

Automated Method for Pre-Straining of Steels for Bake Hardenability Testing

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ABSTRACT

The bake hardening effect in steel, characterized by a boost in yield strength resulting from initial deformation and subsequent heat treatment, holds significant promise for the automotive sector. Bake hardening is characterized by the Bake Hardening Index (BHI), as outlined in the test standards EN 10325:2006 and JIS G 3135:2018. The suggested test procedure involves pre-straining the dogbone samples and subjecting them to thermal cycling. However, the current standards lack specificity regarding the pre-straining procedure and the estimation of elastic recovery in metals, leading to inconsistencies in results across different materials and laboratories. This study addresses this gap by proposing a standardized and fully automated method utilizing in-situ strain measurements to precisely pre-strain uniaxial tension samples to any desired level of plastic strain. This method offers precise control over strains and accurate estimation of strain overcompensation, which accounts for elastic recovery during unloading. In this paper, the proposed method is validated using optical strains using digital image correlation, however the proposed method is independent of the choice of strain measurement method and works with clip-on extensometers, optical extensometers and even the crosshead transducers in the load frame. The foundation and effectiveness of the proposed method are demonstrated through statistical data obtained from testing 11 different steel grades, including bake hardenable steels and Advanced High Strength Steels commonly used in the automotive industry. The proposed method is independent of the choice of steel grade and consistently delivers satisfactory results for all tested steel grades, producing test samples with plastic strains that adhere to the specifications of the testing standards.

KEYWORDS

Bake Hardening, Real-time Strain, Digital Image Correlation, Advanced High Strength Steels, Material Testing

1. Introduction

The bake hardening effect is a phenomenon of increase in the yield strength of steel after pre-straining and subsequent baking. This effect is attractive to the automotive industry where the steel sheets are stamped at room temperature and then exposed to a temperature cycle in the paint curing/baking oven. This results in a bi-fold advantage to the stamped parts: (i) improved dent resistance, which is an important characteristic for outer body panels, and (ii) substantial weight reduction through the possibility of down-gauging while keeping the same dent resistance. The term 'Bake hardenable steels' is conventionally used for the ferrite-based High Strength Steel grades, but this effect is also seen and has been extensively studied in Advanced High Strength Steels (AHSS) [1]–[3] used in structural components where an improved yield strength implies better crash performance. According to the concept of static strain aging, the heat treatment acts as an artificial aging process that boosts the interstitial atoms to diffuse and gather around the dislocations as Cottrell atmospheres due to energy equilibrium [4]. The material needs higher external stress for the dislocations to break through the atmospheres resulting in increased yield strength and thus the BH effect.

The degree of bake hardening exhibited by a material is characterized in terms of the Bake Hardening Index (BHI), as standardized by the popular test standards EN 10325:2006 and JIS G 3135:2018 standard [5], [6]. These standards specify the test conditions and procedures for determining the BHI, which involves pre-straining a uniaxial tension dogbone sample to a 2% plastic strain followed by a thermal cycle simulating paint baking (170 °C for 20 minutes) and pulling it in tension. Bake Hardening Index or BH2 is the difference between the yield strength of the pre-strained and baked sample and the stress corresponding to the 2% plastic pre-strain in the test sample. Figure 1 shows the loading of the test sample to certain strain Point A, elastic recovery upon unloading at which point the sample is baked (Point B), and reloading the sample to fracture for the determination of new yield strength and hence BHI (Point C).

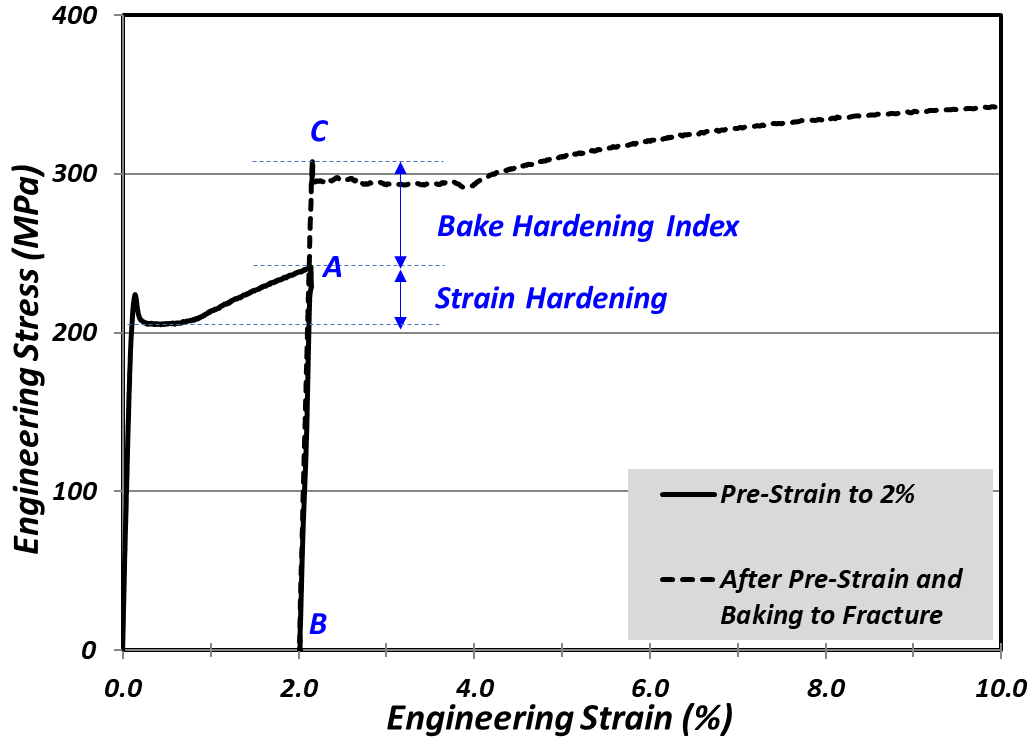


Figure 1. Engineering Stress-Strain curve for a BH steel showing strain hardening and bake hardening index, recreated from the test standard EN 10325:2006 [5]

The test standards mandate tight tolerances on pre-straining the test sample to 2 ± 0.05 % plastic strain (EN 10325:2006) and 2 ± 0.2 % plastic strain (JIS G 3135: 2018) or 5% and 10% strains preferred by some automotive manufacturers. This is because the BHI is sensitive to the plastic strain induced in the test sample, as shown in previous studies [3], [4]. However, the global test standards do not provide any specific instructions on the pre-straining procedure or the estimation of elastic recovery/springback in the sample. The degree of elastic springback is not constant and is proportional to the material strength i.e., significantly higher levels of strain recovery are seen in AHSS compared to conventional steels. The looseness in the test standards regarding pre-straining results in inconsistencies from lab to lab and from material to material. Therefore, there is a need to standardize the pre-straining procedure while accounting for the varying levels of elastic springback in different steel grades.

This work addresses that gap in the test standards and proposes a simple and fully automated method of pre-straining uniaxial tension samples using real-time strain measurements and automatic in-situ calculation of strain limits to achieve an intended level of plastic strain while overcompensating for the elastic strain recovery.

The method proposed in this paper is based on real-time strain measurements which is not dependent on a particular strain measurement method. This method and the script can be implemented using an old-fashioned clip-on extensometer, a laser extensometer, video extensometer, a digital image correlation (DIC) system and even machine crosshead displacement data. In this paper, we chose a DIC to demonstrate the method.

The work covers different grades of automotive steels including mild steel and BH steel, two cold rolled HSLA steels, a hot rolled HSLA steel, a hot rolled complex phase (CP) steel, three dual-phase (DP) steels, TRIP steel, and a martensitic steel. The results presented in the work have been validated on different grades of steel to show that the proposed method is independent of the choice of the grade of steel.

Section 2 presents the materials and methods used in the study, followed by Section 3 on the statistical study of the elastic drop modulus for the different steel grades and the conclusions leading to the proposed method and its implementation. Section 4 provides a verification of the method and a generalization of the test method for other pre-strain levels.

2. Materials and Method

The test setup used for the study consisted of a commercial universal testing machine (UTM) with a 50kN load cell and hydraulic grips. The UTM had a modern test controller capable of receiving strains from external devices (as analog voltage signals). The strain measurements were done optically using a commercial 2 Megapixel stereo digital image correlation (DIC) system capable of real-time strain measurements with low latency. The spatial resolution of the DIC was 50 microns per pixel, and a subset size of 31 pixels was used for creating the end points of a virtual extensometer drawn in the middle of the test sample. The test samples were pulled under displacement control at a constant crosshead speed of 0.04 mm/sec, and the DIC strain measurements were performed in real time at a fixed frequency of 20Hz. The sample geometry was based on the ISO6892-1:2019 Type-1 sample with 12.5mm gauge width and 70mm parallel length. The strain was calculated using a two-point virtual extensometer of gauge length 50mm.

The first set of tests was performed with the test end criteria of 2% total strain i.e., the crosshead stopped on receiving a 2% strain signal from the DIC system and unloaded the specimen at a rate of 300 N/sec. Measuring the strains directly on the surface of the sample using DIC ensured accurate strain measurements while removing the compliance in the test setup, and also enabled precise control over the strain limit.

The tests were conducted for 11 types of automotive grade steels covering all the major steel grades relevant to the automotive industry. The materials chosen for the study are:

- *Mild steel and Bake-Hardenable steel:* 0.7mm CR5 and 0.6mm BH240
- *Cold Rolled High-Strength Low Alloy (HSLA) steel:* 1.5mm CR340LA, 1.0mm CR420LA,
- *Hot Rolled High-Strength Low Alloy (HSLA) and complex phase steel:* 2.4mm HR-CP760, 1.8mm HR500LA
- *Dual-phase (DP) steel:* 1.6mm DP590, 1.6mm DP780, 1.2mm DP980
- *Transformation Induced Plasticity steel and Martensitic steel:* 1.4mm TRIP690 and 2.0mm MS1500 steel.

3. Data Analysis

3.1. Test Results and Statistical Analysis: The engineering stress-strain curves plotted in Figure 2 were obtained from the tension tests stopped exactly at 2% strain and show different magnitudes of plastic strain for each material based on their different elastic strain recovery behaviors and strength levels. To put it into perspective, even after stretching to a 2% strain, the CR5 sample accumulated a plastic strain of 1.89% while the MS1500 sample only accumulated 1.17% plastic strain upon unloading. The trend shows that the magnitude of elastic recovery is dependent on the strength level of the material. The results emphasize the need for strain overcompensation in the test sample in order to achieve a 2% plastic strain after elastic recovery.

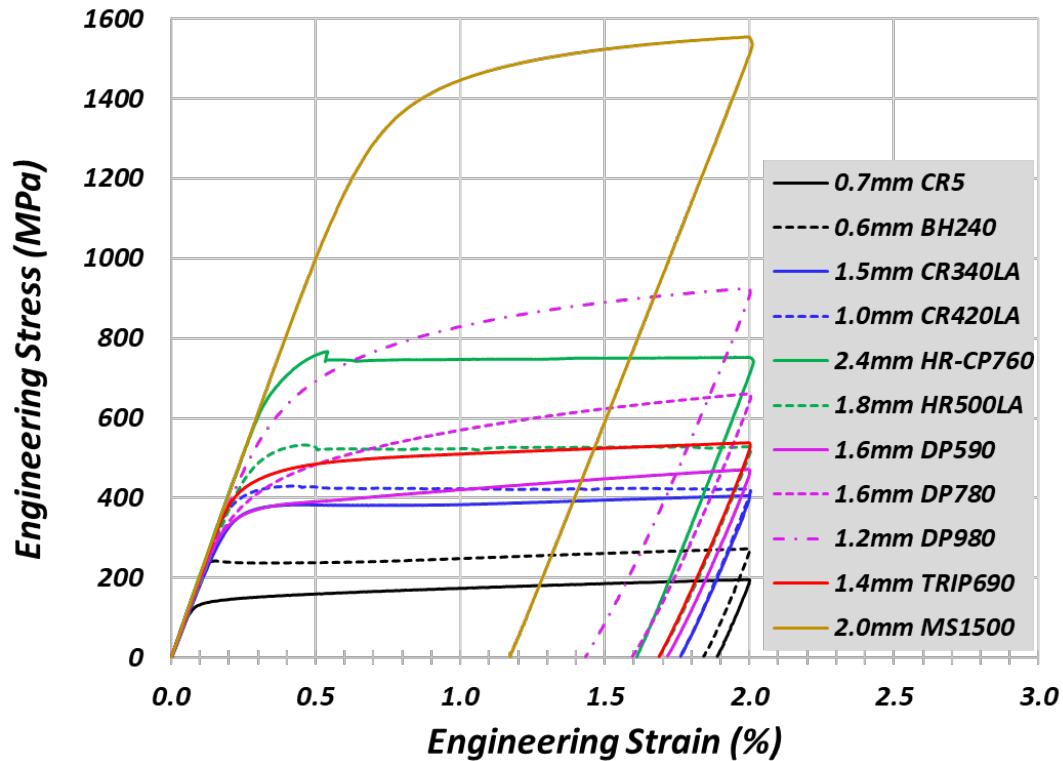


Figure 2. Engineering Stress-Strain Curves for the selected steel grades where the test stops at 2% total strain leading different material specimens to spring back to different values of plastic strain.

Drop Modulus: On further investigation, it was seen that during the unloading phase, the stress followed an almost linear path, with minor non-linearity towards the end. The slope of elastic unloading (slope of the engineering stress-strain curve during the unloading of the test specimen) termed in this paper as ‘drop modulus’ or ‘D’ was calculated using a linear fit of the data points in the unloading phase, and it is different for each grade of steel. The values of drop modulus and Young’s modulus for all 11 materials are summarized in Table A1 in the appendix section. According to the results, Young’s modulus of the 11 steel grades ranges from 185 GPa to 206 GPa, while the drop moduli lie between 159 GPa and 182 GPa with an average modulus of 168 GPa. In other words, a modulus decay of 85% is seen at a pre-strain of 2%.

3.2. Theory behind elastic recovery estimation and its implementation: Based on the trend observed in drop modulus, if the material is strained to a stress level equivalent to the stress of a virtual line of slope ~ 168 GPa passing through 2% on the strain axis, the material should spring back to a plastic strain of 2%. The test must stop as soon as the engineering stress reaches a value given by the straight line at a slope of drop modulus with an intercept of the intended level of plastic strain. In mathematical terms, the crosshead should stop at the test end criteria explained by the inequality given below. The test should stop as soon as the inequality becomes true.

$$\text{Engineering_Stress}(t) \leq (\text{Real_Time_Strain\%}(t) - \epsilon_{PS}) / 100 * D \quad (1)$$

, where ϵ_{PS} is the intended level of plastic strain in the test sample i.e., 2% in this case, and D is the drop modulus in equivalent units. Engineering_Stress(t) is the force at time t divided by the initial area of cross-section, Real_Time_Strain%(t) is the real-time engineering strain (%) at time t measured in this work by the DIC system and sent to the load frame as an analog voltage signal.

The above equation was implemented as a custom end test script in the load frame software. The script makes sure that the test stops as soon as the relationship given in equation (1) becomes true.

Although the DIC system was capable of going at a higher rate, the measurements were performed at a fixed frequency of 20Hz, which was an intentionally induced limiting factor. This was purposely done to showcase the efficacy of the method even with limited hardware capabilities. The test samples were pulled using the strain rate control method at a constant rate of 0.0005 1/sec, followed by unloading at 300 N/sec.

4. Results and Discussion

The proposed script was implemented in the load frame using a custom end test criteria in the universal testing machine/load frame software and a new set of tests was conducted for fresh samples of the same materials. With the new end of test criteria, the tests were automatically stopped when the real-time strain reached a strain level determined by the script running in the background such that the test specimen springs back to 2% plastic strain after undergoing elastic recovery. In this section, the stress strain curves obtained from the new set of tests are presented.

4.1. Verification of the Script: The above script was verified for all the selected steel grades and the stress-strain curves from a new set of tests performing using the proposed script are shown in Figure 3 and tabulated in Table A2 in the appendix section. The curves show that the plastic strain in the test samples after the elastic-recovery is within 2 ± 0.05 % which is well within the requirements of the test standards. The tests were automatically stopped by the end of test script running in the load frame. To enable precise plastic strain points, the script stopped the test for the CR5 sample at 2.1% strain, while the test for the MS1500 sample was stopped at 2.9% strain.

And these stop points were automatically calculated by the script based on the proposed method.

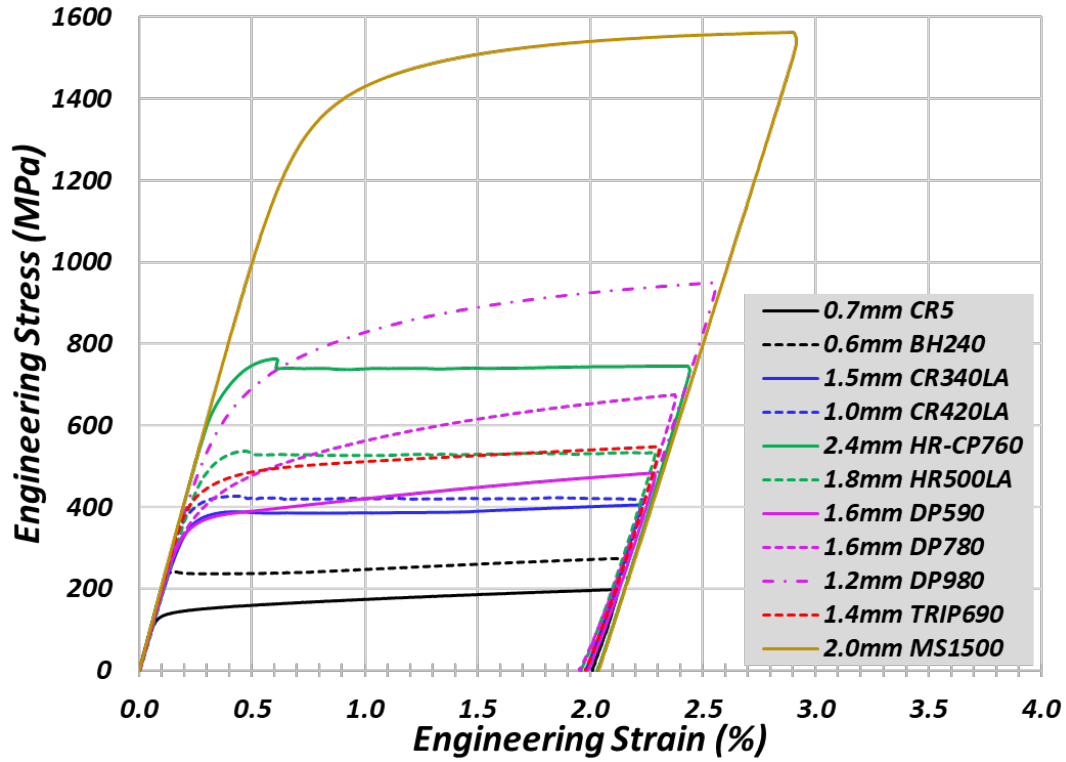


Figure 3. Engineering Stress-Strain Curves obtained from a new set of tests performed using the proposed script, where the tests are automatically stopped by the script at the calculated strain levels to obtain a near 2% accumulated plastic strain after the elastic-recovery.

4.2. Extension of the work to other pre-strain levels: To generalize the method and extend it to other pre-strain levels, the interrupted uniaxial tension tests (similar to Section 3.1) were performed at pre-strain levels of 5% and 10%. The drop modulus for the materials was extracted from the engineering stress-strain curves and the results are presented in Table A1 and Figure 4 in the form of a boxplot. The results show that the drop modulus decays with an increased level of strain in the material. The trend in the drop modulus is in agreement with the drop modulus studies performed in the past [7]–[9].

For implementation of the script at user-defined strain level ϵ_{ps} the average value of drop modulus 'D' may be picked from table A1 and implemented in equation (1) defined in Section 3.2.

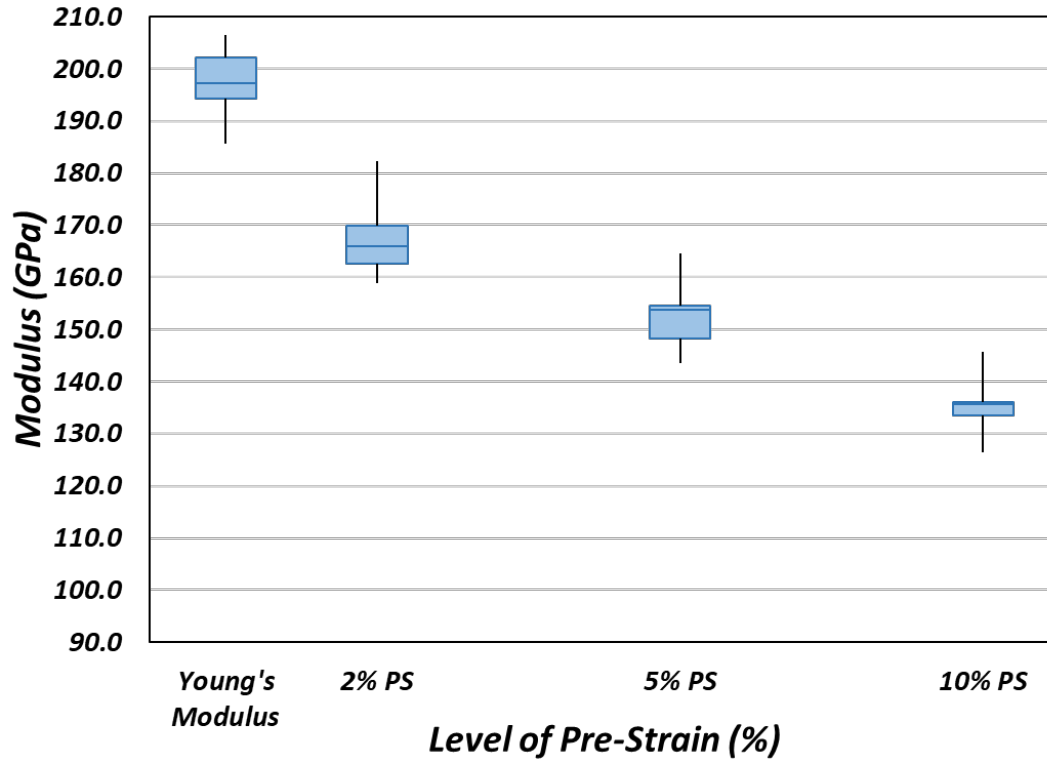


Figure 4. Decay in drop modulus 'D' at varying levels of pre-strain for the selected steel grades for inserting in equation (1).

5. Conclusion

The test standards EN10325:2006 and JIS G 3135 are commonly used for quantifying Bake Hardening in steels. However, these standards provide limited guidance on pre-straining procedures or compensating for elastic recovery. In this study, we propose a simple and fully automated method that utilizes in-situ optical strain measurements to accurately pre-strain uniaxial tension samples to any desired level of plastic strain. This method allows for precise control of strains and accurate estimation of strain overcompensation to account for elastic recovery during unloading. The effectiveness of the proposed method is demonstrated through statistical data obtained from testing various grades of steels, including bake hardenable steels and Advanced High Strength Steels commonly used in the automotive industry. To verify the accuracy and reliability of our approach, we implemented it on a universal testing load frame coupled with real-time DIC analysis. The method demonstrates its effectiveness and yields satisfactory results for all the tested steel grades, generating test samples with plastic strains that align with the specifications of the test standard. Additionally, a generalization of this method is proposed to enable testing at any desired level of plastic strain, together with recommendations for its practical application. The method works independently of the strain measurement technique. However, the strains measured directly on the sample (using a clip-on extensometer, or an optical extensometer) are free from the compliance in the test grips and the machine. The strains measured by the crosshead data in the load frame are subjected to errors arising from the compliance effects in the grips and the test machine. Therefore, the accuracy of the method

will drop as the accuracy of the strain measurement drops. Since the bake hardenability tests (as per the EN 10325 and JIS G 3135) are conducted at the room temperature, the drop modulus decay results presented here (Figure 4) are also measured at room temperature, and they would change at high/low temperatures.

Conflict of Interest

The authors certify that they have NO affiliations with or involvement in any organization or entity with any financial interest, or non-financial interest in the subject matter or materials discussed in this manuscript.

Appendix

Table A1. Young's modulus and drop modulus at 2%, 5% and 10% strain for the selected steel grades

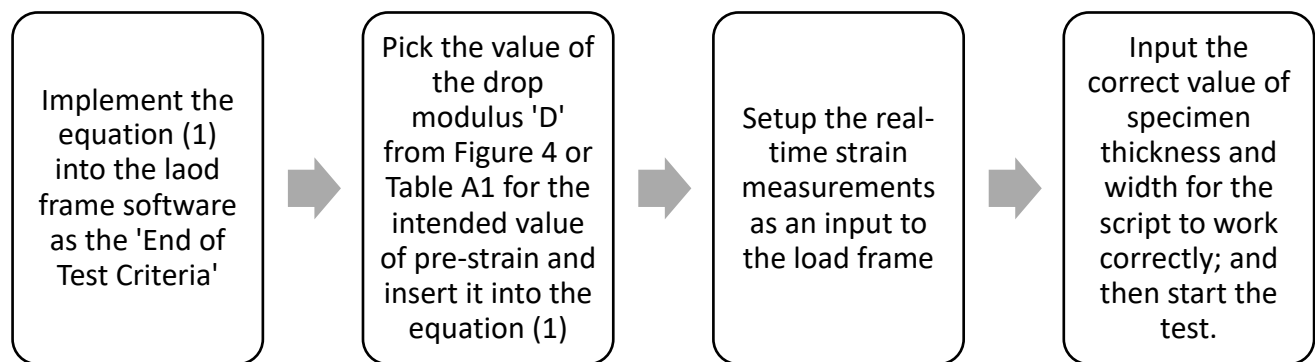
<i>Material Grade</i>	<i>Young's modulus (GPa)</i>	<i>Drop Modulus (GPa)</i>		
		<i>At 2% strain</i>	<i>At 5% strain</i>	<i>At 10% strain</i>
0.7mm CR5	197.3	169.0	148.3	135.5
0.6mm BH240	202.3	168.3	154.2	134.9
1.5mm CR340LA	185.7	166.0	153.7	135.7
1.0mm CR420LA	198.4	170.7	154.7	136.8
2.4mm HRCP760	206.5	182.4	164.5	145.7
1.8mm HR500LA	187.3	164.5	154.5	-
1.6mm DP590	195.9	160.8	-	129.6
1.6mm DP780	193.0	159.0	143.5	126.5
1.2mm DP980	195.4	160.7	145.7	-
1.4mm TRIP690	202.2	165.2	152.5	135.9
2.0mm MS1500	203.8	182.4	-	-
Average	197.1	168.1	152.4	135.1
Std Dev	6.6	8.0	6.1	5.6

Table A2. Verification of the script showing the accumulated plastic strain after elastic recovery for the selected steel grades

<i>Material Grade</i>	<i>Plastic Strain after elastic recovery (%)</i>
0.7mm CR5	2.01
0.6mm BH240	1.99
1.5mm CR340LA	1.98
1.0mm CR420LA	1.99
2.4mm HRCP760	2.03

1.8mm HR500LA	1.96
1.6mm DP590	1.99
1.6mm DP780	1.95
1.2mm DP980	1.96
1.4mm TRIP690	1.98
2.0mm MS1500	2.04
Minimum	1.95
Maximum	2.04

Flowchart A3. Steps to implement the procedure:



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