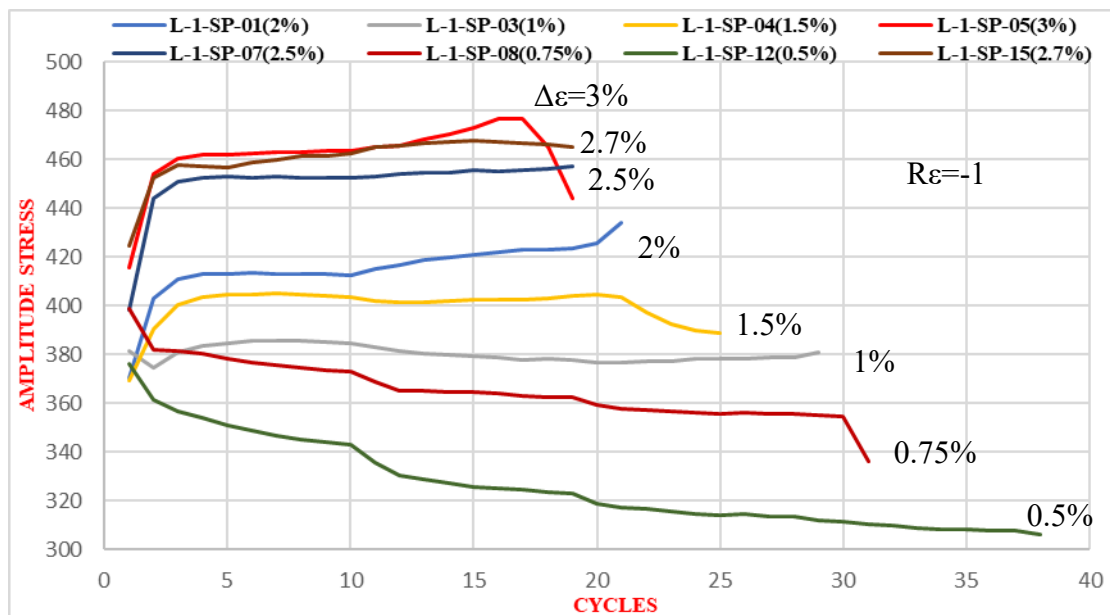


Fig 3.8 Amplitude stress versus cycles curves of X52_SP-steel.

One more occasion is the S355MC (**Fig 3.9**) and S460MC, that as increases the $\Delta\epsilon$ (%), the amplitude stress versus cycles curves start to demonstrate a region with cyclic hardening behavior, and after it return to the initial downward trend (softening behavior), (**Fig 3.10**).

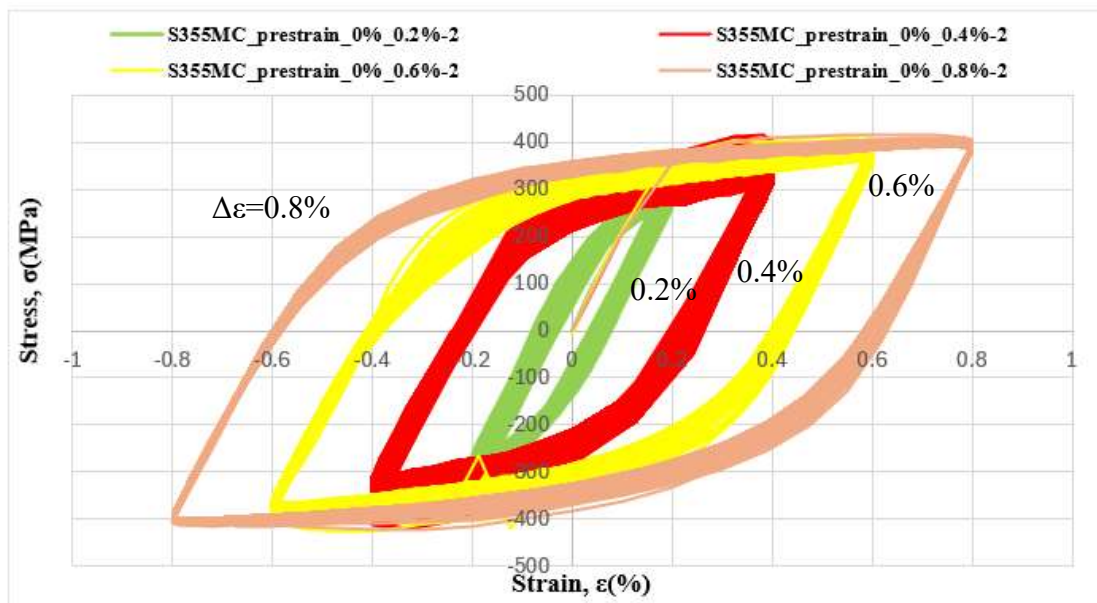


Fig 3.9 Strain control hysteresis loops for S355MC_0% steel coupons for $\Delta\epsilon=0.2\%, 0.4\%, 0.8\%$.

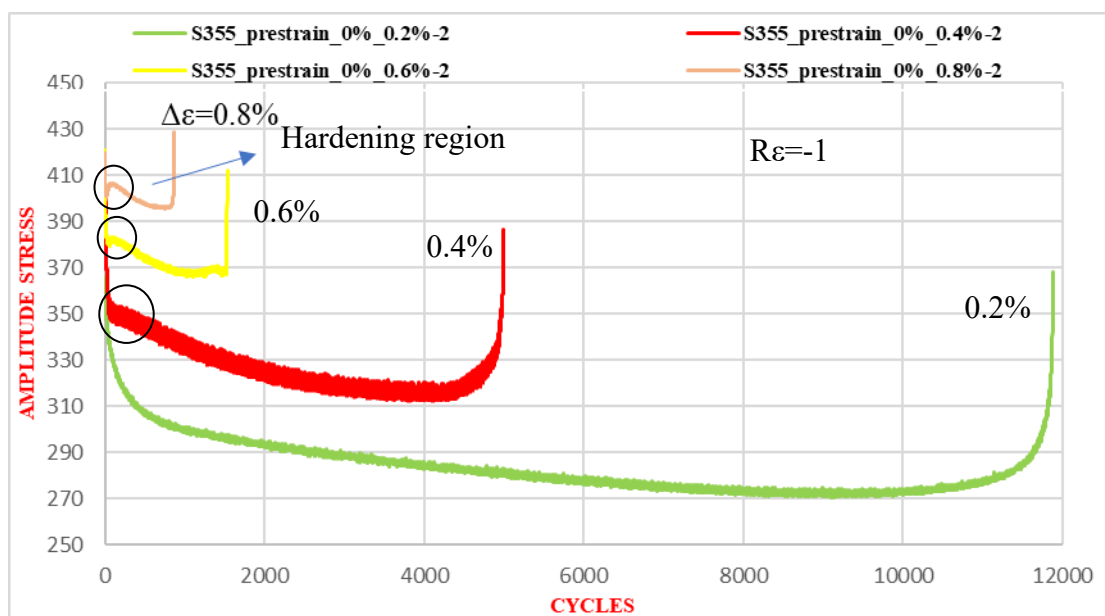


Fig 3.10 Amplitude stress versus cycles curves of S355MC_0%-steel.

3.2.3 Characterization of specimen's cyclic behavior

Next, the strain-controlled experiments classify based on the materials' cyclic softening or hardening responses. The 625 stainless steel was subjected to cyclic loading for only three cycles. Consequently, it is observed that it exhibits cyclic hardening behavior, with an increase in stress amplitude of approximately 50 MPa at a strain range ($\Delta\epsilon$) of 3% and 80 MPa at a strain range of 6% when comparing the first and third cycles.

The ASME-S234 steel coupons show a continuous, constant increase in stress per cycle after the initial 40 cycles, during which they alternate between hardening and softening with no stabilization, (Fig 3.4). The P355N generally presents a hardening behavior, as the stress increases when comparing the first and last cycles. However, after a significant stress increase in the first 4-5 cycles, the stress levels slightly increase, decrease, or remain stable depending on the strain range, (Fig 3.6) (there is data only for about 52 cycles).

The S355(L-N), S700(L-N), and S275J2 (Fig 3.11) exhibit hardening responses in the initial cycles, followed by stabilization. In contrast, the S700(MATCH) (Fig 3.12) and S500(MATCH) (except for the TEST1-0.5% specimen, which stabilizes after 1500 cycles) show significant softening behavior, while the TS590 steel also exhibits softening with no stabilization. For the X65(MLP) steel, data is available for only three cycles, suggesting a softening behavior, but three cycles are an insufficient number to draw definitive conclusions, especially since most materials in the database exhibit initial hardening followed by softening.

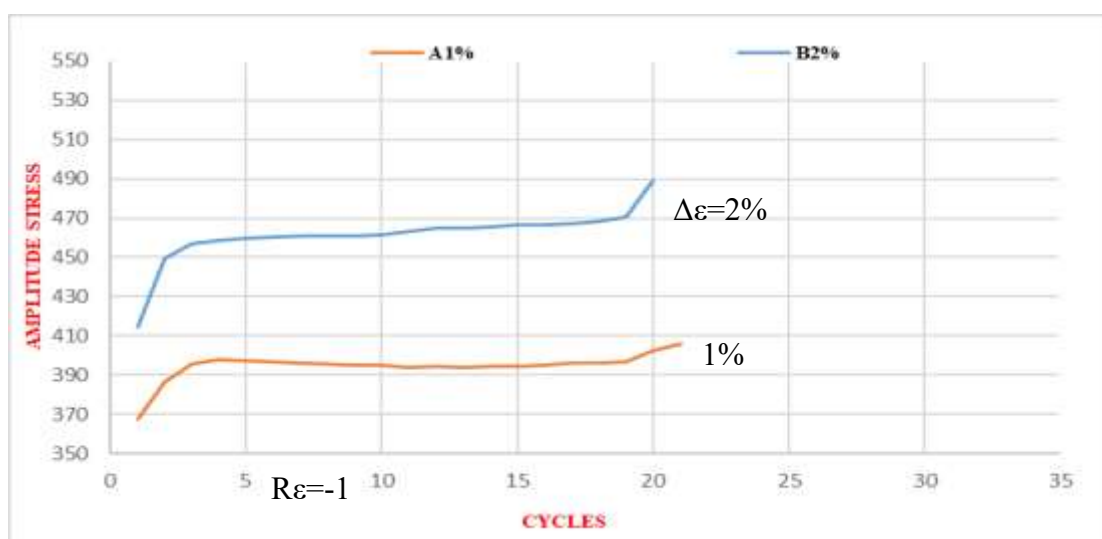


Fig 3.11 Amplitude stress versus cycles curves of S275J2- steel.

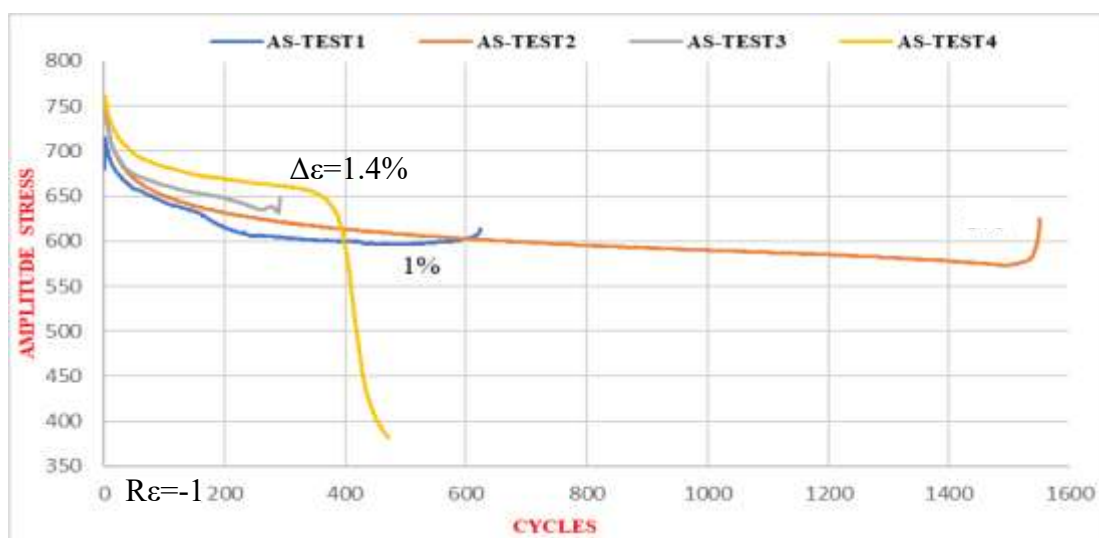


Fig 3.12 Amplitude stress versus cycles curves of S700(MATCH)-steel.

The S355MC_0% steel specimens indicate a fully softening behavior, with a continuous reduction in stress amplitude and stabilized region, though there is a slight hardening, as the strain range increases. For 9% (Fig 3.13) and also 12-13% pre-strain, the behavior of the material is full softening and don't observed the small hardening interval as in the un-strained experiment. However, the stability region of the curves is negligence going from 1.2% towards 0.2% strain ranges, for 1.5% don't seem to stabilize.

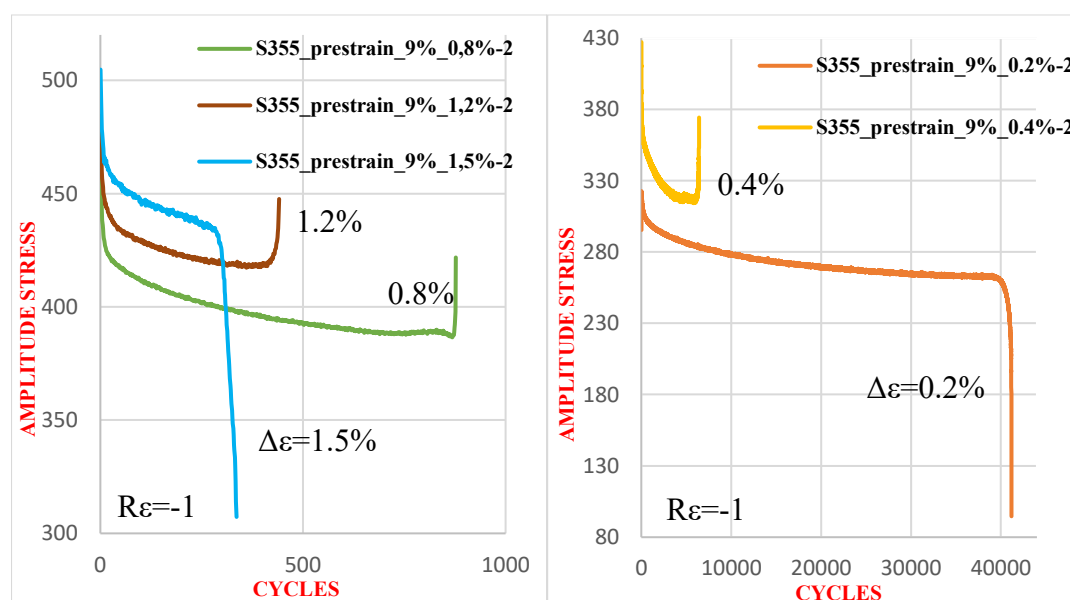


Fig 3.13 Amplitude stress versus cycles curves of S355MC-steel for 9% prestrain.

The unstrained and pre-strained 460MC steel exhibit complete softening without stabilization, except for the samples subjected to a 0.2% strain amplitude, which do not show a hardening phase as seen in unstrained S355MC steel subjected to the same mechanical process. Additionally, for all applied strain ranges, the stress amplitude is highest for 0% prestrain, followed by 8-9%, and finally 12-13% pre-strain, as shown in Fig 3.14.

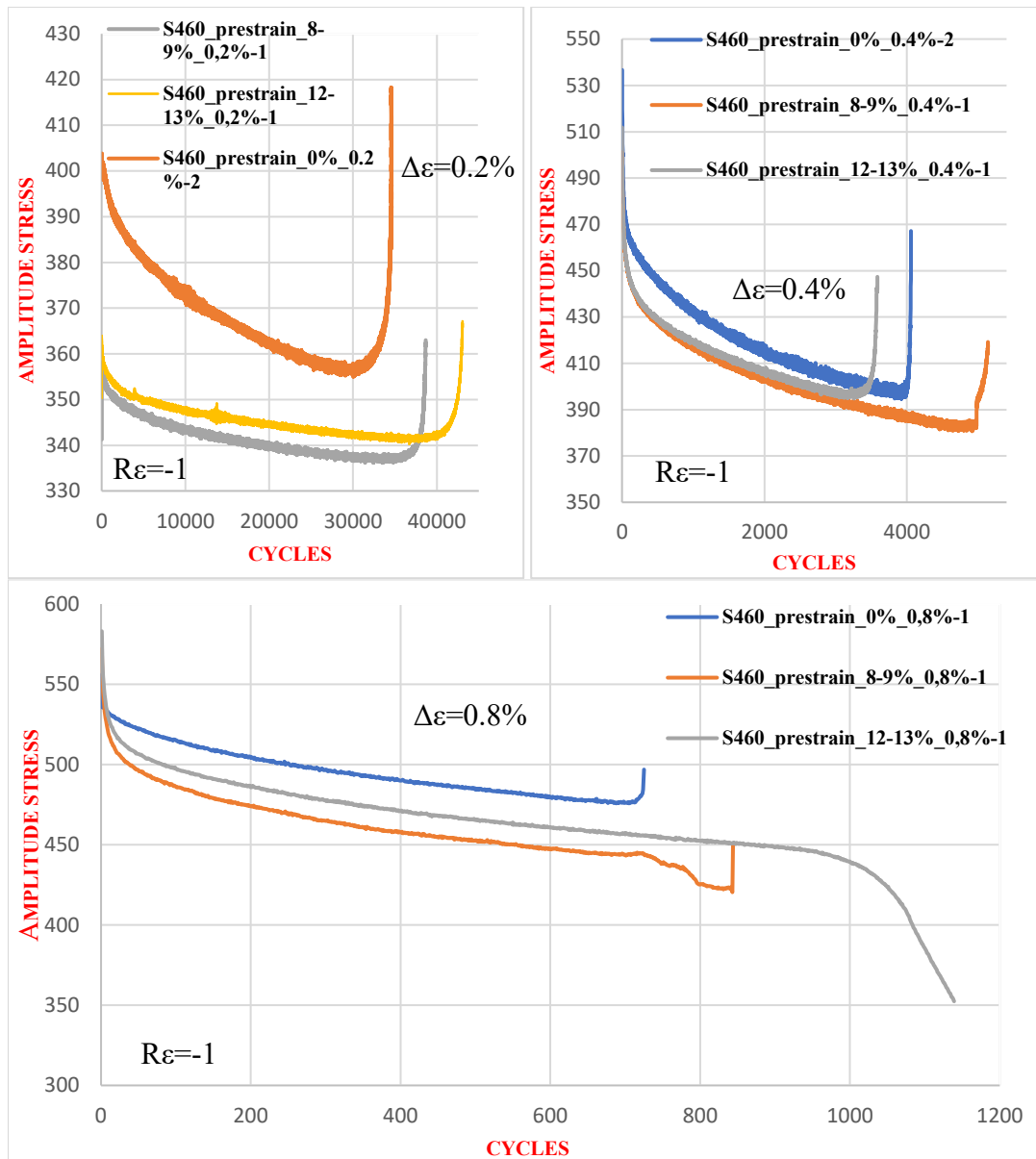


Fig 3.14 Amplitude stress versus cycles curves of S460MC for 0%, 8-9% and 12-13% for the same strain range.

In Fig 3.15, the S355_T2 specimens from kormos and pelma seem to follow a hardening behavior as after an abrupt increase at first cycles continuous to increase at a constant small rate, while the number of cycles decreases for higher strain amplitudes. Also, comparing the specimens from pelma and kormos that have been applied to 1% strain amplitudes, it is observed that the S355_T2 Pelma_1% achieve higher amplitude stress, the same happens and for 0.8% applied strain range.

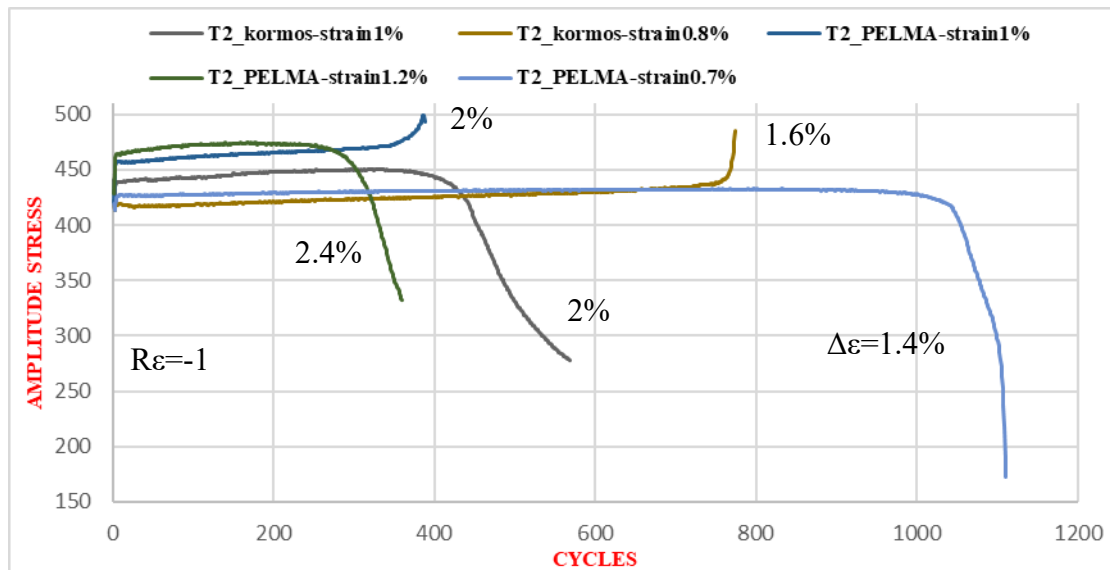


Fig 3.15 Amplitude stress versus cycles curves of S355_T2-steel.

The S355_T1 exhibited similar behavior to S355_T2, showing that for the same strain amplitude, the Kormos specimens have lower stress amplitude and reduced hardening, as reflected by the slope of the curve. Additionally, the S355_T1 Kormos specimen at 0.8% strain amplitude stabilized after 100 cycles, whereas the S355_T1 Pelma specimen at 0.8% strain amplitude experienced an increase in stress amplitude (Fig 3.16).

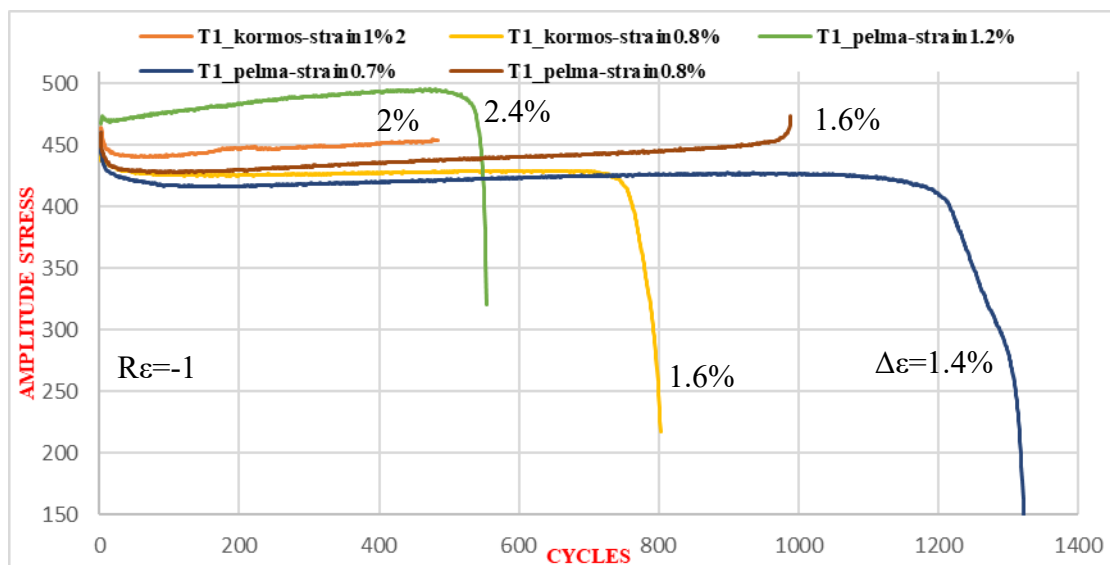


Fig 3.16 Amplitude stress versus cycles curves of S355_T1-steel.

For 43A-steel, follows a comparison for the same strain ranges between IDF and ODF specimens that provided from inner and the outer surface of the pipe, respectively and also the second ones have subjected to 9% prestrain. As illustrated in Fig 3.17, for 0.2%, the ODF have full softening behavior while the IDF stabilized and also resist for more cycles. For 0.4%, the IDF now demonstrate a hardening behavior and the ODF maintain a constant amplitude stress, after the initial softening. Furthermore, the number of cycles are reduced significantly for ODF from

about 22000 to 4000 cycles and for IDF from 14000 to 1000 cycles. Next, for 0.8% the IDF have less 3000 number of cycles until failure and higher hardening rate in relation to 0.4%. On the other hand, the ODF shows a reduction in the number of cycles, decreasing from approximately 4000 to 1000. It maintains a small range of stable stress amplitude before gradually softening at a slow rate until failure.

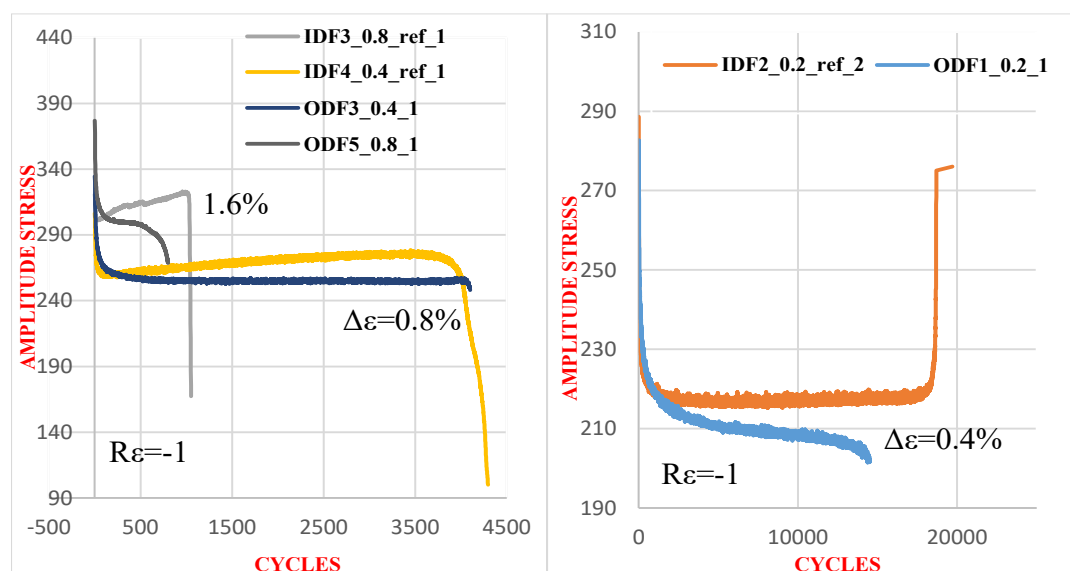


Fig 3.17 Amplitude stress versus cycles curves of BS4360 43A-steel for 0% and 9%.

3.2.4 Mean stress results

It is observed at P355N-steel that, as the strain amplitude increases from 1.5% to 4.5%, the mean stress curves move from positive to negative value in the region where stabilize (**Fig 3.18**). The same fact, i.e. the movement of the mean stress curves towards down with increasing strain amplitude, happens to S355MC_0%,9%,12-13%, S460_0%,9%,12-13%, ASME-S234, 43A-steel, S275J2, S355_T1 and S355_T2 kormos specimens.

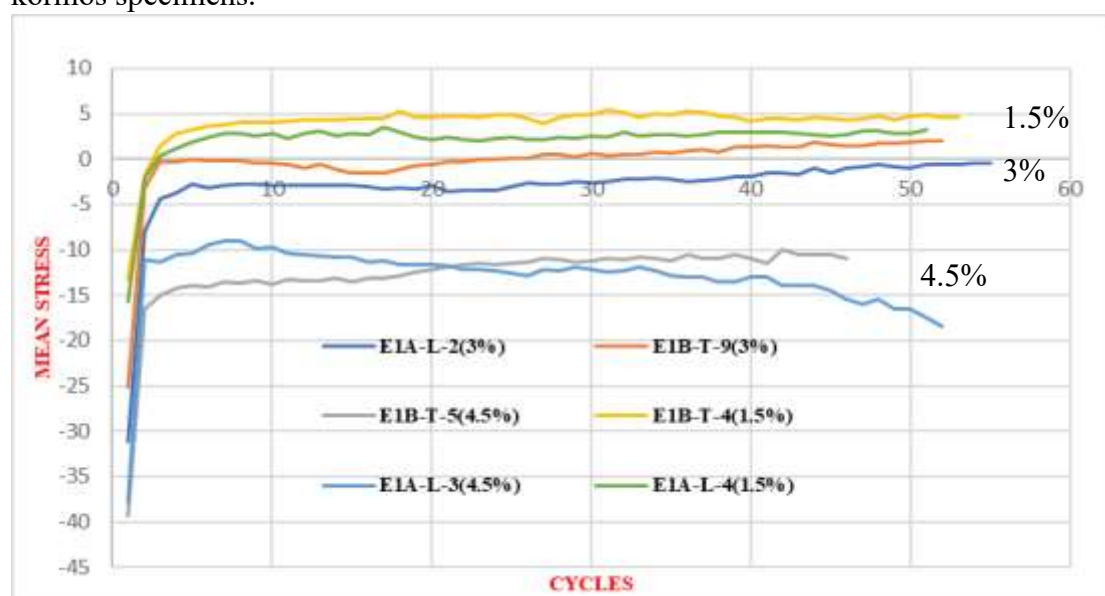


Fig 3.18 Mean stress versus cycles for P355-steel.

Moreover, all experiments present a stable mean stress after the first cycles and at the last cycles maybe increases or decreases, showing that the failure approaches. However, an example of unwanted mean stress behavior is of S700-E07%repeat which value drops from 80 MPa to -130MPa and there is no stabilization region are shown in **Fig 3.19**.

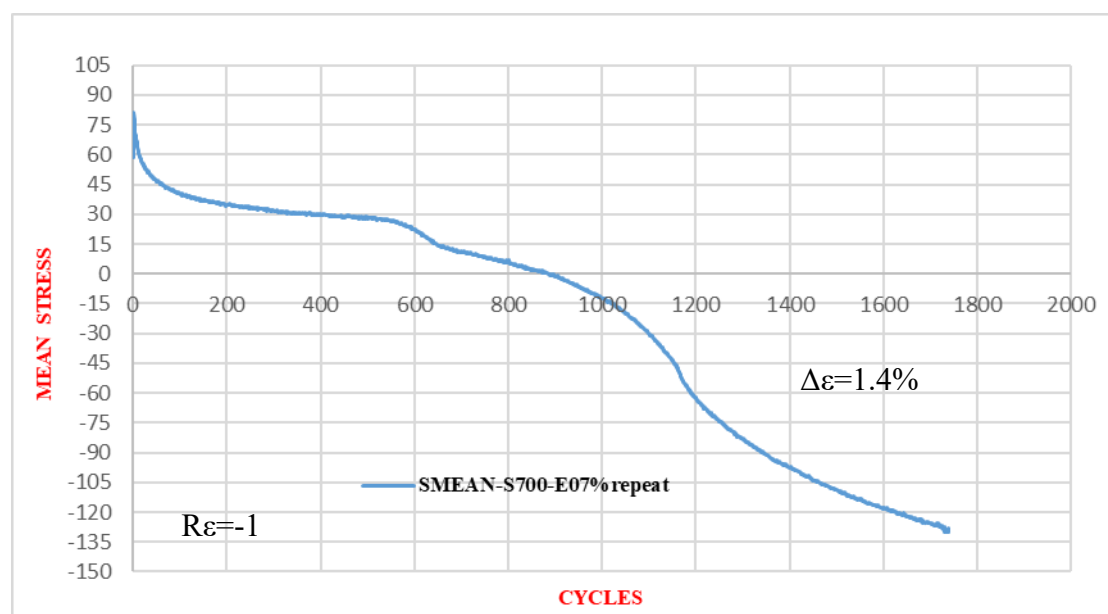


Fig 3.19 Mean stress versus cycles for S700(MATCH)-steel.

Other specimens that also have not straight evolution of curve are S700(MATCH)-E05%repeat2, S700(MATCH)_TEST1, X52_L-1_SP-04, X52_L-1_SP-10 and X52_L-1_SP-11.

3.2.5 Bauschinger effect results

Next, are calculated the difference between the yield limit at a 0.2% offset on the tension curve and the yield limit at the unloading curve. For the measure of elastic modulus and of the yield limit are used as a reference the first point of the unloading curve, and the point with stress equal to zero for the strain offset, respectively. From **Table 3.2 & Fig 3.20**, it is clear that in 625-stainless steel, the Bauschinger effect is significantly more noticeable at a 6% strain amplitude compared to a 3% strain amplitude, which shows a substantial reduction of over 36%. Additionally, the decrease in elastic modulus is minimal, around 2% for the 3% strain range and approximately 8% for the 6% strain range.

Table 3.2 Calculation of differences between tension and compression curve of 625 stainless steel for elastic modulus and yield limit, $R\epsilon = -0,12$ for $\Delta\epsilon = 3\%$ and $R\epsilon = -0,06$ for $\Delta\epsilon = 6\%$.

625-STAINLESS STEEL	L180	L90	L270	L180	L90	L270
$\Delta\epsilon$	3%	3%	3%	6%	6%	6%
E(MPa)-TENSILE	187850	187090	195000	188895	181563	181059
$\sigma_{y0.2\%}$ (MPa)-TENSILE	493	496	522	484	502	512
E(MPa)-COMPRESSION	183570	183730	191730	172130	169120	166980
$\sigma_{y0.2\%}$ (MPa)-COMPRESSION	-315	-316	-325	-260	-264	-265
ΔE	2.28%	1.80%	1.68%	8.88%	6.85%	7.78%
$\Delta\sigma_{y0.2\%}$	36.11%	36.29%	37.74%	46.28%	47.41%	48.24%

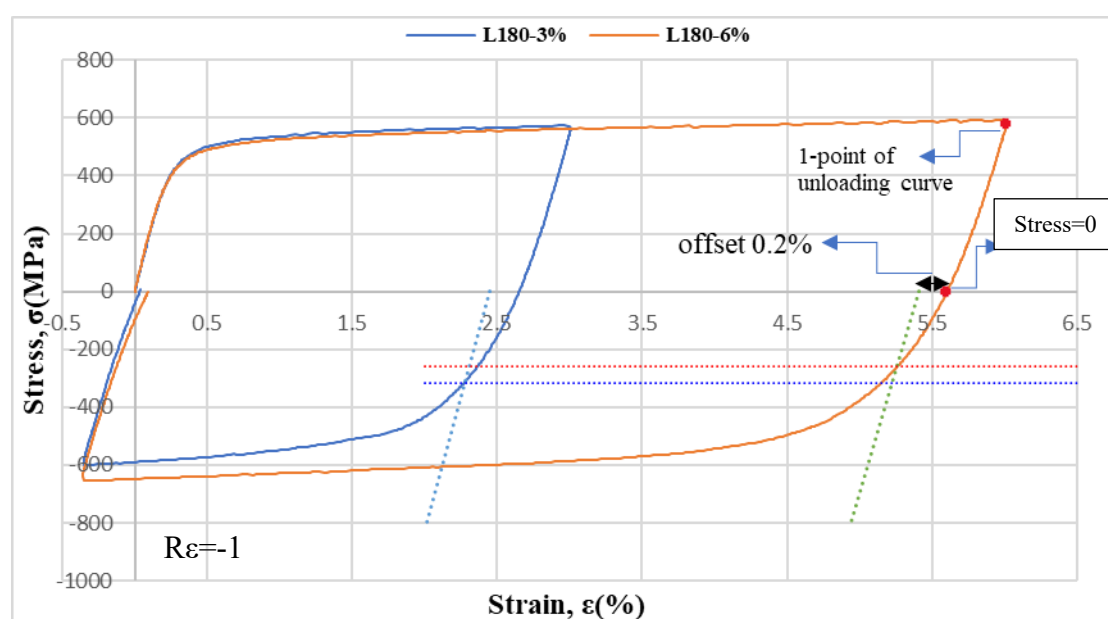


Fig 3.20 First cycle of 625 stainless steel L180 specimen for 3% and 6% strain amplitude.

In addition, at TS590(355*12)-steel, it appears that the Bauschinger effect is more pronounced at higher strain amplitudes, and this effect is even more significant in TS590(323.7*10). For S500-steel, there is no substantial change in the elastic modulus, but the yield limit shows a greater reduction for 1.40% strain amplitude compared to 1%, approximately 6-7% more. The S275J2-steel experiences a greater decrease in yield limit, more noticeable for 4% strain amplitude than 2%. **Table 3.3** proves that the P355-steel specimens traverse direction, as the strain amplitude increases from 1.5% to 4.5%, the difference on yield limit increases, too. While, in longitudinal direction for 4.5% strain amplitude, the Bauschinger effect is smaller than for 3%.

Table 3.3 Calculation of differences between tension and compression curve of P355N steel for elastic modulus and yield limit, $R_{\varepsilon}=-1$.

P355-STEEL	E1A-L-2	E1B-T-9	E1B-T-5	E1B-T-4	E1A-L-3	E1A-L-4
$\Delta\varepsilon$	3.00%	3.00%	4.50%	1.50%	4.50%	1.50%
E(MPa)-TENSILE	210640	208602	204402	213030	183957	202890
$\sigma_{y0.2}$ (MPa)-TENSILE	403	291	329	314	367	307
E(MPa)-COMPRESSION	191900	185540	198000	204250	190230	197280
$\sigma_{y0.2}$ (MPa)-COMPRESSION	-282	-243	-258	-273	-282	-267
ΔE	8.90%	11.06%	3.13%	4.12%	-3.41%	2.77%
$\Delta\sigma_{y0.2}$	30.02%	16.49%	21.58%	13.06%	23.16%	13.03%

For X65(MLP) steel, the longitudinal specimens show a significant reduction in elastic modulus (between tension and compression curve) of about 17%, whereas the transverse specimens exhibit only a 0.74% difference. The S700(MATCH) steel shares the same elastic modulus value as 625 stainless steel and shows similar Bauschinger effect behavior to X65(MLP). The X65(HFW)-steel also experiences a 40% reduction in yield limit, with no major difference in elastic modulus. From **Table 3.4**, in ASME-S234 steel there are no distinguish compared to the strain amplitude, the reduction fluctuates between 18.75% and 29.33% and the elastic modulus have small differences.

Table 3.4 Calculation of differences between tension and compression curve of ASME-S234 steel for elastic modulus and yield limit, $R_{\varepsilon}=-1$.

ASME-S234 STEEL	D1 E1.5%	D2 E2.5%	D3 E2%	D4 E2.5%	D7 E3%	D8 E1.5%
$\Delta\varepsilon$	0.015	0.025	0.02	0.025	0.03	0.015
E(MPa)-TENSILE	209666	211104	215000	215000	208515	204442
$\sigma_{y0.2}$ (MPa)-TENSILE	320	312	300	300	300	290
E(MPa)-COMPRESSION	189500	203570	210870	191140	188810	190820
$\sigma_{y0.2}$ (MPa)-COMPRESSION	-260	-248	-217	-222	-212	-220
ΔE	9.62%	3.57%	1.92%	11.10%	9.45%	6.66%
$\Delta\sigma_{y0.2}$	18.75%	20.51%	27.67%	26.00%	29.33%	24.14%

As it seems in **Fig 3.21**, the S700(L-N) sample in both longitudinal(L3_cy) and transverse(T3_cy) directions- even though the tensile experiments show that there is anisotropy -the yield limit in compression is about 30% lower than in tension, and the elastic modulus is about 10% lower.

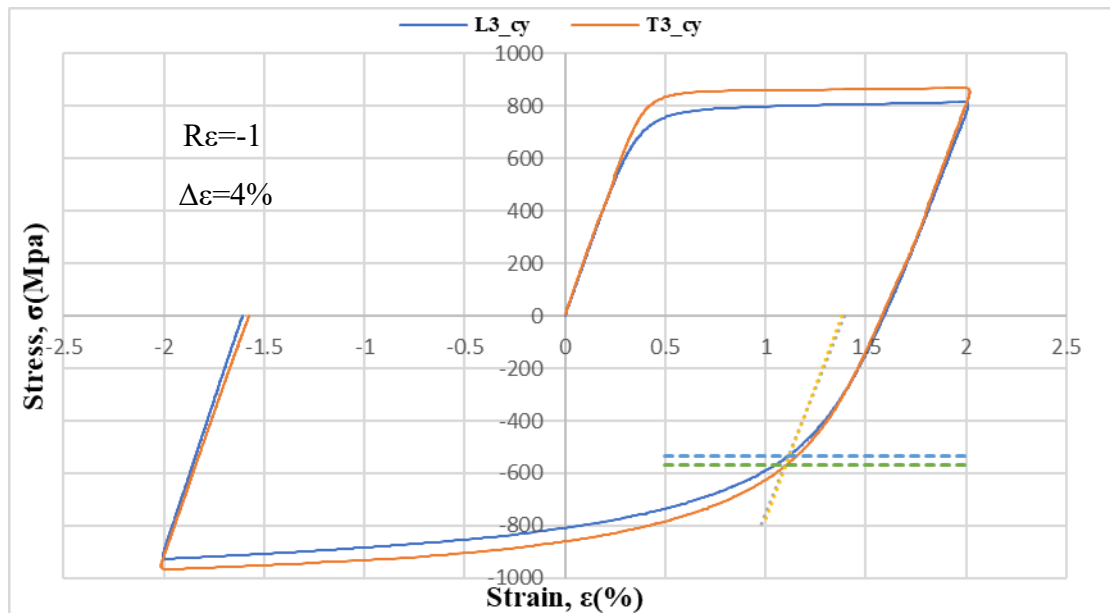


Fig 3.21 First cycle of S700(L-N) steel specimens for 4% strain amplitude.

The X65_PLATE-1 steel shows a reduction in yield limit ranging from 27.55% to 38.45%, with the elastic modulus also significantly reduced, ranging from 15.18% to 25.81%. The X65_PLATE-2 steel exhibits a yield limit reduction from 32.57% to 46.85%, with the elastic modulus also showing a substantial decrease, ranging from 3.27% to 30.05%. For X60-steel, the yield limit reduction ranges from 13.58% to 39.38% and the elastic modulus decreases significantly, ranging from 7.21% to 39.82%, with one specimen showing a 2.73% reduction. In **Table 3.5** is denoted that the S355(L-N) steel shows a significant reduction in yield limit, with the longitudinal(L2_cy) direction exhibiting an 10% higher reduction. This difference is not substantial, indicating that the material has isotropic behavior.

Table 3.5 Calculation of differences between tension and compression curve of S355(L-N) steel for elastic modulus and yield limit, $R\epsilon=-1$.

S355(L-D)	L2_cy	T3_cy b
E(MPa)-TENSILE	195260	213800
$\sigma_{y0.2\%}$ (MPa)-TENSILE	349	360
E(MPa)-COMPRESSION	183910	203100
$\sigma_{y0.2\%}$ (MPa)-COMPRESSION	-210	-255
ΔE	5.81%	5.00%
$\Delta \sigma_{y0.2\%}$	39.83%	29.17%

The S355_T1 material exhibits a significantly greater reduction in yield limit, nearly twice that of S355_T2. Additionally, from **Table 3.6** specimens from pelma, compared to those from kormos for both materials, demonstrate a more pronounced Bauschinger effect, which becomes more evident with increasing applied strain amplitudes (except from kormos T1 specimens, where the yield limit reduction is slightly higher at a 0.8% strain range). The reduction in elastic modulus, however, is not substantial.

Table 3.6 Calculation of differences between tension and compression curve of S355_T1 and S355_T2 steel for elastic modulus and yield limit, $R_{\varepsilon}=-1$.

S355(MATCH)	Kormos_T1_0.8%	Kormos_T1_1%	Pelma_T1_0.8%	Pelma_T1_1%	Pelma_T1_1.2%
E(MPa)-TENSILE	198013	202736	195637	215440	205768
$\sigma_{y0.2\%}$ (MPa)-TENSILE	431	438	452	445	450
E(MPa)-COMPRESSION	167056	195014	189022	204870	202337
$\Delta y_{0.2\%}$ (MPa)-COMPRESSION	-270	-285	-320	-274	-267
ΔE	15.63%	3.81%	3.38%	4.91%	1.67%
$\Delta \sigma_{y0.2\%}$	37.35%	34.93%	29.20%	38.43%	40.67%
S355(MATCH)	Kormos_T2_0.8%	Kormos_T2_1%	Pelma_T2_0.8%	Pelma_T2_1%	Pelma_T2_1.2%
E(MPa)-TENSILE	229849	203843	198246	205133	213548
$\sigma_{y0.2\%}$ (MPa)-TENSILE	408	408	408	405	403
E(MPa)-COMPRESSION	220914	198102	190825	192100	198066
$\sigma_{y0.2\%}$ (MPa)-COMPRESSION	-352	-330	-325	-322	-303
ΔE	3.89%	2.82%	3.74%	6.35%	7.25%
$\Delta \sigma_{y0.2\%}$	13.73%	19.12%	20.34%	20.49%	24.81%

The S355MC and S460MC steels show an increasing reduction in yield limit as the prestrain level rises. At 0% prestrain, the reduction is about 20%, at 9% prestrain, it is around 39%, and for 12-13% prestrain, the reduction is slightly higher (43%). (Table 3.7)

Table 3.7 Calculation of differences between tension and compression curve of S355MC steel for elastic modulus and yield limit, $R_{\varepsilon}=-1$.

S355MC $D_{\varepsilon}(\%)$	0.60%	0.80%	0.80%	1.20%	1.50%	0.80%	1.20%	1.50%
PRESTRAIN	0%	0%	8-9%	8-9%	8-9%	12-13%	12-13%	12-13%
E(MPa)-TENSILE	219560	207860	177880	187490	180240	192930	180030	180240
$\sigma_{y0.2\%}$ (MPa)-TENSILE	400	410	505	478	502	520	508	540
E(MPa)-COMPRESSION	214960	205390	175960	175510	173930	176330	170650	177990
$\sigma_{y0.2\%}$ (MPa)-COMPRESSION	-338	-315	-298	-293	-294	-294	-295	-300
ΔE	2.09%	1.18%	1.07%	6.38%	3.50%	8.60%	5.21%	1.245
$\Delta \sigma_{y0.2\%}$	15.5%	23.17%	40.99%	38.70%	41.43%	43.46%	41.92%	44.44%

For BS4360 43A-steel, the specimen IDF with a 0.4% applied strain amplitude exhibits a smaller yield limit reduction (13.77%) compared to the specimen with 0.8% applied strain amplitude (25%). The ODF coupon, which has undergone a prestrain process, shows a significantly higher Bauschinger effect, around 50% for a 0.8% strain amplitude. So, the two prementioned materials shows that the existence of

Bauschinger effect become obviously more noticeable when the material have been submitted to prestrain process. (Table 3.8)

Table 3.8 Calculation of differences between tension and compression curve of BS4360 GRADE 43A- steel for elastic modulus and yield limit, $R\epsilon=-1$.

BS4360 GRADE 43A	IDF3 0.8 ref 1	IDF4 0.4 ref 1	ODF5 0.8 1	ODF6 0.8 2
$\Delta\epsilon$	1.6%	0.8%	1.6%	1.6%
E(MPa)-TENSILE	214995	225768	183252	180333
$\sigma_{y0.2\%}$ (MPa)-TENSILE	300	305	420	417
E(MPa)-COMPRESSION	213154	219489	186023	177478
$\sigma_{y0.2\%}$ (MPa)-COMPRESSION	-225	-263	-205	-205
ΔE	0.86%	2.78%	-1.51%	1.58%
$\Delta\sigma_{y0.2\%}$	25.00%	13.77%	51.19%	50.84%

Table 3.9 presents the X52-steel specimen characterized by L-1, which has a minimum strain to maximum strain ratio of -1, and the specimen characterized by L0, which has a ratio of 0. It is observed that the Bauschinger effect is unaffected by these ratio values. The percentages of yield limit reduction are very close.

Table 3.9 Calculation of differences between tension and compression curve of X52_L0 and L-1 specimens for elastic modulus and yield limit, $R\epsilon=-1$.

X52-steel	L-1-SP-03	L-1-SP-04	L-1-SP-01	L-1-SP-07	L-1-SP-14	L-1-SP-05
$\Delta\epsilon$	1.00%	1.50%	2.00%	2.50%	2.70%	3.00%
E(MPa)-TENSILE	203066	197691	194084	191082	198993	207997
$\sigma_{y0.2\%}$ (MPa)-TENSILE	366	356	364	364	365	368
E(MPa)-COMPRESSION	194016	192378	184253	185848	189741	189915
$\sigma_{y0.2\%}$ (MPa)-COMPRESSION	-293	-265	-225	-241	-241	-242
ΔE	4.46%	2.69%	5.07%	2.74%	4.65%	8.69%
$\Delta\sigma_{y0.2\%}$	19.95%	25.56%	38.19%	33.79%	33.97%	34.24%

X52-steel	L0-SP-1	L0-SP-3	L0-SP-5	L0-SP-7	L0-SP-13	L0-SP-14
$\Delta\epsilon$	1.00%	1.50%	2.00%	2.50%	2.75%	3%
E(MPa)-TENSILE	205171	212801	205874	204790	197833	205688
$\sigma_{y0.2\%}$ (MPa)-TENSILE	367	358	360	360	354	360
E(MPa)-COMPRESSION	202539	200160	186615	181560	178497	180456
$\sigma_{y0.2\%}$ (MPa)-COMPRESSION	-271	-244	-244	-245	-244	-235
ΔE	1.28%	5.94%	9.35%	11.34%	9.77%	12.27%
$\Delta\sigma_{y0.2\%}$	26.16%	31.84%	32.22%	31.94%	31.07%	34.72%

3.2.6 Bauschinger effect in later cycles

Table 3.10 indicates that the elastic modulus remains relatively stable around the value of the initial curve, without showing any clear increasing or decreasing trend, except the last cycles where appears the failure. The $\sigma_{y0.2\%}$ decreases significantly from the 1st to the 10th cycle (by 20%), and subsequent reductions are less than

6.59%. This pattern is likely due to the slope of the amplitude stress curve decreasing, as seen in **Fig 3.22**, resulting in smaller differences between the hysteresis loops.

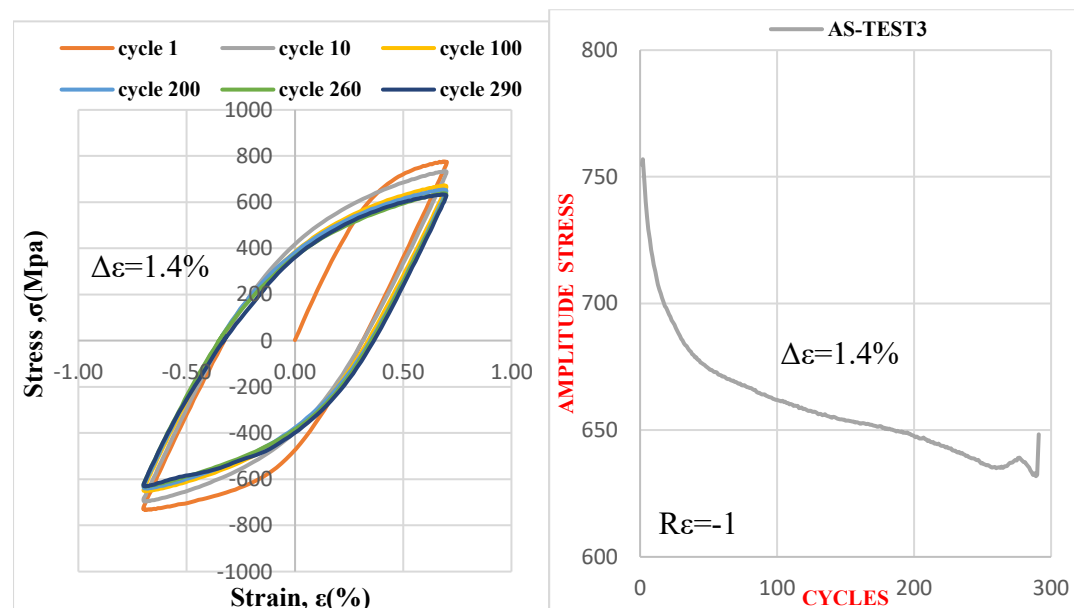


Fig 3.22 Diagram of stress-strain curve for 1,10,100,200,260,290 cycles and amplitude stress versus cycles diagram for S700(MATCH)_TEST3 specimen.

Table 3.10 Values of S700(MATCH)_TEST3 steel specimen for 1,10,100,200,260,290 cycles, $R\epsilon=-1$.

S700(MATCH)_TEST 3	CYCLE-1	CYCLE-10	CYCLE-100	CYCLE-200	CYCLE-260	CYCLE-290
E(MPa)-COMPRESSION	209000	202930	198930	202540	193250	210320
$\sigma_{y0.2\%}$ (MPa)-COMPRESSION	-606	-483	-455	-425	-425	-421
ΔE	-	-2.90%	1.97%	-1.81%	4.58%	-8.83%
$\Delta\sigma_{y0.2\%}$	-	20.29%	5.79%	6.59%	0%	0.94%

According to **Fig 3.23** the TS590_4-1 specimen (2.5% strain amplitude) clearly shows softening behavior. However, from **Table 3.11**, the $\sigma_{y0.2\%}$ increases when comparing the 1st and 10th cycles, and after the 30th cycle, only minor changes in its magnitude are observed. A similar pattern is noted in the TS590_4-2 specimen, which was subjected to a 1.9% strain amplitude.

Table 3.11 Values of TS590_4-1 steel specimen for 1,10,30,50,70,100 cycles, $R\epsilon=-1$.

TS590_4-1	CYCLE-1	CYCLE-10	CYCLE-30	CYCLE-50	CYCLE-70	CYCLE-100
E(MPa)-COMPRESSION	197320	193120	191830	193840	197080	196400
$\sigma_{y0.2\%}$ (MPa)- COMPRESSION	-457	-492	-478	-468	-469	-466
ΔE	-	2.12%	0.66%	-1.04%	-1.67%	0.34%
$\Delta\sigma_{y0.2\%}$	-	-7.65%	2.84%	2.09%	-0.21%	0.63%

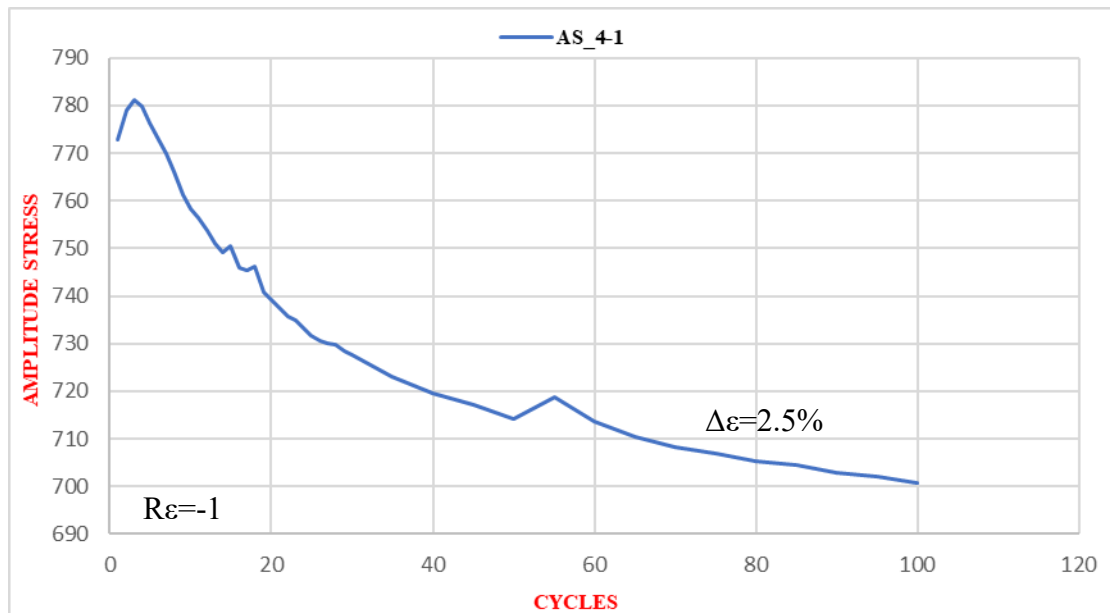


Fig 3.23 Diagram of stress-strain curve of TS590-steel specimen for 1,10,100,200,260,290 cycles and amplitude stress versus cycles diagram.

In **Fig 3.24** seems that except for the last cycles, the specimen ASME-S234_D1 shows stress amplitude fluctuations of around 20 MPa, which is a small range given the number of cycles.

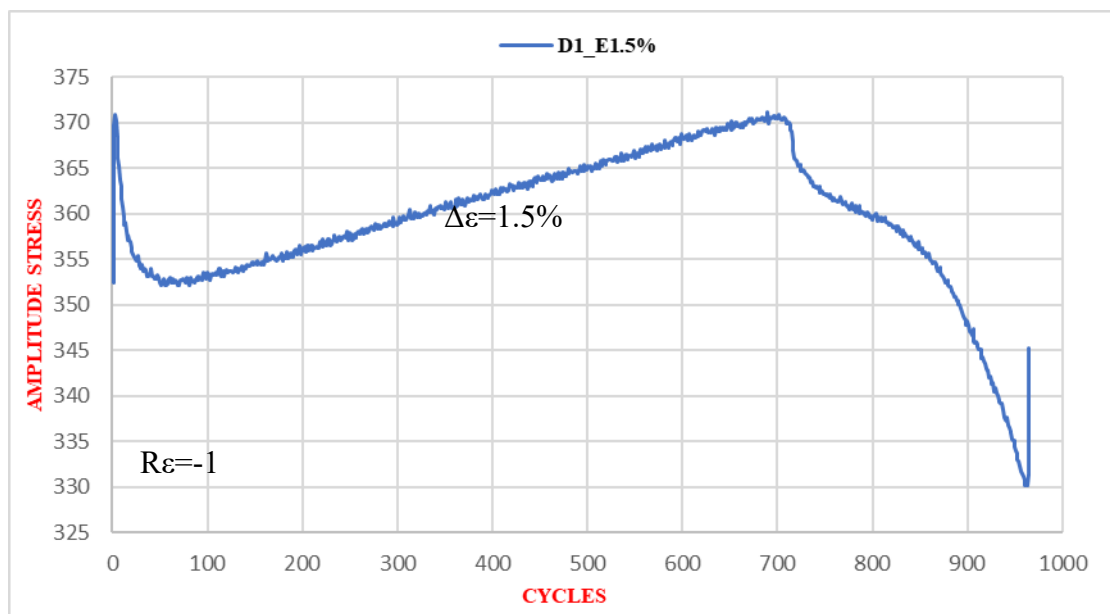


Fig 3.24 Diagram of amplitude stress versus cycles diagram of ASME-S234 steel.

This explains the minimal changes in the elastic modulus and the yield strength ($\sigma_y 0.2\%$) as depicted in **Table 3.12**. However, after 800 cycles, a more significant reduction is observed (at cycle 900, $E = 163.190$ MPa, and at cycle 850, $E = 174860$). Finally, in cycle 965, an unacceptable magnitude of E indicates the approach of failure. The ASME-S234_D7 steel coupon exhibits similar behavior, with an increase

in the elastic modulus in the last cycles within acceptable limits this time, and the yield strength also increases.

Table 3.12 Values of ASME-S234_D1 steel specimen for 1,10,400,700,800,850,900,965 cycles, $R\epsilon=-1$.

ASME S234-steel	CYCLE-1	CYCLE-10	CYCLE-400	CYCLE-700	CYCLE-800	CYCLE-850	CYCLE-900	CYCLE-965
E(MPa)-COMPRESSION	189500	192060	194160	202860	186720	174860	163190	267970
$\sigma_{y0.2\%}$ (MPa)-COMPRESSION	-262	-262	-248	-248	-231	-224	-229	-207
ΔE	-	-1.35%	-3.31%	-4.48%	7.95%	6.35%	6.67%	-64.20%
$\Delta\sigma_{y0.2\%}$	-	0%	0.8%	0%	6.85%	3.03%	-2.23%	9.60%

Table 3.13 shows that for the 43A_IDF3 steel specimen, as the number of cycles increases, the elastic modulus and yield limit on the unloading curve decrease gradually. After 800 cycles, these values begin to rise but then drop significantly in the final cycles, indicating failure with very low elastic modulus and yield limit values. As shown in Fig. 3.25, cycles 1040 and 1052 exhibit a significant gap and also undergo notable changes in shape.

Table 3.13 Values of BS4360 GRADE 43A-steel specimen for 1,10,100,800,1020,1040,1052 cycles, $R\epsilon=-1$.

43A_IDF3	CYCLE-1	CYCLE-10	CYCLE-100	CYCLE-600	CYCLE-800	CYCLE-1020	CYCLE-1040	CYCLE-1052
E(MPa) - COMPRESSION	213154	210854	197516	198173	204449	238662	207892	106432
$\sigma_{y0.2\%}$ (MPa)-COMPRESSION	-225	-204	-196	-196	-190	-206	-159	-94
ΔE	-	1.08%	6.33%	-0.33%	-3.17%	-16.73%	12.89%	48.80%
$\Delta\sigma_{y0.2\%}$	-	9.33%	3.92%	0.00%	3.06%	8.42%	22.82%	40.88%

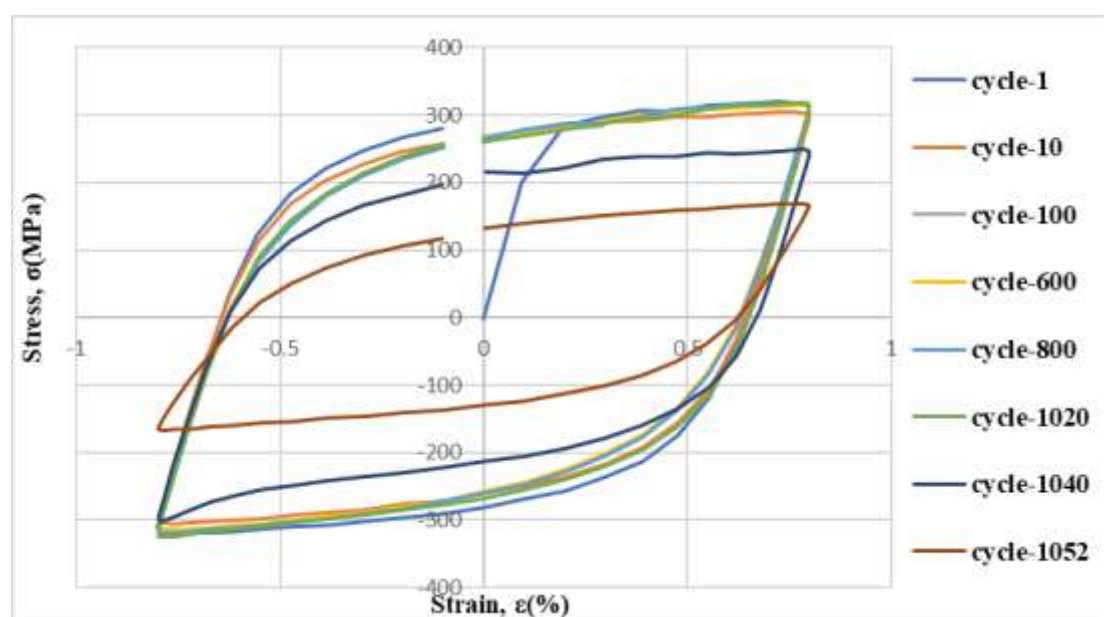


Fig 3.25 Diagram of stress-strain curve for 1,10,100,600,800,1020,1040 and 1052 cycles versus cycles for BS4360 43A-steel specimen.

In **Table 3.14**, the 43A_ODF6 steel specimen, (that have been subjected to pre-straining), shows reduced elastic modulus and yield strength ($\sigma_{y0.2\%}$) compared to the previously mentioned coupon, with smaller fluctuations in these properties as the number of cycles increase. However, significant variations are observed for each of two pre-mentioned specimens in the cycles just before failure when the high softening rate starts as is demonstrated by **Fig 3.26**.

Table 3.14 Values of BS4360 GRADE 43A-steel specimen for 1,10,100, 400,600,800,900,1094 cycles, $R\epsilon=-1$.

43A_ODF6	CYCLE-1	CYCLE-10	CYCLE-100	CYCLE-400	CYCLE-600	CYCLE-800	CYCLE-900	CYCLE-1094
E(MPa)-COMPRESSION	177478	176128	181911	185196	178126	172181	162400	119269
$\sigma_{y0.2\%}$ (MPa)-COMPRESSION	-205	-190	-185	-177	-171	-161	-152	-107
ΔE	-	0.76%	-3.28%	-1.80%	3.82%	3.34%	5.68%	26.56%
$\Delta \sigma_{y0.2\%}$	-	7.32%	2.63%	4.32%	3.39%	5.85%	5.59%	29.61%

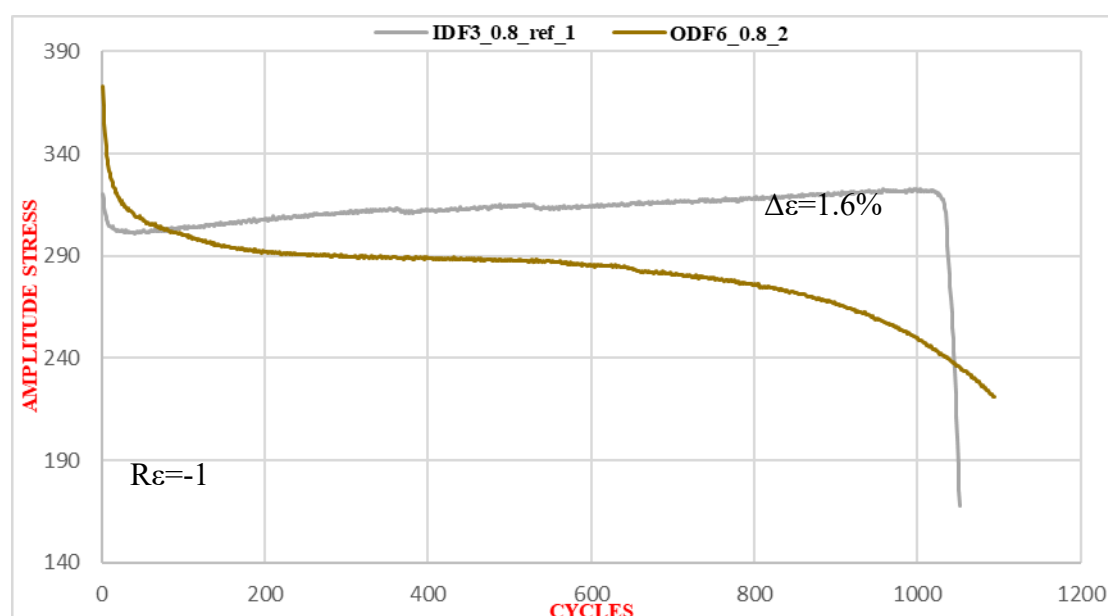


Fig 3.26 Diagram of amplitude stress versus cycles diagram of BS4360 GRADE 43A-steel

As proved from **Table 3.15**, the P355_E1A-L-4 steel specimen, except the cycle-10 where observed a higher chance in yield limit, in the other cycles there is no significant difference (the same behavior is obtained for the other P355 specimens, also). Although the number of cycles is small (about 50), the coupon is stabilized and that seems from amplitude stress-cycle diagram (**Fig 3.27**), that have no too big variations, if compare the first 10 cycles with the next ones.

Table 3.15 Values of P355_E1A-L-4 steel specimen for 1,10,20,30,40,51 cycles, $R\epsilon=-1$.

P355_E1A-L-4	CYCLE-1	CYCLE-10	CYCLE-20	CYCLE-30	CYCLE-40	CYCLE-51
E(MPa)-COMPRESSION	197280	190630	189710	190230	191780	191040
$\sigma_{y0.2\%}$ (MPa)-COMPRESSION	-267	-305	-301	-297	-295	-295
ΔE	-	3.37%	0.48%	-0.27%	-0.81%	0.39%
$\Delta\sigma_{y0.2\%}$	-	-14.23%	1.31%	1.33%	0.67%	0.00%

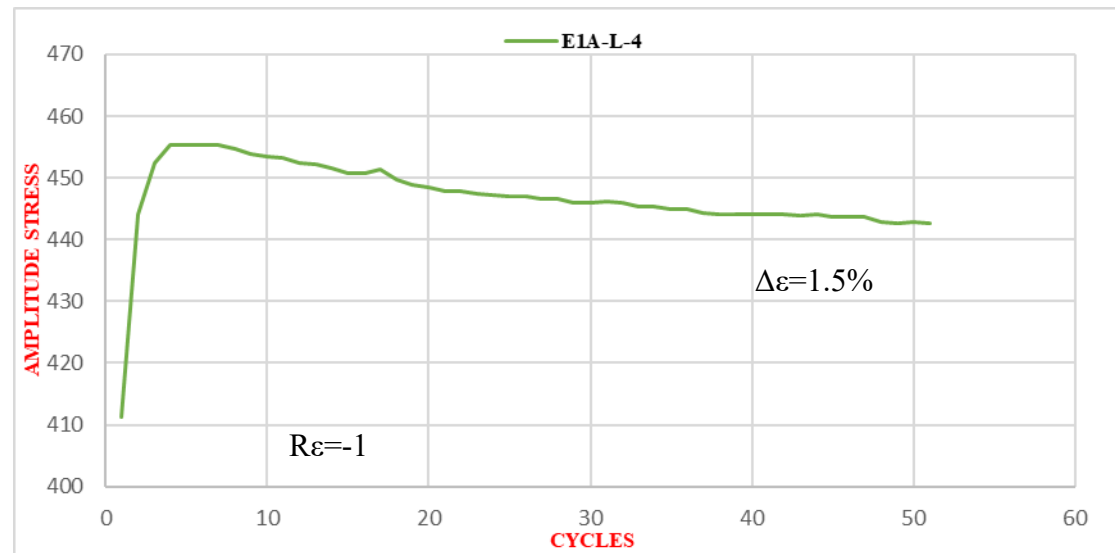


Fig 3.27 Diagram of amplitude stress versus cycles diagram of P355_E1A-L-4 steel specimen.

Table 3.16 demonstrates that the yield limit of the S500(MATCH)-steel TEST2-0.5 specimen decreases as the number of cycles increases, with no significant differences observed at higher cycle counts.

Table 3.16 Values of S500_TEST2-0.5 steel specimen for 1,10,100,400,800,1600,2400,2740 cycles, $R\epsilon=-1$.

TEST2-0.5	CYCLE-1	CYCLE-10	CYCLE-100	CYCLE-400	CYCLE-800	CYCLE-1600	CYCLE-2400	CYCLE-2740
E(MPa)-COMPRESSION	201910	194500	197740	198960	197250	199490	199240	198870
$\sigma_{y0.2\%}$ (MPa)-COMPRESSION	-445	-432	-396	-350	-333	-318	-314	-311
ΔE	-	2.82%	-1.67%	-0.62%	0.86%	-1.14%	0.13%	0.19%
$\Delta\sigma_{y0.2\%}$	-	2.92%	8.33%	11.62%	4.86%	4.50%	1.26%	0.96%

According to **Table 3.17**, this specimen, subjected to a 0.7% strain amplitude, shows a reduction in strength by cycle-10 compared to the first cycle, followed by a gradual increase, ultimately leading to failure at cycle 190 ($E = 259830$).

Table 3.17 Values of S500_TEST1-0.7 steel specimen for 1,10,100,130,150,170,190 cycles, $R\epsilon=-1$.

TEST1-0.7	CYCLE-1	CYCLE-10	CYCLE-100	CYCLE-130	CYCLE-150	CYCLE-170	CYCLE-190
E(MPa)-COMPRESSION	201800	186300	193710	193910	218350	217990	259830
$\sigma_y 0.2\%$ (MPa)-COMPRESSION	-437	-365	-355	-355	-320	-277	-229
ΔE	-	7.73%	-3.98%	-0.10%	-12.60%	0.16%	-19.19%
$\Delta \sigma_y 0.2\%$	-	16.48%	2.74%	0.00%	9.86%	13.44%	17.33%

Fig 3.28 reveals that the TEST1-0.7 specimen experiences a much more abrupt softening compared to TEST2-0.5, with failure occurring after approximately 14 times fewer cycles, indicating more unstable values for both E and $\sigma_y 0.2\%$. Fact which keeps up with results of the two pre-mentioned tables.

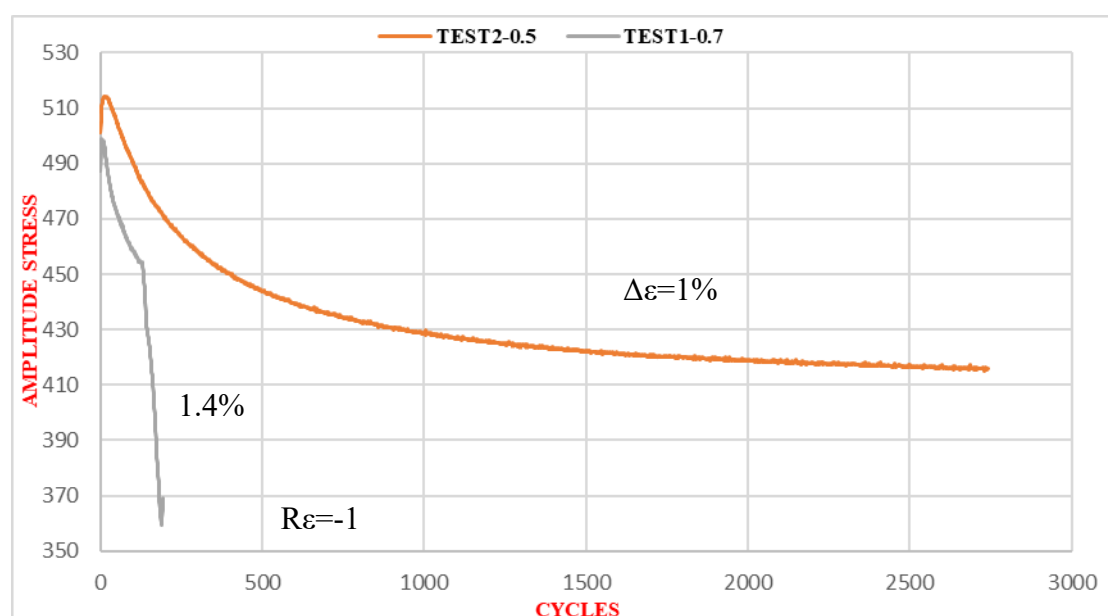


Fig 3.28 Diagram of amplitude stress versus cycles diagram of S700(MATCH) TEST2_0.5% and TEST1_0.7% specimens.

From the second chapter for tension experiments has proved that the yield limit is higher for higher prestrain level. However, comparing the results of **Table 3.18** and **Table 3.19**, which present the S355MC for 0.8% applied strain amplitude and for 8-9% and 12-13% pre-strain respectively, it seems that as the prestrain level increases the magnitude of the yield limit on compression curve and also the elastic modulus decreases for the same number of cycles. The reduction of these properties is small and about at the same levels in any of three occasions (0%, 8-9% and 12-13% prestrain), for the calculated cycles. Reaching to the failure, the elastic modulus and yield limit are increased and the values of E beyond limits, identify that moment. The same behavior is observed on the elastic modulus of S460MC, while the yield limit for 12-13% is higher than that with 8-9% prestrain.

Table 3.18 Values of S355MC_8-9%_0.8%-2 steel specimen for 1,100,200,400, 500, 700,800,877 cycles, $R\epsilon=-1$.

S355MC_8-9% 0.8%	CYCLE- 1	CYCLE- 100	CYCLE- 200	CYCLE- 400	CYCLE- 500	CYCLE- 700	CYCLE- 800	CYCLE- 877
E(MPa)- COMPRESSION	175960	185230	187030	185400	191210	190370	200700	217480
$\sigma_y 0.2\%$ (MPa)- COMPRESSION	-285	-270	-268	-255	-245	-230	-228	-238
ΔE	-	-5.27%	-0.97%	0.87%	-3.13%	0.44%	-5.43%	-8.36%
$\Delta \sigma_y 0.2\%$	-	5.26%	0.74%	4.85%	3.92%	6.12%	0.87%	-4.39%

Table 3.19 Values of S355MC_12-13%_0.8%-2 steel specimen for 1,100,200,400,700,900,1000 ,1020 cycles, $R\epsilon=-1$.

S355MC_12- 13% 0.8%	CYCLE- 1	CYCLE- 100	CYCLE- 200	CYCLE- 400	CYCLE- 700	CYCLE- 900	CYCLE- 1000	CYCLE- 1020
E(MPa)- COMPRESSION	176330	182170	179700	186630	184250	187770	197280	240700
$\sigma_y 0.2\%$ (MPa)- COMPRESSION	-274	-251	-250	-230	-225	-222	-230	-277
ΔE	-	-3.31%	1.36%	-3.86%	1.28%	-1.91%	-5.06%	-22.01%
$\Delta \sigma_y 0.2\%$	-	8.39%	0.40%	8.00%	2.17%	1.33%	-3.60%	-20.43%

4. CHAPTER – STRESS CONTROLLED TEST ANALYSIS

4.1 Stress controlled test summary

In **Table 4.1**, are measured the mean values of E , $\sigma_{y0.2\%}$, and $R_{t0.5\%}$ for the prestrain curve, before starting the application of constant load range, with the respective divergences for each value. Additionally, the materials have been categorized in the aforementioned table based on their yield limits, listed in ascending order. The variations in $\sigma_{y0.2\%}$ range from 0.1% to 11.37%, while $R_{t0.5\%}$ fluctuates between 0.0% and 11.38%, showing similar diverges for the same metal. The elastic modulus magnitude is on the limits and the diverges fluctuate between 0.25% and 9.29%. The percentages are low, indicating the reliability of the experiments. The ranking order remains consistent whether based on $\sigma_{y0.2\%}$ or $R_{y0.5\%}$. In contrast to the tensile experiments, in which S355_T1 coupons are less ductile than S355_T2 and the kormos ones than pelma, it is unusual that the S355_T1 has lower values for $\sigma_{y0.2\%}$ and $R_{t0.5\%}$ as calculated by the prestrain curve compared to S355_T2. This discrepancy can be explained by the fact that the S355_T1 specimens were provided by pelma which is a more ductile region than kormo, from where the one specimen of S355_T2 were extracted.

4.2 General Observations

Table 4.1 Summary of database stress-controlled tests with measured yield strength at 0.2% offset ($\sigma_{y0.2\%}$) and at 0.5% total plastic strain ($R_{t0.5\%}$) and Elastic modulus (E).

GRADE	C_STRESS	$\sigma_{y0.2\%}$ (MPa)	div- $\sigma_{y0.2\%}$	$R_{t0.5\%}$ (MPa)	div- $R_{t0.5\%}$	E (MPa)	div-E
ASME-S234	3	292.3	1.59%	301.6	1.76%	209476	3.23%
S355(L-N)	2	354.1	1.1%	350.5	0.42%	195500	0.25%
S355_T1	3	392.6	11.37%	389.3	11.38%	190930	9.29%
S355_T2	2	398.5	0.12%	397.5	0.12%	214518	1.47%
625 stainless steel	2	495.5	0.10%	505	0.00%	201555	1.61%
S500	6	504.3	6.80%	509.3	6.93%	196634	2.98%
TS590(323.7*10)	2	729.6	2.42%	729.6	2.42%	207004	3.41%
S700(MATCH)	2	750	2.66%	740	1.35%	233855	3.78%
TS590(355*12)	4	754	1.06%	754	1.06%	213990	2.81%
S700(L-N)	2	795.5	4.71%	782.5	6.32%	215000	6.97%

4.2.1 Stress amplitude and Ratio versus Cycles

It is observed that for the same material, as the applied stress range and also the ratio of maximum to minimum stress are increased, the number of cycles until failure are reduced. An instance is illustrated in **Fig 4.1**, where for stress amplitude equal to

1100MPa and $R=1/3$, the coupon fails at about 1017 cycles while for 1300MPa and $R=2/3$ at about 104 cycles. In **Fig. 4.2**, it appears that for the specimen with higher R and $\Delta\sigma$, the distance between the hysteresis loops becomes increasingly larger as the number of cycles increases. In contrast, the loops in **Fig. 4.3** are much more condensed.

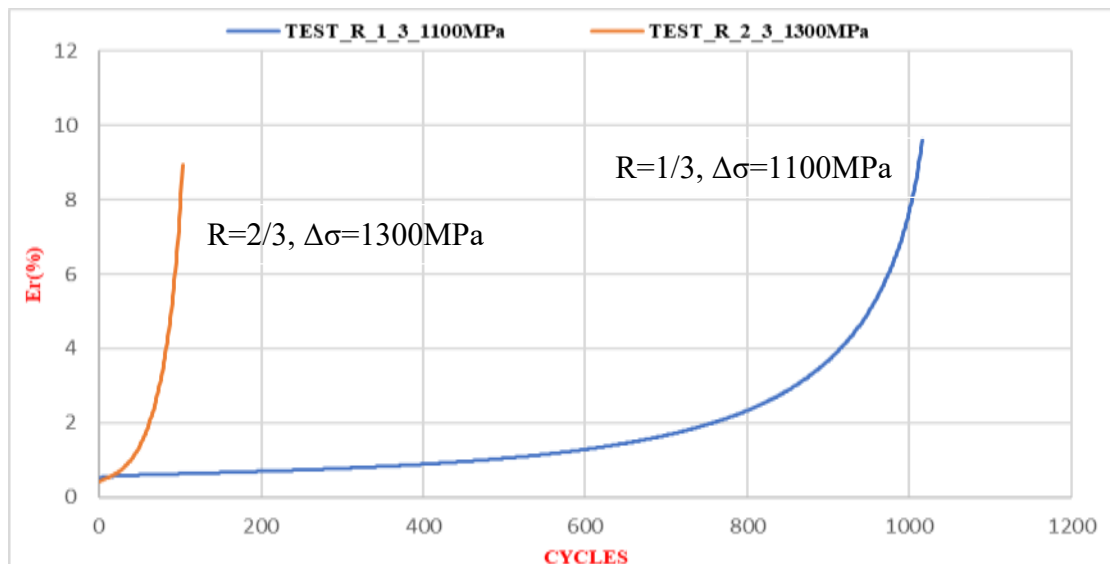


Fig 4.1 Ratcheting strain curve E_r (%) - N of S700(MATCH)-steel.

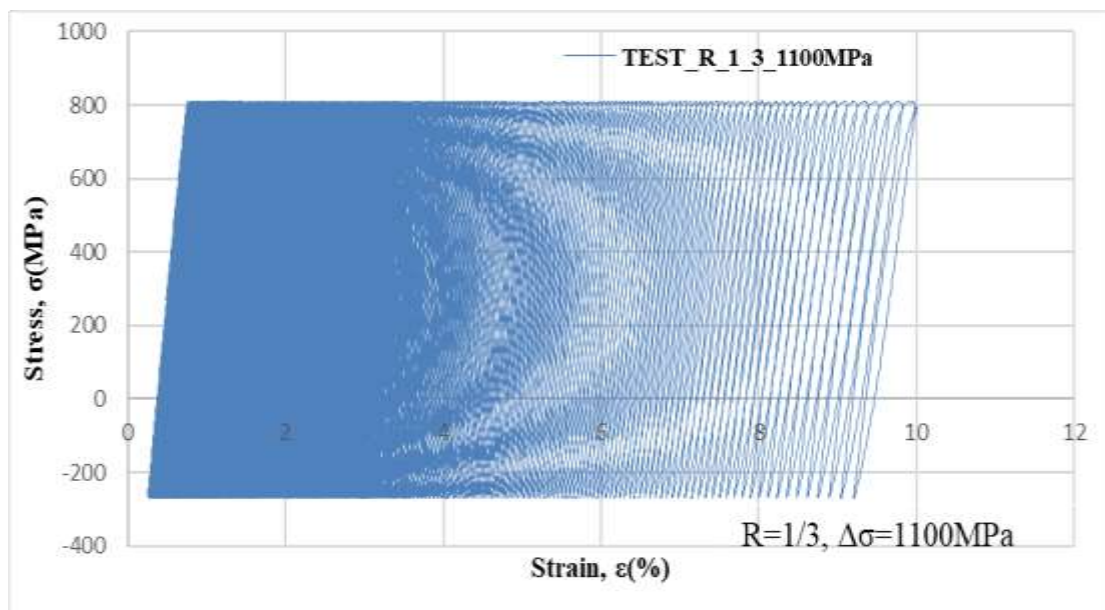


Fig 4.2 Ratcheting failure of S700(MATCH)_TEST_R_1_3_1100MPa-steel at 1017 cycles.

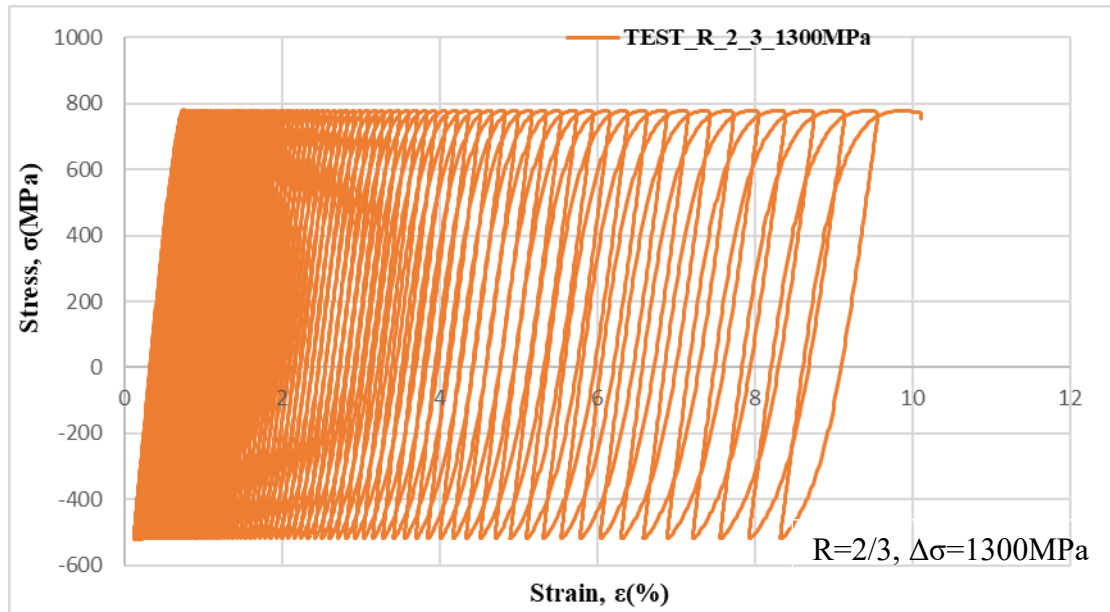


Fig 4.3 Ratcheting failure of S700(MATCH)_TEST_R_2_3_1300MPa-steel at 104 cycles.

One more example of the prementioned phenomenon, it seems at **Fig 4.4** where the two specimens have submitted under the same stress ratio but different stress amplitude. The specimen subjected to 560 MPa endured over 2200 cycles, while the one exposed to 700 MPa failed after approximately 1200 cycles, showing greater ratcheting strain accumulation, as evidenced by the steeper slope of the curve.

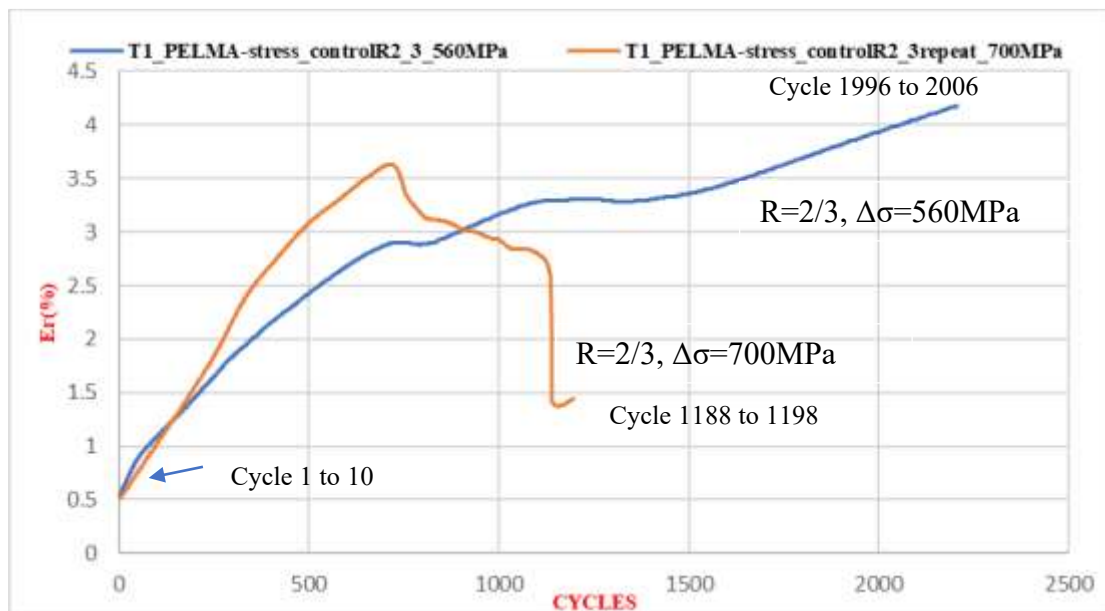


Fig 4.4 Ratcheting strain curve E_r (%) - N of S355(MATCH)-steel.

Fig 4.5 and **Fig 4.6** depict the initial and final 10 cycles for each specimen, with the latter cycles corresponding to failure. It appears that in the last 10 cycles, the hysteresis loops expand compared to the first 10 cycles, especially for $\Delta\sigma=460\text{MPa}$ ($\Delta\varepsilon=0.87\% > 0.78\%$), and the loops also tend to coincide.

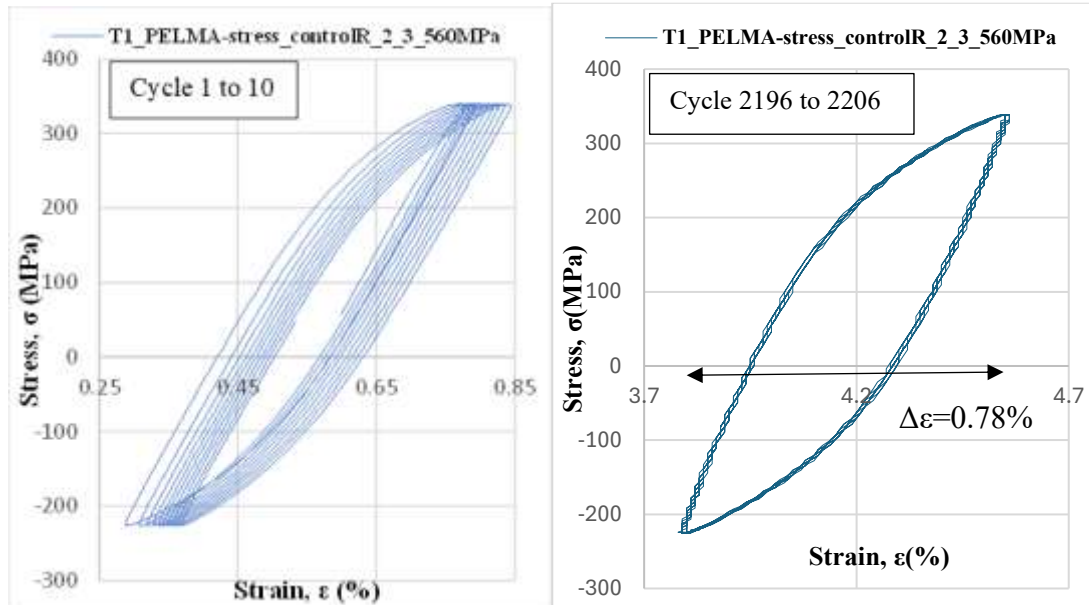


Fig 4.5 Ratcheting stress-strain curve of S355(MATCH)_T1_PELMA stress_controlR_2_3_560MPa-steel at 1-10 and 2196 to 2206 cycles.

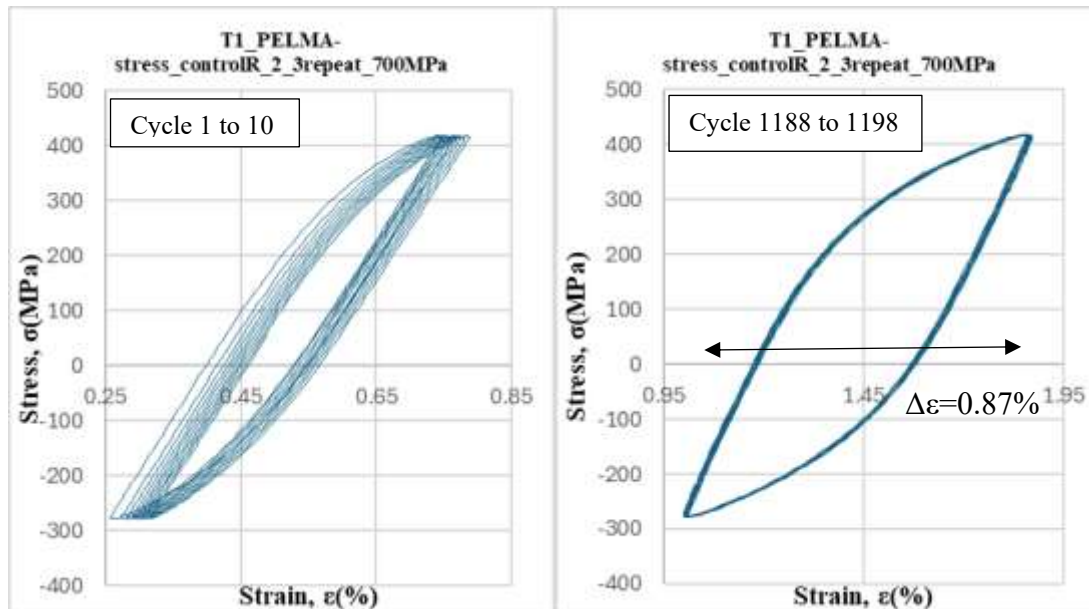


Fig 4.6 Ratcheting stress-strain curve of S355(MATCH)_T1_PELMA-stress_controlR_2_3_700MPa-steel at 1-10 and 1188 to 1198 cycles.

4.2.2 Ratcheting behavior

- 625 stainless steel

The 625 stainless steel specimens were subjected to a 1000 MPa stress amplitude. The specimen extracted from the L180 pipe position exhibited clear plastic shakedown behavior for all cycles (approximately 95 cycles) without exceeding the prestrain value. The L90 specimen displayed similar behavior, showing a constant ratcheting rate on the E_r (%) - N diagram, indicated by the slope of the curve, **Fig 4.7**. However, the increase of E_r (%), i.e. the dislocation of the hysteresis loop center reaching only 0.1% over 100 cycles, which is a negligible value. **Fig 4.8** illustrates that the ratcheting strain accumulation in each cycle remains consistent, as the difference between the $\Delta\epsilon$ in each cycle is nearly the same (These two experiments interrupt before failure).

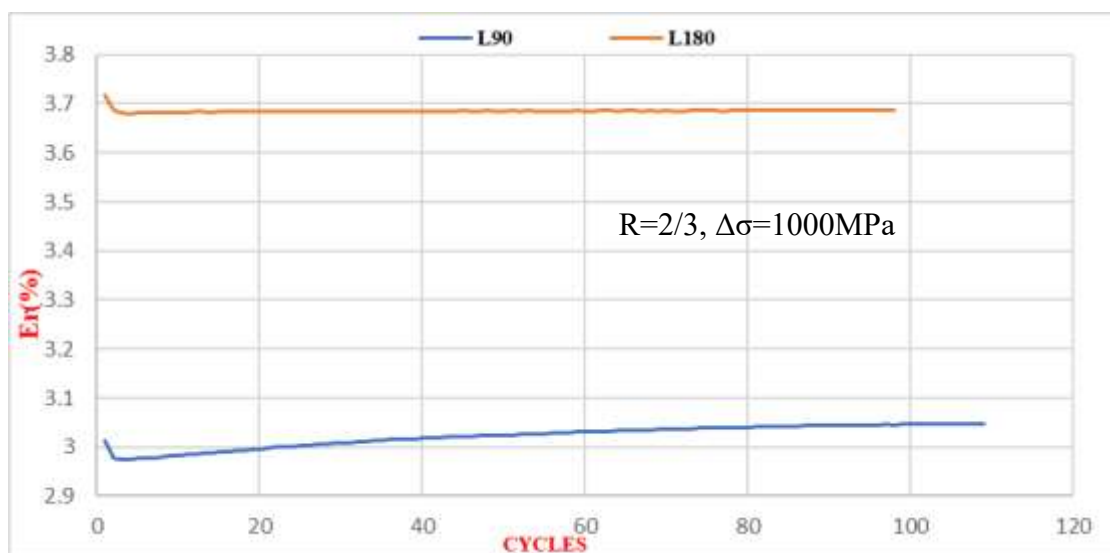


Fig 4.7 Ratcheting strain curve E_r (%) - N of 625 stainless-steel.

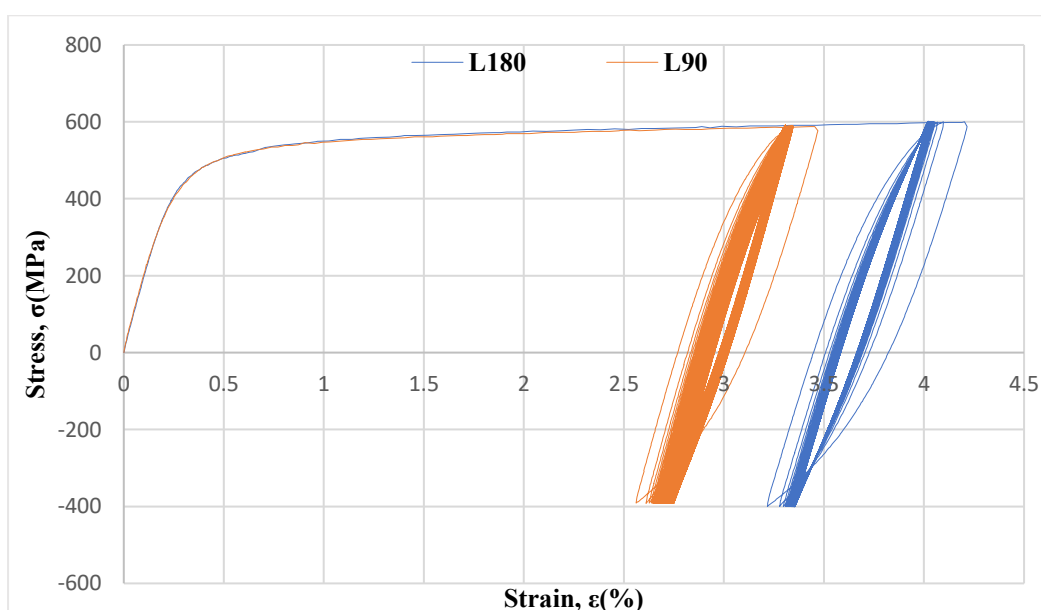


Fig 4.8 Ratcheting stress-strain curve of 625 stainless-steel.

- **S700(L-N) & S700(Match)**

Next, a comparison is presented between S700(L-N), extracted from a cold drawing plane and S700(Match) from a quenched hollow section. According to **Fig. 4.9** in which the decreasing ratcheting rate illustrates the hardening behavior, the S700(L-N) coupon in the transverse direction, subjected to 1400 MPa, exhibits higher hardening in the primary zone (cycle-20). This is followed by the longitudinal direction coupon with an applied stress range of 1200 MPa, which shows similar hardening but extends until cycle-30. In contrast, the S700(Match) specimen with $\Delta\sigma=1300$ MPa (cycle-10) shows negligible hardening, while the specimen with $\Delta\sigma=1100$ MPa does not exhibit any hardening.

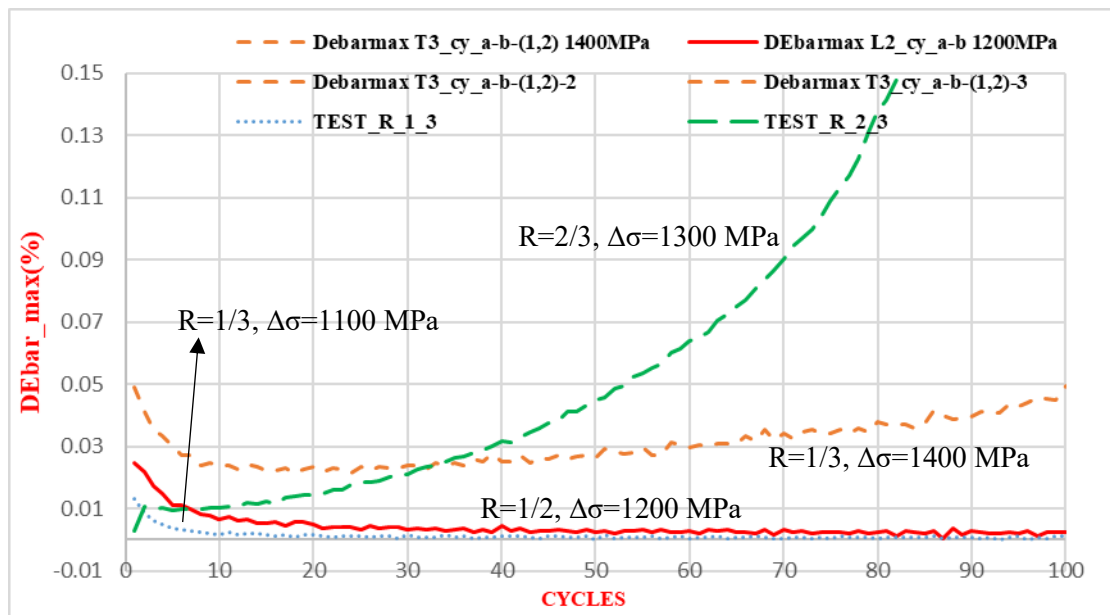


Fig 4.9 Ratcheting strain curve Debar_max(%) - Ni of S700(L-N) and S700(MATCH) steel (until cycle-100).

Subsequently, in **Fig 4.10** is demonstrated that the S700(L-N) _T3 enters the secondary region, characterized by constant strain accumulation at a high rate (slope) until about 150 cycles. The S700(Match) _TEST-R13, with lower stress amplitude and ratio, shows constant strain accumulation at a very slow rate, close to zero until cycle 600, which are responded to plastic shakedown. Until cycle-900 the rate is increased, but it stays also constant. The S700(L-N) _L2 specimen follows a similar pattern i.e. all cycles after cycle-40 have almost zero accumulation rate. The S700(Match) _TEST-R23 exhibits the secondary region until cycle-40 with a slightly higher rate than the previously mentioned coupons.

The third region is marked by cycling softening behavior, indicating the onset of failure. The highest softening rate occurs in the S700(Match) _TEST-R23, followed closely by the S700(L-N) _T3, and finally, by the S700(Match) _TEST-R13 with a more extended softening region and a lower rate (smaller slope).

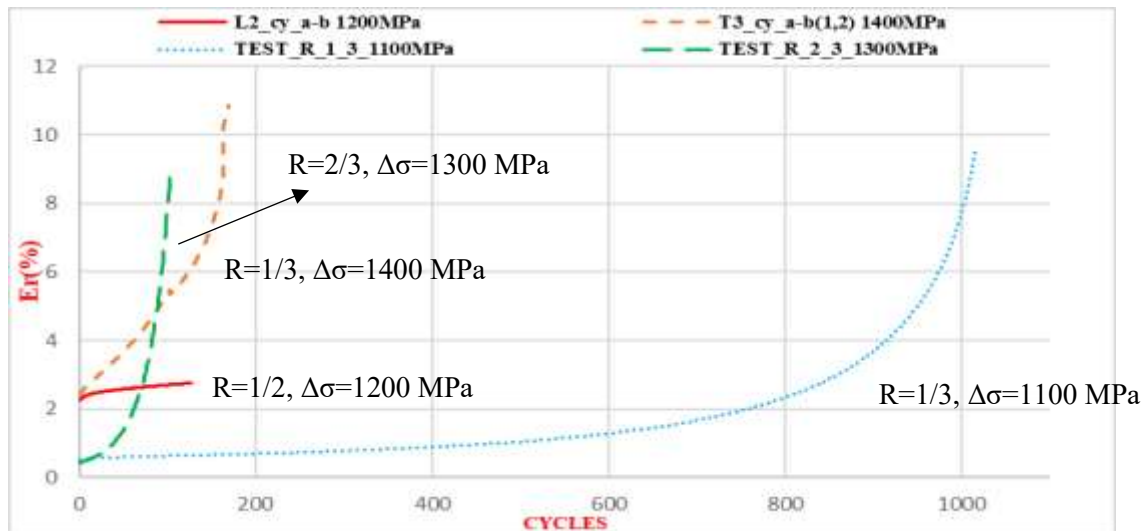


Fig 4.10 Ratcheting strain curve E_r (%) - N of S700(L-N) and S700(MATCH) -steels.

- **TS590(323,7*10) & TS590(355*12)**

The stress-controlled tests with a ratio $R=0$ or $R=1/3$, which have lower stress amplitudes, exhibit very low strain hardening behavior for approximately the first 40 cycles, **Fig 4.11**.

Beyond this point, the ratcheting curve stabilizes, indicating the onset of the plastic shakedown phenomenon. For a ratio $R=2/3$, TEST(4-5) shows a higher ratcheting rate throughout all regions compared to TEST(5-5). In TEST(4-5), cyclic hardening occurs until the 10th cycle, followed by a constant rate up to the 29th cycle, and then enter in third region until cycle 50. In contrast, TEST(5-5) exhibits cyclic hardening until the 10th cycle, maintains a constant rate until the 45th cycle, and then enters the softening mechanism from cycle 30 to 80. At around 50 cycles for the (4-5) specimen and 80 cycles for the (5-5) specimen, there is a sixfold increase in the final strain accumulation compared to other specimens.

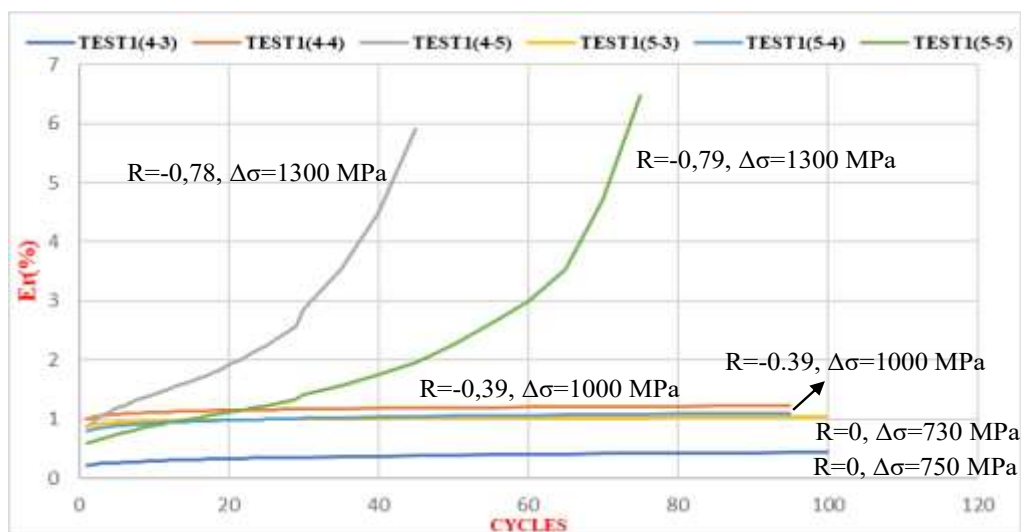


Fig 4.11 Ratcheting strain curve E_r (%) - N of TS590(323.7*10) and TS590(355*12)-steel.

The stress-strain response in **Fig 4.12** of specimens (4-5), illustrates the significant strain accumulation in the final cycles, the $\Delta\epsilon$ (%) progressively increases, ultimately resulting in failure.

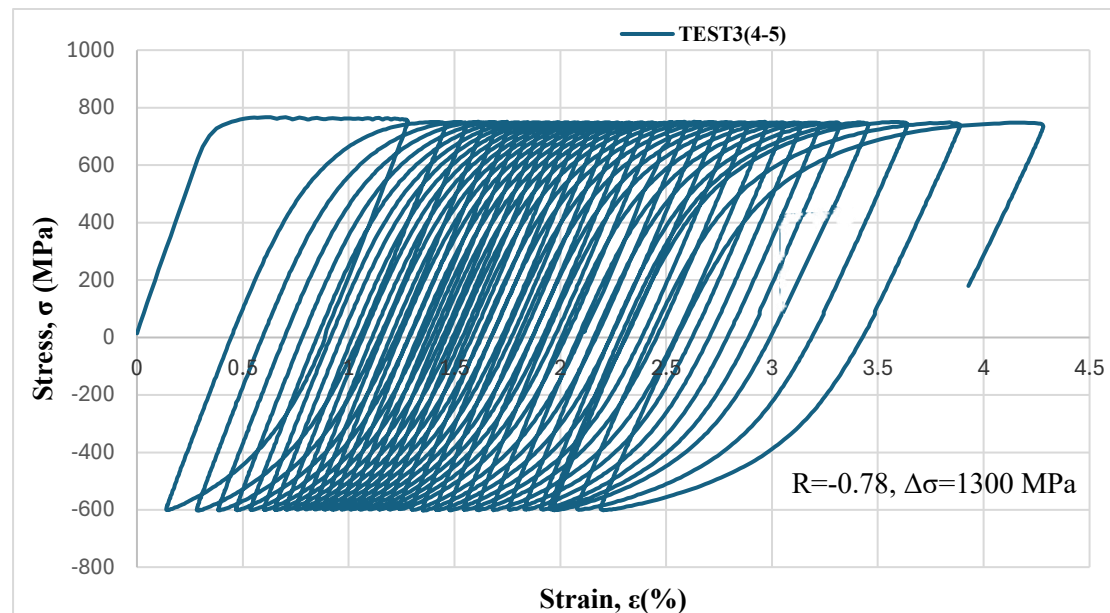


Fig 4.12 Ratcheting stress-strain curves of and TS590_4-5 steel specimens.

- **ASME S234-steel**

In **Fig 4.13** is presented the E_r (%) - N diagram of ASME S234- steel, respectively. For the specimen with a stress ratio of 1/3, the primary zone is maintained up to approximately 10 cycles, during which the steel undergoes cyclic hardening. Afterward, ratcheting strain accumulation stabilizes, indicating that the material has entered the secondary zone. At 280 cycles, strain accumulation begins to show cyclic hardening behavior until around cycle-300, after which the E_r (%) decreases, signaling that the hysteresis loop shifts leftward. In the specimen with a higher stress ratio of 1/2, cyclic hardening is observed up to 200 cycles. Surprisingly, despite being subjected to higher compressive stress and more challenging cyclic conditions, the material continues to harden until the last cycle at 1132, where softening would be expected to occur sooner. However, it is consistent with the observation that for the same number of cycles, this specimen exhibits significantly higher strain accumulation. The final specimen, with a stress ratio of 2/3, also displays hardening behavior up to cycle-200. Between cycles 200 and 413, the material remains in the secondary zone, but beyond cycle-413, there is an abrupt drop in E_r (%), indicating a reduction in strain accumulation, which approaches near zero.

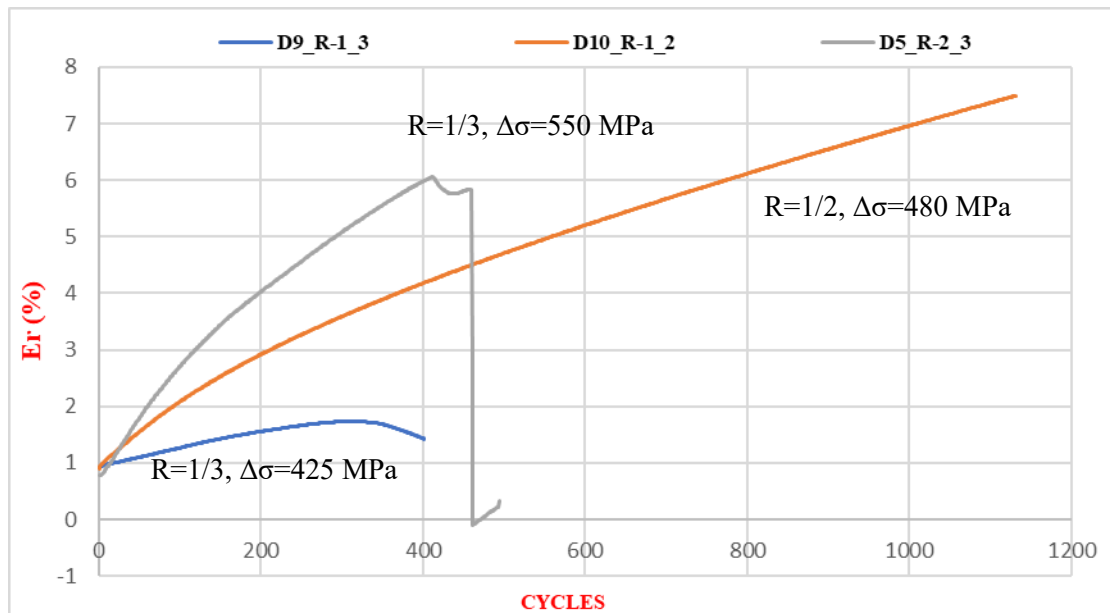


Fig 4.13 Ratcheting strain curve Er (%) - N of ASME S234-steel.

- **S355(L-N)**

Certainly, these experimental tests are induced until the rate of ratcheting become constant, and before any failure exist. The ratio between max compression and tension stress is 2/3 for transverse and 1/3 for longitudinal test and the $\Delta\sigma = 700\text{MPa}$ for each one. It is clear from **Fig 4.14** that in longitudinal direction, the coupon has cyclic hardening until cycle-30 and after is stabilized around a constant value. The same way is followed by the transverse specimen too, but with less hardening for about the first 30 cycles and also less strain accumulation (at cycle 53 the difference is 2.6%).

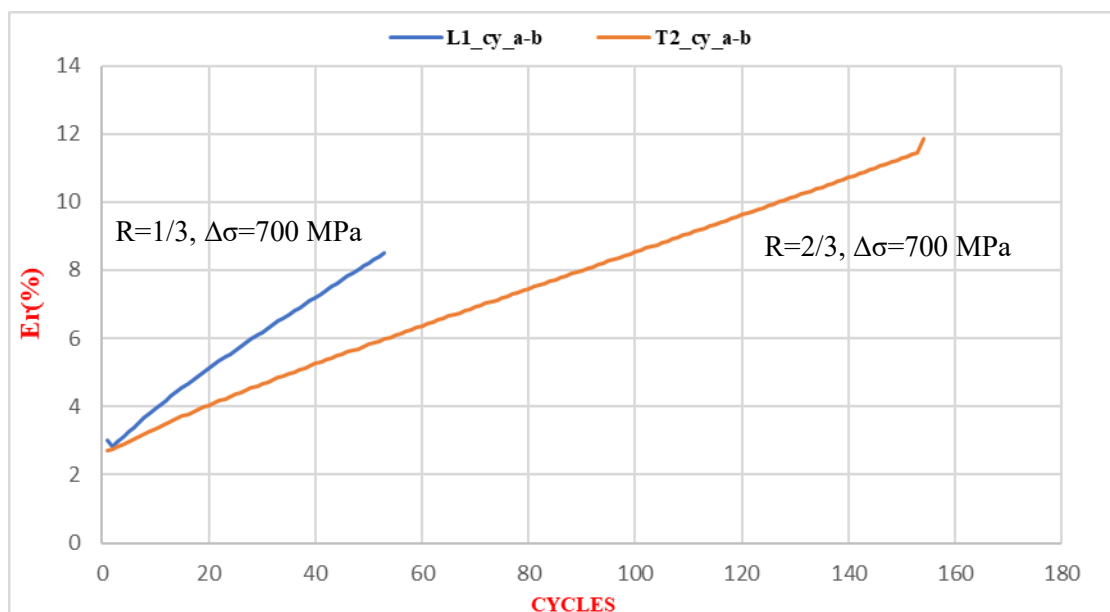


Fig 4.14 Ratcheting strain curve Er (%) - N of S355(L-N)-steel.

- **S355(MATCH) T1 & T2**

For the S355_T1 material, there are three available stress-controlled tests, but all coupons are extracted from pelma of HEA, while for S355_T2 there is one from pelma and one from kormo. All the pre-mentioned experimental tests have been subjected under max compression stress equal to 2/3 of max tension stress.

According to **Fig 4.15**, the T1_PELMA-R2_3 specimen which exhibits the lowest stress range of $\Delta\sigma = 560$ MPa, shows minimal strain accumulation and demonstrates greater resistance over a higher number of cycles. The curve indicates that the specimen undergoes rapid hardening within the first 3-4 cycles, similar to the behavior observed in other tests. After this initial phase, the strain increases at a constant rate until approximately cycle 700. Beyond this point, some fluctuations are observed, suggesting alternating periods of softening and hardening, before the strain increase rate stabilizes once again. The T1_PELMA-R2_3repeat has $\Delta\sigma=700$ MPa, demonstrate constant increasing rate and after continuing to increase, but due to cyclic hardening until about cycle 730 where start an abrupt drop on strain accumulation. The last pelma coupon with $\Delta\sigma=670$ MPa, demonstrates an increasing accumulation strain clearly because of hardening, as indicated by curve's trend.

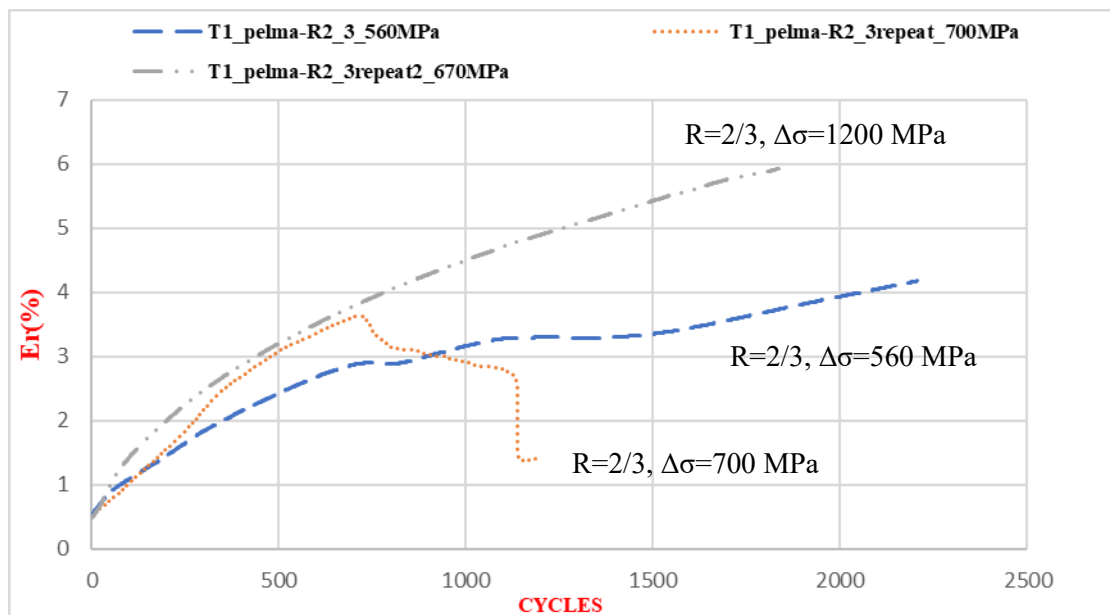


Fig 4.15 Ratcheting strain curve $Er(\%)$ -N of S355_T1-steel.

For S355(MATCH)_T2-steel (**Fig 4.16**), the specimens from kormo and much more from pelma present higher strain accumulation in relation to the prementioned material's specimens. That from kormos and pelma has almost standard strain accumulation rate for all cycles except the second one, that at a few first cycles seems to show cyclic softening.

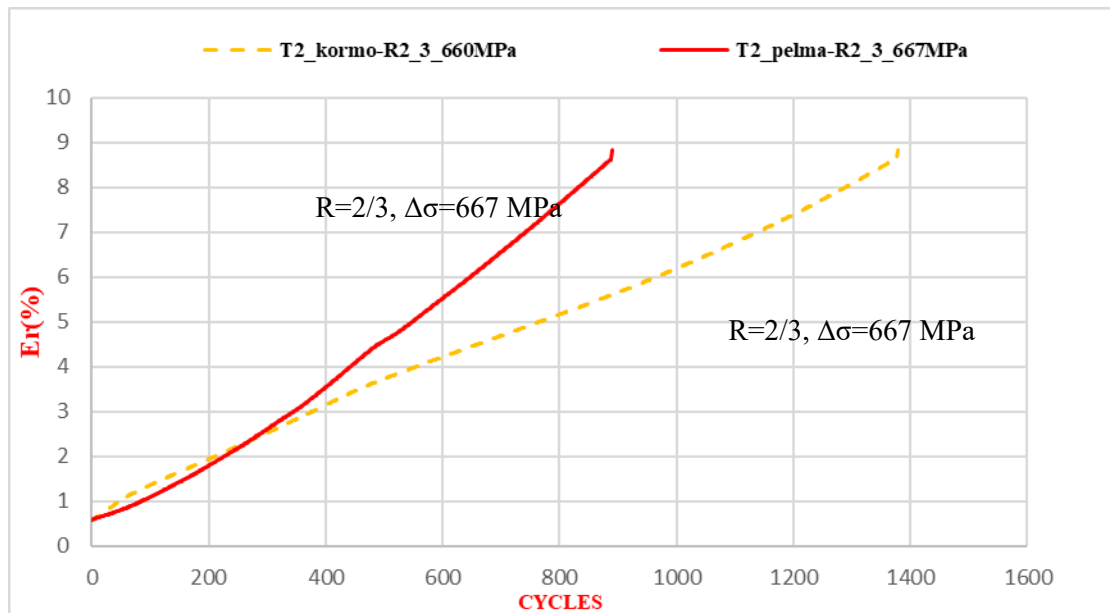


Fig 4.16 Ratcheting strain curve Er (%) - N of S355_T2-steel.

In general, the S355_T1 under the same cycling loads resist for more cycles and be more stable, that may be explained by the higher yield strength limits as are proven by tensile analysis tests. Because the applied cyclic stress, which is closer to the yield limit, causes higher the ratcheting rate.

- **S500(MATCH)-steel**

As it is proved from **Fig 4.17** and **Fig 4.18**, the S500 steel specimen with an R ratio of $1/3$, exhibits a negligible increase in strain accumulation, indicating the occurrence of plastic shakedown. In the 2S500-R2_3 and 2S500-R3_3 tests, data available up to 270 and 116 cycles, respectively, reveal a slight but constant ratcheting rate, which is more pronounced in the latter experiment. The 2S500-R3_4 specimen demonstrates a rapid increase in accumulated ratcheting strain, reaching about 9.7% after 171 cycles, likely due to cyclic softening as indicated by the slope of the curve. The TEST_R23 specimen shows plastic shakedown until approximately 400 cycles, followed by a very low and constant strain accumulation until 900 cycles, after which a sudden 7.5% increase in ratcheting strain occurs at 550 cycles, attributed to cyclic softening.

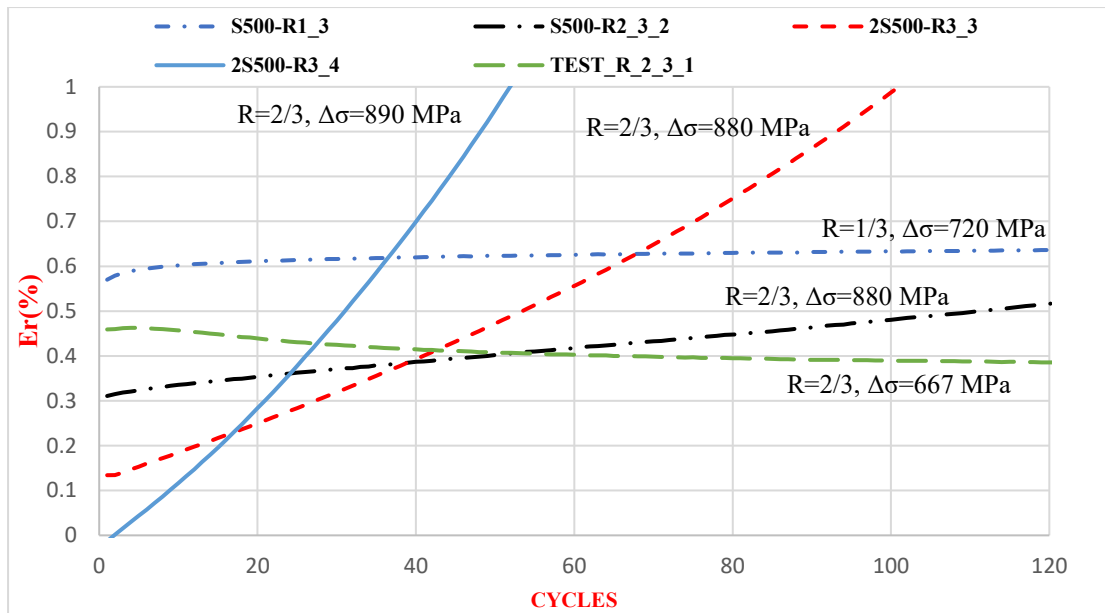


Fig 4.17 a) Ratcheting strain curve E_r (%) - N of S500(MATCH)-steel(cycle-120)

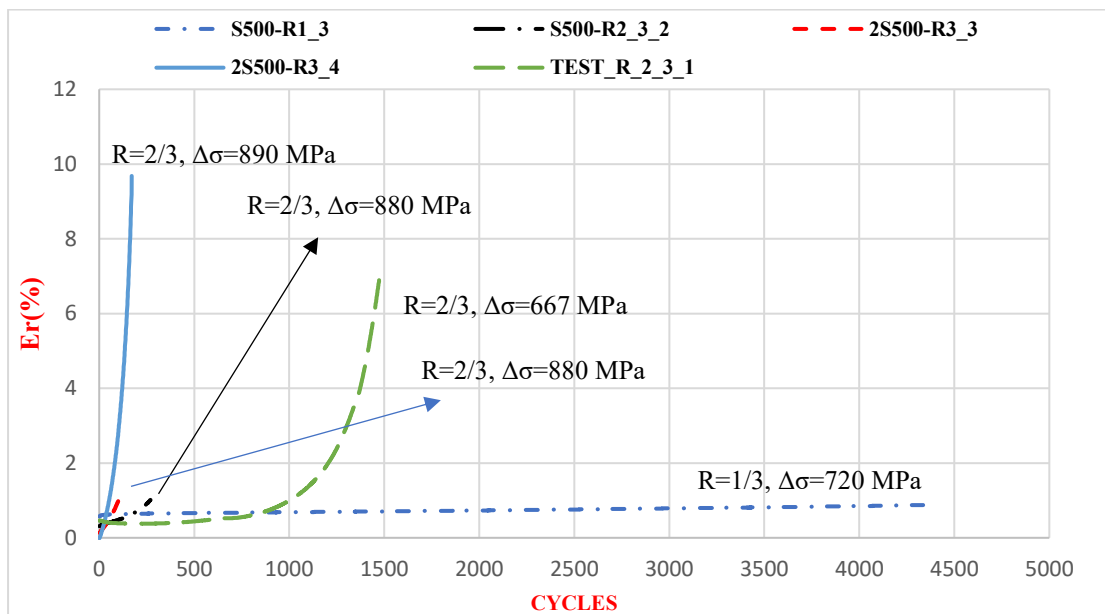


Fig 4.18 b) Ratcheting strain curve E_r (%) - N of S500(MATCH)-steel(overall).

4.2.3 Elastic modulus & cycles

The TEST(4-3) and TEST(5-3) specimens that until cycle-100 present a stable situation, it is logical that the elastic modulus doesn't have a significant change, that is visible from **Fig 4.19** in which the curves of each mentioned cycle seems the same. On the other hand, the other two coupons, as it seems from **Fig 4.20**, face an abrupt increase of ratcheting strain accumulation due to softening, while the elastic modulus demonstrates a visible and major drop due to the change in slope of unloading curve. (**Table 4.2**)

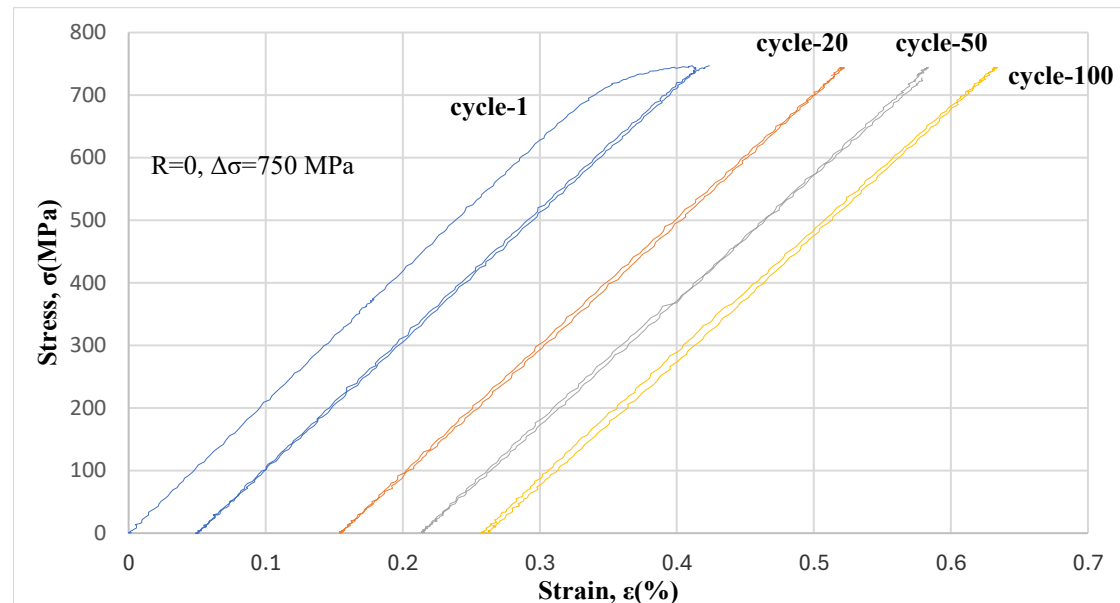


Fig 4.19 Ratcheting stress-strain curve of TS590_TEST (4-3)-steel at 1,20,50 and 100 cycles.

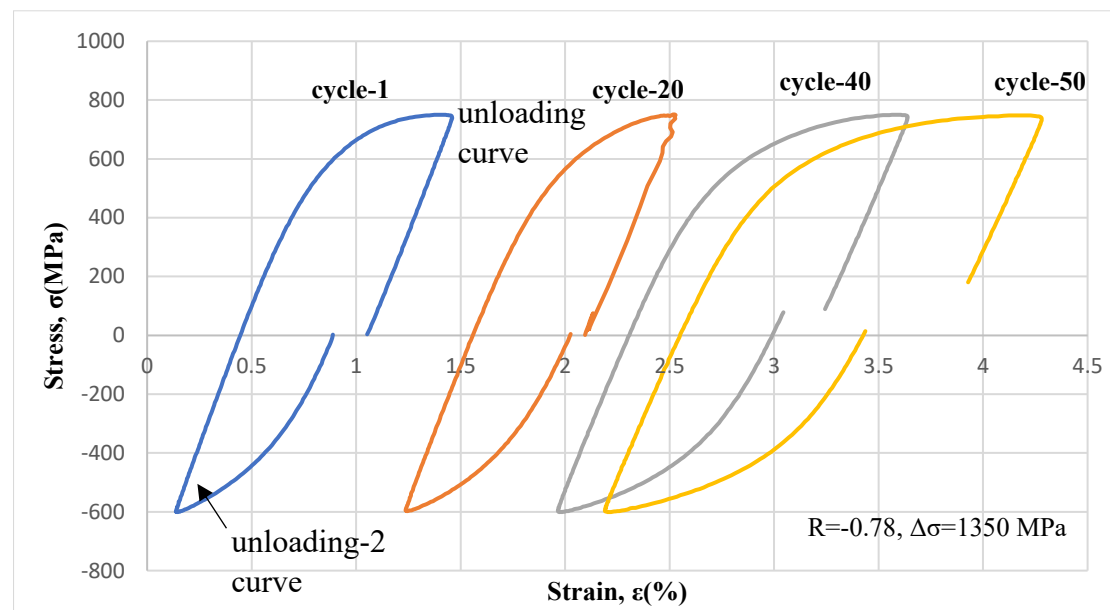
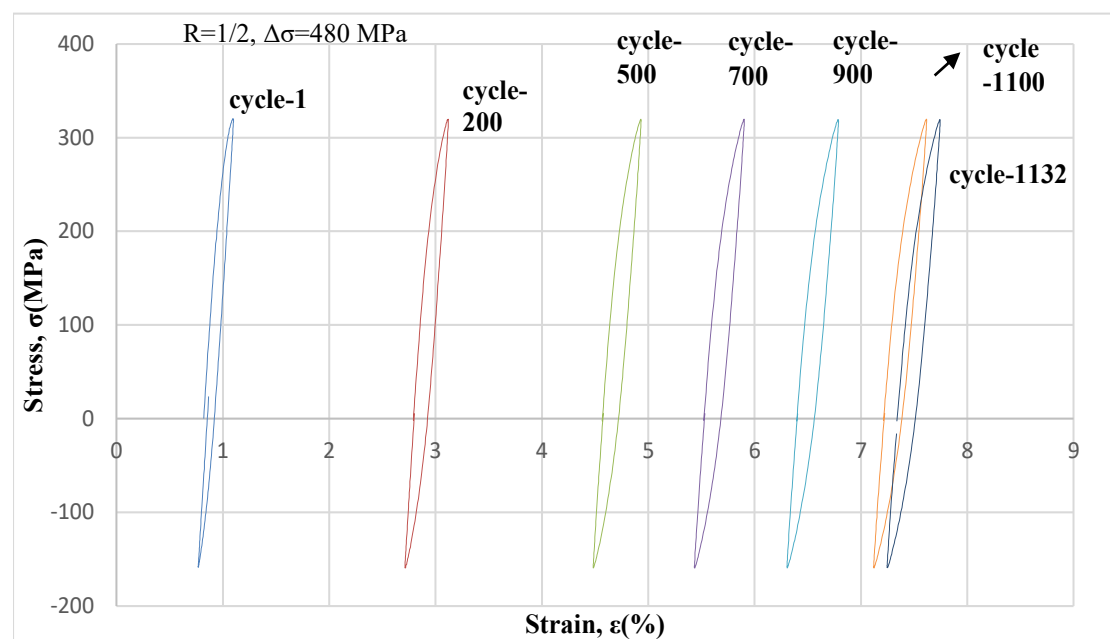


Fig 4.20 Ratcheting stress-strain curve of TS590_TEST(4-5)-steel at 1,20,40 and 50 cycles.

Table 4.2 Elastic modulus of unloading curve for TS590-steel.

TEST(4-3)	cycle-1	cycle-20	cycle-50	cycle-100
E unloading (MPa)	205 820	204090	203650	203170
TEST(4-5)	cycle-1	cycle-20	cycle-40	cycle-50
E unloading (MPa)	192160	197590	177670	166300
TEST(5-3)	cycle-1	cycle-20	cycle-50	cycle-100
E unloading (MPa)	198990	200220	200350	198910
TEST(5-5)	cycle-1	cycle-40	cycle-70	cycle-80
E unloading (MPa)	202870	191420	179360	172580

Also in **Table 4.3**, another experiment is about the ASME-S234 steel coupons, which were submitted until failure, and are presented with a gradual decrease of elastic modulus. The calculated cycles are presented in **Fig 4.21**.

**Fig 4.21** Ratcheting stress-strain curve of ASME-S234_D10_R-1_2 steel at 1,200,500,700,900,1100 ad 1132 cycles.**Table 4.3** Elastic modulus of unloading curve for ASME-S234 steel.

D9_R-1_3	cycle-1	cycle-50	cycle-150	cycle-250	cycle-350	cycle-400	cycle-402
E unloading (MPa)	194470	196610	205440	192470	190980	185630	185470
D10_R-1_2	cycle-1	cycle-200	cycle-500	cycle-700	cycle-900	cycle-1100	cycle-1132
E unloading (MPa)	197140	185890	175990	171410	167430	162380	162900
D5_R-2_3	cycle-1	cycle-50	cycle-150	cycle-250	cycle-350	cycle-450	cycle-493
E unloading (MPa)	195520	189330	179590	172850	168820	166670	173750

In relation to the first unloading curve, in the second one for the corresponding cycles, the elastic modulus has just a bit higher value, while demonstrate the same behavior i.e. the elastic modulus decreases for the specimens, that soften reaching the failure time. (**Table 4.4** and **Table 4.5**.)

Table 4.4 Elastic modulus of unloading-2 curve for TS590-steel.

TEST(4-3)	cycle-1	cycle-20	cycle-50	cycle-100
E unloading-2(MPa)	207890	209050	204430	207580
TEST(4-5)	cycle-1	cycle-20	cycle-40	cycle-50
E unloading-2(MPa)	202920	195180	187460	176930
TEST(5-3)	cycle-1	cycle-20	cycle-50	cycle-100
E unloading-2(MPa)	204120	204060	203120	203820
TEST(5-5)	cycle-1	cycle-40	cycle-70	cycle-80
E unloading-2(MPa)	218050	206840	195290	188930

Table 4.5 Elastic modulus of unloading-2 curve for ASME-S234 steel.

D9 R-1 3	cycle-1	cycle-50	cycle-150	cycle-250	cycle-350	cycle-400	cycle-402
E unloading (MPa)	199840	200970	196930	194700	193700	194490	193090
D10 R-1 2	cycle-1	cycle-200	cycle-500	cycle-700	cycle-900	cycle-1100	cycle-1131
E unloading(MPa)	196130	186800	180350	174700	172940	166820	167330
D5 R-2 3	cycle-1	cycle-50	cycle-150	cycle-250	cycle-350	cycle-450	cycle-493
E unloading (MPa)	206250	196800	185370	177330	172470	170450	177430

5. CHAPTER – COMPRESSION TEST ANALYSIS

5.1 Compression test summary

In **Table 5.1**, are represented the mean values of E , $\sigma_{y0.2\%}$, and $R_{t0.5\%}$ for the compression curve, along with the corresponding deviations for each value, to assess the accuracy of the experiments. The available compression experiments data stop at about 1% strain, so there is no information for the failure time.

The specimens for each pipe had extracted by different positions that characterized by inner or outer surface, and the angle. Also, the 30in and 16in pipe coupons have distinguished in specimens before and after the thermal process. The 30in and 26in have specimens from traverse or longitudinal direction, while 16in only from traverse. So, this big range of coupons, explain the high percentages in deviation values with the larger to appear at X65_26in steel pipe. The elastic modulus magnitude is normal with some samples of 30in pipe to extend lightly the upper limit (230000 MPa). Now, according to the yield limit $\sigma_{y0.2\%}$ and $R_{t0.5\%}$ the pipe with 26inches diameter demonstrate the lower value after follows the 30in pipe and finally the 16in pipe with significantly higher values. The pipes from the same materials (26in and 16in) with different diameter indicate that the lower diameter led to higher yield limit.

Table 5.1 Summary of database compression tests with measured yield strength at 0.2% offset ($\sigma_{y0.2\%}$) and at 0.5% total plastic strain ($R_{t0.5\%}$) and Elastic modulus (E).

GRADE	COM	$\sigma_{y0.2\%}$ (MPa)	div- $\sigma_{y0.2\%}$	$R_{t0.5\%}$ (MPa)	div- $R_{t0.5\%}$	E (MPa)	div-E
X65_26in	12	457.08	26.07%	467.71	24.88%	203791	23.06%
X60_30in	13	491.61	14.97%	508.84	11.23%	230533	13.24%
X65_16in	14	579.78	14.27%	583.99	12.92%	219360	11.54%

5.2 General Observations

- **X65_26in**

Based on **Table 5.2**, in **Fig 5.2** are illustrated the specimens which are differentiated by direction (L and T) and angular position, as it shows **Fig 5.1**. Firstly, the specimens at the 180° position exhibit a higher yield strength than the others, with the longitudinal direction showing the greatest value, approximately 85 MPa more than the transverse direction. Following this, the 270° position ranks second, while the 90° position has the lowest yield strength, except for the T-90, which slightly exceeds T-270, though the difference is minimal. A similar trend is observed for $R_{t0.5\%}$. Regarding the elastic modulus in the longitudinal direction, the overall magnitude is lower, but for each direction, the 180° position has the highest value.

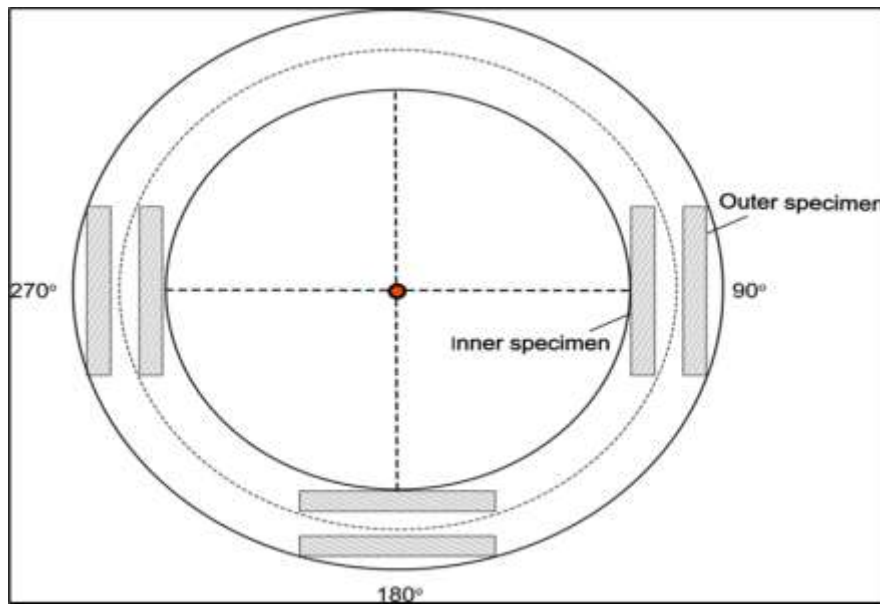


Fig 5.1 Position and orientation of sample collection from the pipe

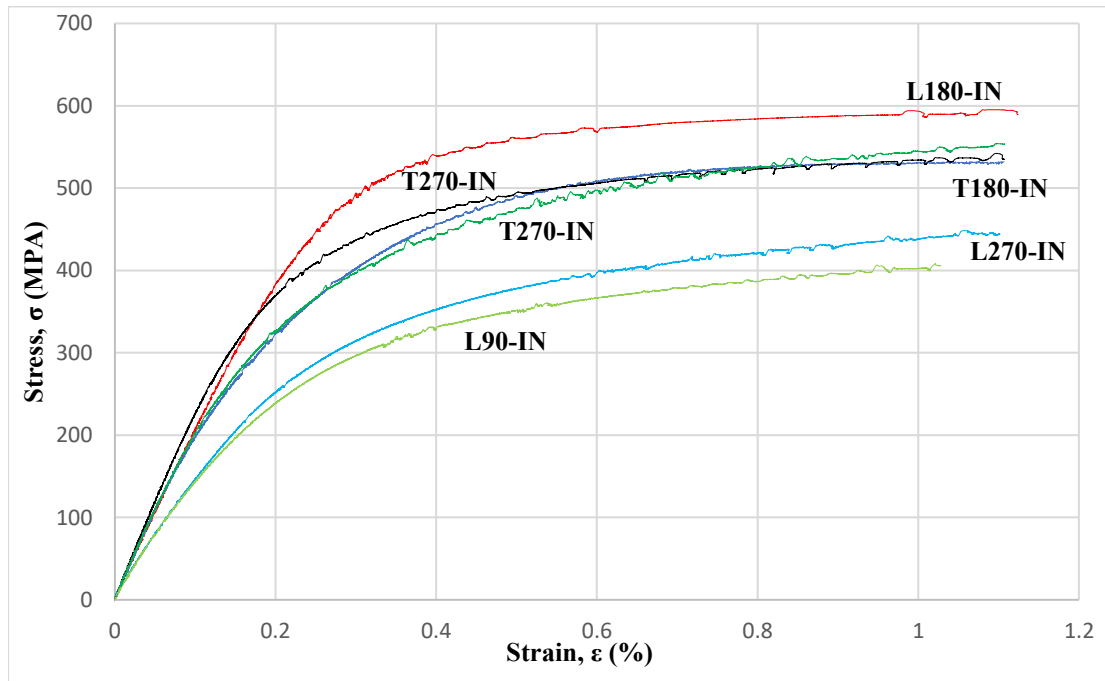


Fig 5.2 Stress-strain compression curves for a single specimen from each extraction point (Longitudinal /Transverse- 90/180/270) for X65_26in.

Table 5.2 Summary of database compression tests with measured yield strength at 0.2% offset ($\sigma_{y0.2\%}$) and at 0.5% total plastic strain (Rt0.5%) and Elastic modulus (E).

X65_26in	$\sigma_{y0.2\%}$ (MPa)	div- $\sigma_{y0.2\%}$	Rt0.5% (MPa)	div-Rt0.5%	E (MPa)	div-E
L-90	405	17.28%	419.5	16.26%	177665	11.19%
L-180	569	2.46%	572.1	2.02%	207320	2.83%
L-270	432.5	16.70%	447.3	15.50%	175940	10.88%
T-90	427.5	8.77%	455.4	7.57%	217415	3.44%
T-180	487.5	17.94%	463.7	6.58%	227485	0.12%
T-270	421	6.88%	447.9	5.83%	216925	3.45%

In **Table 5.3**, are compared the direction with the inner or outer extraction position of the specimen yields somewhat ambiguous results, as neither the direction nor the position consistently indicates a trend in terms of increasing or decreasing properties. However, the elastic modulus is higher in the transverse direction and for specimens extracted from the outer position. It has to be noticed that in L-IN specimens, the elastic modulus has very low value and that is also visible from **Fig 5.3**.

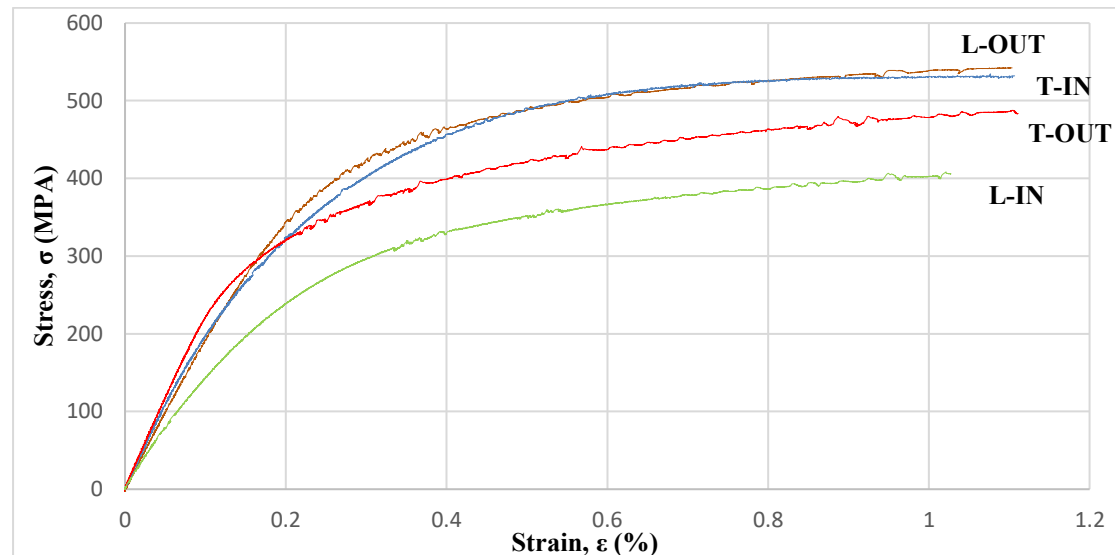


Fig 5.3 Stress-strain compression curves for a single specimen from each extraction point (Longitudinal /Transverse- INNER/OUTER) for X65_26in.

Table 5.3 Summary of database compression tests with measured yield strength at 0.2% offset ($\sigma_{y0.2\%}$) and at 0.5% total plastic strain ($R_{t0.5\%}$) and Elastic modulus (E).

X65_26in	$\sigma_{y0.2\%}$ (MPa)	div- $\sigma_{y0.2\%}$	$R_{t0.5\%}$ (MPa)	div- $R_{t0.5\%}$	E (MPa)	div-E
L-IN	416.6	33.20%	429.8	30.39%	172003	17.11%
L-OUT	521	11.90%	529.5	10.25%	201946	5.56%
T-IN	496.6	15.77%	486.1	2.47%	215523	5.41%
T-OUT	394	1.52%	425.3	1.86%	225693	0.56%

- **X65_16in**

The specimens from 16in pipe which are fabricated (AF), indicate lower values in each of three properties, in relation to the values after thermal process (HT) as illustrated at **Table 5.4**. **Fig 5.4** presents stress-strain curves from various coupons, highlighting the previously mentioned observations regarding the presence or absence of thermal processing.

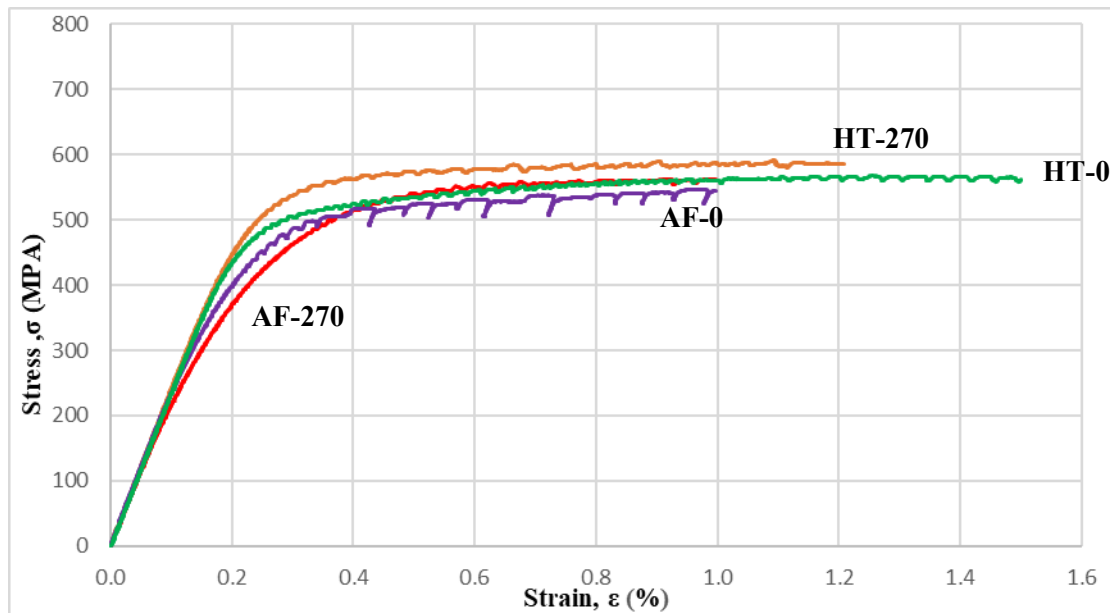


Fig 5.4 Stress-strain compression curves for a single specimen from each extraction point (90/180/270) and with or without thermal process for X65_16in.

Table 5.4 Summary of database compression tests with measured yield strength at 0.2% offset ($\sigma_{y0.2\%}$) and at 0.5% total plastic strain ($R_{t0.5\%}$) and Elastic modulus (E).

X65_16in	$\sigma_{y0.2\%}$ (MPa)	div- $\sigma_{y0.2\%}$	$R_{t0.5\%}$ (MPa)	div- $R_{t0.5\%}$	E (MPa)	div-E
AF	553.57	17.78%	560.24	15.57%	208471	11.78%
HT	606	13.03%	607.74	11.95%	230250	2.64%

Table 5.5 below presents the mean coupon values based on the angle and the inner or outer position. Specimens from the outer surface exhibit higher elastic modulus values, while those from the inner surface generally show greater yield limits, except for IN-180, which is only slightly lower than OUT-180. In **Fig 5.5** are illustrated some specimens for each occasion.

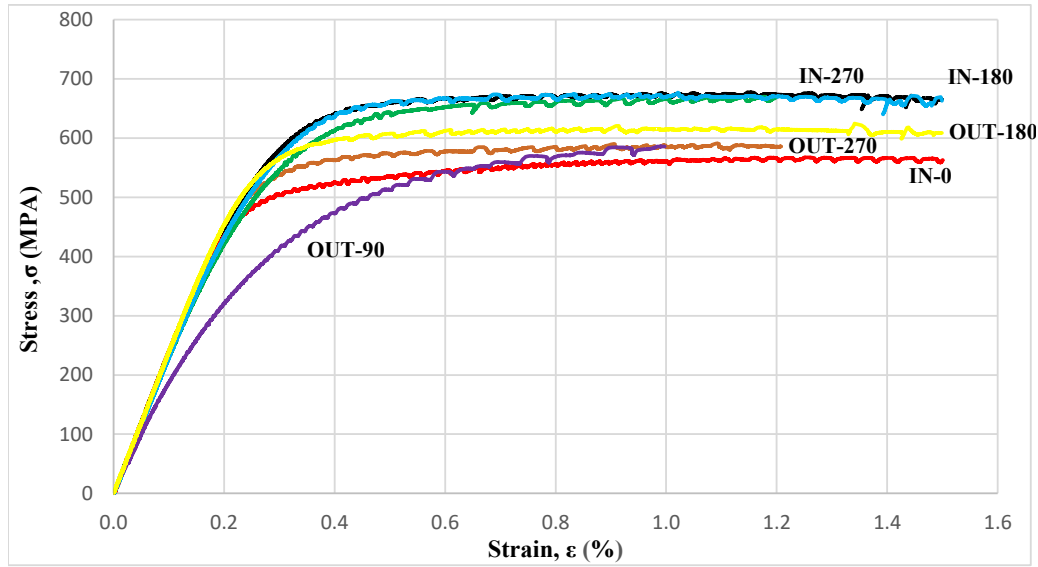


Fig 5.5 Stress-strain compression curves for a single specimen from each extraction point (90/180/270- INNER/OUTER) for X65_16in

Table 5.5 Summary of database compression tests with measured yield strength at 0.2% offset ($\sigma_{y0.2\%}$) and at 0.5% total plastic strain ($R_{t0.5\%}$) and Elastic modulus (E).

X65_16in	$\sigma_{y0.2\%}$ (MPa)	div- $\sigma_{y0.2\%}$	$R_{t0.5\%}$ (MPa)	div- $R_{t0.5\%}$	E (MPa)	div-E
IN-0	591.7	12.60%	596.7	12.21%	218999	11.40%
IN-90	602.5	5.39%	608	5.71%	210905	6.58%
IN-180	588.5	11.30%	596	10.95%	211135	8.10%
IN-270	654	0.30%	653.5	0.91%	221190	5.26%
OUT-90	536	7.28%	543.6	5.71%	212900	5.29%
OUT-180	598	1.00%	600.4	1.17%	218450	7.75%
OUT-270	557.5	5.83%	556.8	2.90%	228180	2.47%

- **X60_30in**

Table 5.6 presents the mean property values of the specimens, categorized based on whether the thermal process was applied and the angle position, while in **Fig 5.6** are demonstrated some stress-strain curves of these compression tests. In all cases, the elastic modulus exhibits a notably high magnitude, reaching approximately 230000 MPa, with the A-90 specimens exceeding this value ($E = 245290$ MPa). The yield strength is higher in the samples that underwent the thermal process, while the angle position appears to have minimal influence on the values, as they remain similar. The exception is at the 180° position, where a lower yield strength is observed, particularly in the A-180 specimen ($\sigma_{y0.2\%} = 454.5$ MPa), with the B-180 to have higher magnitude that time, ($\sigma_{y0.2\%} = 494$ MPa).

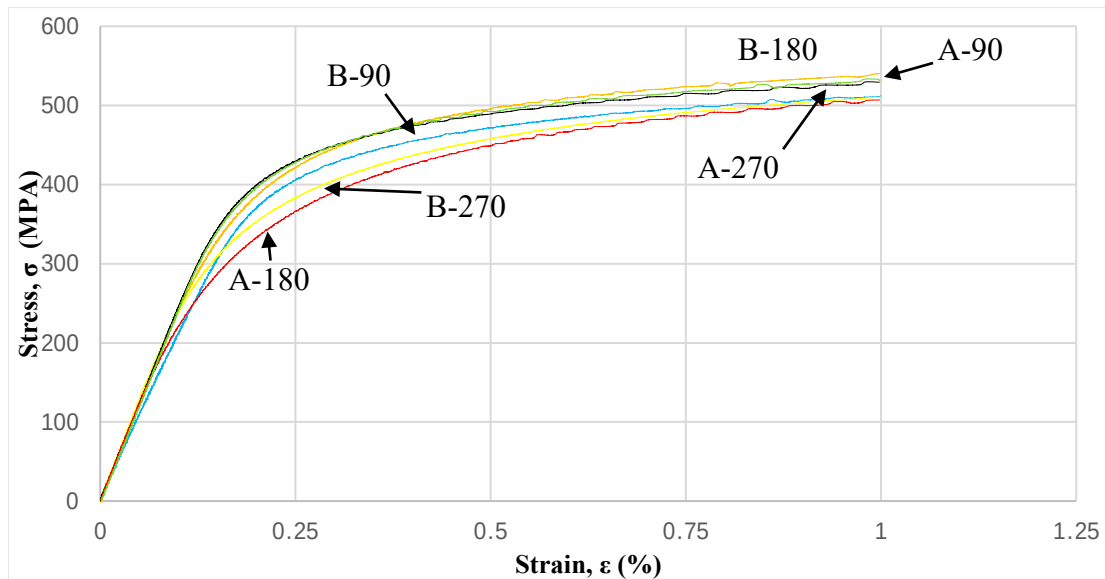


Fig 5.6 Stress-strain compression curves for a single specimen from each extraction point (90/180/270) and after/before thermal process for X60_30in.

Table 5.6 Summary of database compression tests with measured yield strength at 0.2% offset ($\sigma_{y0.2\%}$) and at 0.5% total plastic strain ($R_{t0.5\%}$) and Elastic modulus (E).

X60_30in	$\sigma_{y0.2\%}$ (MPa)	div- $\sigma_{y0.2\%}$	$R_{t0.5\%}$ (MPa)	div- $R_{t0.5\%}$	E (MPa)	div-E
B-90	487.6	5.87%	503	6.16%	228976	9.95%
B-180	494	2.83%	510	2.74%	230485	3.36%
B-270	482.5	10.88%	500.5	8.49%	221320	9.63%
A-90	516.5	8.61	529	6.99%	245290	1.90%
A-180	454.5	8.03%	486	7.40%	227660	9.97%
A-270	516.5	8.42%	527.5	7.10%	230260	4.27%

In **Table 5.7**, the mean values of $\sigma_{y0.2\%}$, $R_{y0.5\%}$, and E for the 30in pipe are presented, categorized by T-B (Transverse direction - Before thermal process), L-B (Longitudinal direction - Before thermal process), T-A (Transverse direction - After thermal process), and L-A (Longitudinal direction - After thermal process). For L-B and L-A, data is available for only one specimen, which accounts for the 0% deviation. The yield strength is generally higher in the longitudinal direction and in specimens that have undergone thermal processing. The T-A group follows, with slightly lower values than T-B. Thus, the primary criteria for ordering the experiments in descending order are the direction and thermal process. The elastic modulus of L-B specimens is significantly lower than the other specimens, as it seems also from **Fig 5.7**.

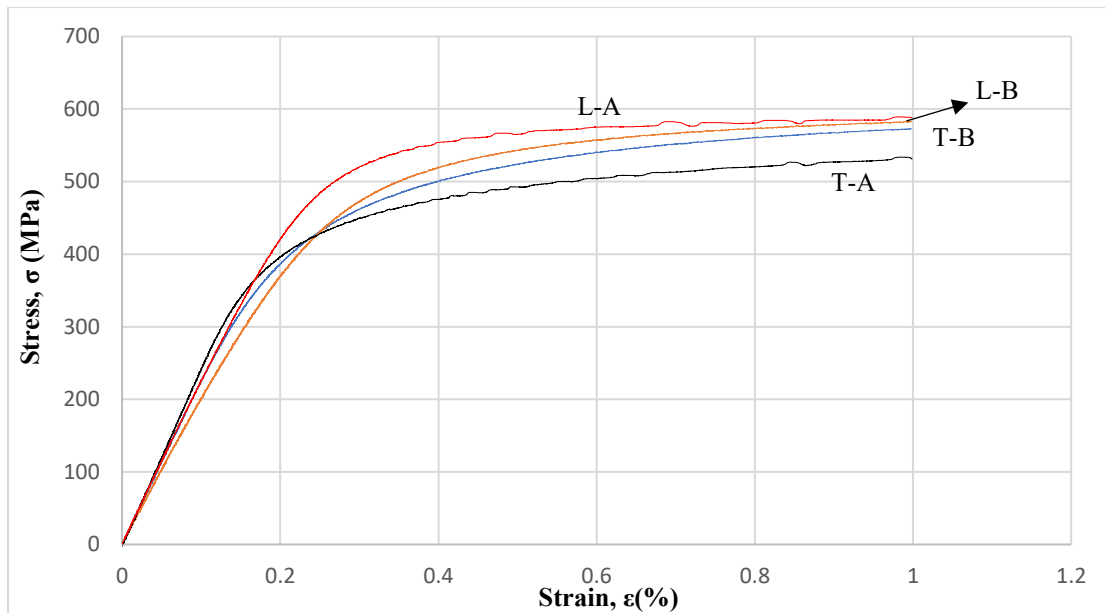


Fig 5.7 Stress-strain compression curves for a single specimen from each extraction point (Longitudinal/Transverse) and after/before thermal process for X60_30in.

Table 5.7 Summary of database compression tests with measured yield strength at 0.2% offset ($\sigma_{y0.2\%}$) and at 0.5% total plastic strain ($R_{t0.5\%}$) and Elastic modulus (E).

X60_30in	$\sigma_{y0.2\%}$ (MPa)	div- $\sigma_{y0.2\%}$	$R_{t0.5\%}$ (MPa)	div- $R_{t0.5\%}$	E (MPa)	div-E
T-B	480.16	10.44%	497.83	8.00%	231756	11.03%
L-B	535	0.00%	543	0.00%	200000	0.00%
T-A	483	16.14%	504	12.30%	237202	7.07%
L-A	560	0%	565	0%	220410	0%

6. CHAPTER – CONCLUSIONS

The objective of this thesis was to develop a comprehensive database of small-scale uniaxial material experiments, primarily conducted at UTH, aimed at estimating the mechanical behavior of steels under both monotonic and cyclic loading conditions highlighting specific mechanical properties. The database includes 425 uniaxial tests on structural steels: 109 tensile tests, 210 strain-controlled tests, 29 stress-controlled tests, and 39 compression tests. This effort represents an initial attempt at systematically documenting material data, with the database expected to expand as further experiments are conducted. The stress-strain data from each experimental procedure have been analyzed to categorize the tests and extract valuable insights into the cyclic and monotonic behavior of the materials. The key findings from the experimental study are summarized below:

- In all type of experiments, are prove that the materials' classification according to the yield limit are the same either it is based on $\sigma_{y0.2\%}$ or the $R_{t0.5\%}$.
- According to tensile tests, the materials, that submitted under prestrain process and as higher it become, indicate lower maximum elongation (until fracture), and also higher maximum strength which appears at lower strain value, so the material be less ductile.
- It was noted that materials with a lower yield point exhibit a greater increase in ultimate strength.
- It is observed that specimens taken from pipes typically do not display a plastic plateau, only those extracted longitudinally from the pipe show this behavior, while specimens from the hoop direction do not. Coupons with notches also lack a plastic plateau. Specimens made from plates and rectangular hollow sections exhibit a more pronounced plastic plateau. Additionally, it is evident that no plateau is present in specimens taken from plates subjected to pre-strain processing.
- In strain-controlled test, as the percentage of applied $\Delta\varepsilon$ (%) increases, so the number of cycles for fatigue decreases
- Variations in the applied strain amplitude can result in either an increase or decrease in the rate of cyclic hardening or softening. It can also cause a transition from hardening to softening behavior or create an intermediate phase of hardening in a full softening behavior, for example.
- The Bauschinger effect becomes much more pronounced at higher strain amplitudes.
- As the prestrain increase in S355MC the specimens start to present an increasing hardening interval in the full softening curve of un-strained coupons, which is not observed at 460MC. Furthermore, it is observed that for all applied strain ranges, the amplitude stress become higher as the prestrain level decrease.
- The S355MC and S460MC steels show an increasing reduction in yield limit according to the number of cycles, as the prestrain level rises.

- For X52-steel, it has been observed that the Bauschinger effect remains unaffected by variations in strain ratio values.
- The 43A-steel specimens that underwent a prestrain process show lower elastic modulus and yield strength ($\sigma_{y0.2\%}$) values and exhibit less variation in these properties over multiple cycles compared to the unstrained specimens.
- In stress- controlled tests, as the applied stress range and stress ratio increases, the number of cycles until failure reduces.
- In all types of experiments, the location or direction from which the specimens are extracted, as well as any manufacturing processes they have undergone, significantly influence the variations in the calculated mechanical properties.

The comprehensive analysis of both strain-controlled and stress-controlled experiments provides valuable insights into the mechanical behavior of the tested materials. The cyclic performance, including hardening and softening trends, was thoroughly assessed in strain-controlled tests, while the ratcheting behavior was characterized in stress-controlled tests. Also, the materials were classified based on maximum elongation until fracture, as determined from tensile tests. So, a more detailed understanding of their performance under different loading conditions was achieved. This classification enhances the ability to predict material behavior in various applications, contributing to the development of more reliable and robust structural designs.

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