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Effect of Continuous Bending under Tension on Dual-Phase Steels

Gabriela Vincze[1,2,a*], Ricardo C. Alves[1,b], Rafael O. Santos[3,c]
and Marilena C. Vincze[1,2,d]

[1]Centre of Mechanical Technology and Automation (TEMA), Department of Mechanical Engineering, University of Aveiro, 3810-193 Aveiro, Portugal

[2]LASI - Intelligent Systems Associate Laboratory, 4800-058 Guimarães, Portugal

[3]Graduate Program in Metallurgical Engineering, Universidade Federal Fluminense - UFF, Volta Redonda, Rio de Janeiro, Brazil

[a*]gvincze@ua.pt, [b]ricardo.camilo@ua.pt, [c]rafaeloliveirasantos@id.uff.br, [d]cbutuc@ua.pt

*Corresponding author

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Abstract. Lightweighting plays a critical role in reducing vehicle emissions, a major source of air pollution in the European Union. While weight reduction during the use phase is important, environmental impacts across production and end-of-life stages must also be considered. Advanced forming technologies enable the use of high-strength materials while maintaining formability and energy efficiency. Continuous-bending-under-tension (CBT) is a promising forming technique capable of inducing higher plastic deformation than conventional processes. In this study, CBT experiments were conducted on dual-phase 1000 low-yield (DP1000-LY) steel. The material was subjected to uniaxial tensile loading combined with cyclic bending through a moving three-roll system. The effects of key process parameters, bending depth and speed ratio between the bending assembly and tensile loading, were systematically investigated. The results show that lower bending depths allow greater total deformation before fracture and result in higher tensile forces. Higher speed ratios lead to earlier failure both during and after CBT processing. Hardness measurements indicate comparable surface hardness on both sides of the specimens, regardless of single or double roll contact. These findings contribute to a better understanding of CBT process parameters and support its potential application in lightweight automotive component manufacturing.

Introduction

Reducing vehicle weight during use is important, but Sato and Nakata [1] highlight that environmental impacts across production and end-of-life stages must also be considered. Achieving lighter and safer components requires a strategic combination of materials such as steel, aluminum, and composites. To meet increasing demands for better formability and energy efficiency, advanced metal forming methods are gaining attention. Among these, continuous-bending-under-tension (CBT) has emerged as a promising technique, allowing greater plastic deformation than conventional processes [2,3].

The idea of enhancing elongation-to-fracture by superimposing bending on tension was first noted by Swift in 1948 [4]. However, the first experimental application of CBT for improving elongation in both ferrous and non-ferrous metals was carried out by Benedyk et al. in 1971 [5]. Using three moving rollers to bend and unbend metal sheets, they observed multiple cracks at large deformations. This was attributed to a reduction of the net axial force due to the added bending.

CBT was revisited in 2009 by Emmens and van den Boogaard [6], who developed a device to study incremental metal forming, as CBT reproduces similar deformation conditions. Their parametric studies on aluminum and mild steel identified the bending radius as the most influential factor. Later work extended to stainless steel, brass, and titanium [7,8], and included a simple mechanical model showing that many CBT behaviors are governed by loading conditions rather than material properties.

At the University of New Hampshire, a novel CBT machine was developed [9], featuring stationary rollers while the specimen and its axial loading system reciprocate. This setup was used to study AA6022 and various dual-phase (DP) steels. Notably, DP1180 exhibited over five times higher elongation under CBT compared to standard uniaxial tension. Lower DP grades showed moderate improvements, while increased sheet thickness reduced elongation gains. Furthermore, the strength increase with repeated CBT cycles was more pronounced in sheets with lower martensite content.

This work focuses on the effect of CBT parameters on the mechanical behavior of DP1000-LY. The article is structured in three main parts: material characterization, description of the CBT apparatus, and presentation and discussion of results, concluding with a summary of the findings.

Material and Experimental Details

Material

The study material is 1.5 mm thick dual-phase 1000 low-yield (DP1000-LY) steel. Tensile tests were conducted using a Shimadzu Autograph Machine (Shimadzu, Japan) with a 100 kN load cell, and strain was measured via Digital Image Correlation (DIC) using the GOM system and ARAMIS 5M software (GOM, Germany). The resulting engineering and true stress–strain curves are shown in Fig. 1, and the mechanical properties are summarized in Table 1.

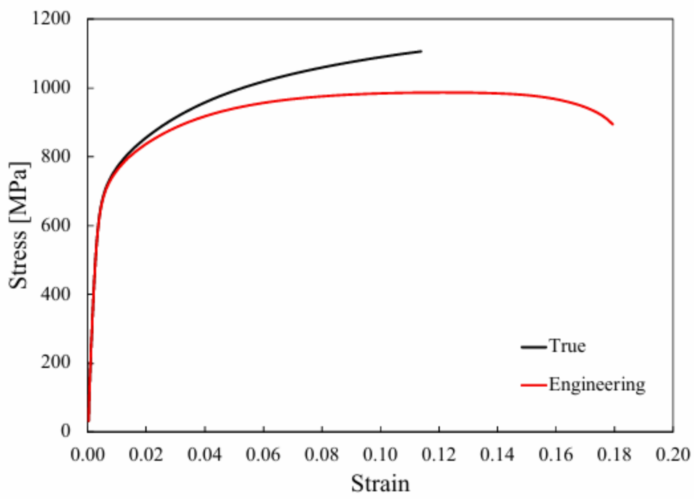

Fig. 1. Mechanical behavior of DP1000-LY tested in rolling direction.

Table 1. Mechanical properties of of DP1000-LY tested in rolling direction.

E [GPa]	σ_y [MPa]	σ_{UTS} [MPa]	ε_u [%]	ε_t [%]	r	n
205 ± 11	657 ± 30	990 ± 3	11.8 ± 0.8	17.8 ± 4	0.790± 0.005	0.150 ± 0.002

Continuous-Bending-under-Tension (CBT) Equipment

Figure 2 shows the CBT equipment developed at the University of Aveiro, along with a schematic representation of the process highlighting the main parameters: roll diameter D, roll distance L, center roll depth setting P, tensile velocity v_t and bending assembly velocity v_b. Recent numerical investigations of the CBT process by Perreira et al. [11] indicate that roll diameter has little influence on the results. In this study, the focus is on the center roll depth P and the velocity ratio v_t/v_b. Specifically, three values of P were investigated, 2, 3, and 4 mm and two velocity ratios were considered 0.0088 and 0.0118. The CBT equipment is mounted in the Shimadzu Autograph Machine (Shimadzu, Japan) with a 100 kN load cell used previously for material chracaterization. The sample geometry is represented in Fig. 2c.

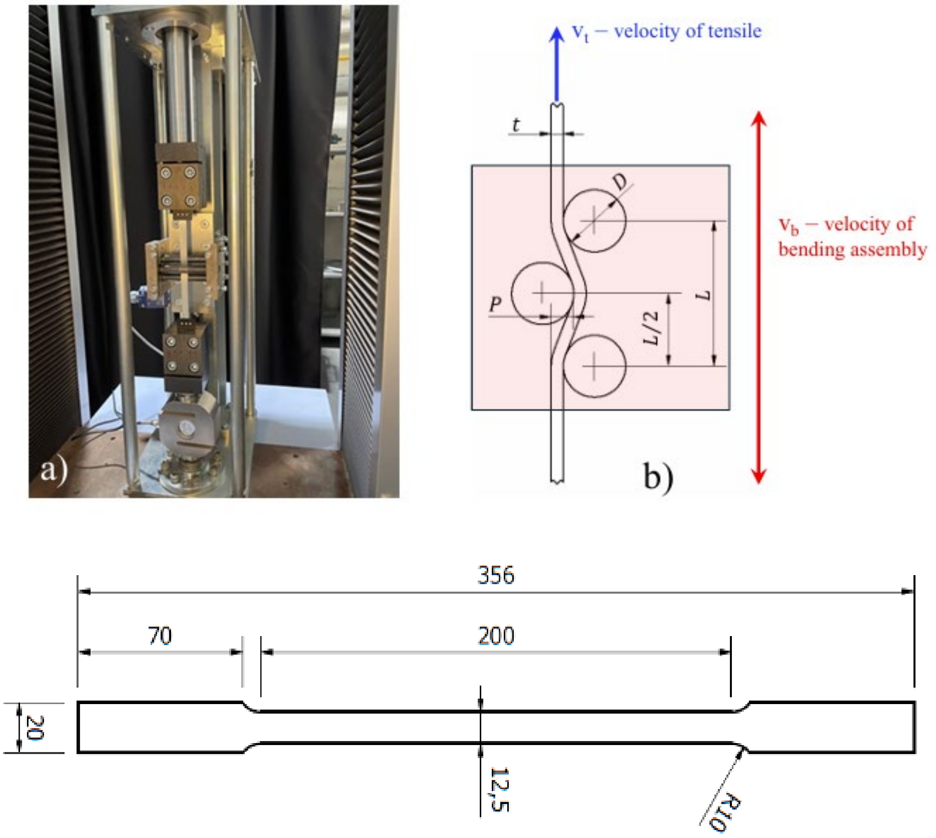

Fig. 2. Continuous-bending-under-tension (CBT) equipment (a), a schematic view (b) and sample geometry (c).

After CBT, sub-size specimens were extracted from the utilized zone of the CBT sample for subsequent tensile and Vickers microhardness testing, as shown in Fig. 3. Microhardness measurements were performed using a Falcon 600G2 (Netherlands) with a load of 0.3 kgf applied for 10 seconds.

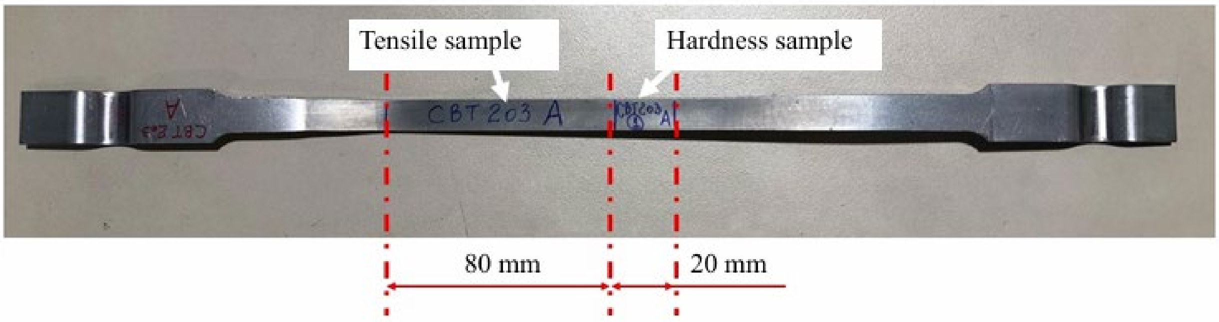

Fig. 3. Location of sub-size specimens for tensile and microhardness testing on the CBT sample.

Results and Discussion

The first set of samples was tested until fracture. The conditions of these tests are summarized in Table 2. The results, shown in Fig. 3, indicate that global deformation was higher under all CBT conditions compared to standard tensile tests. It appears that higher speed ratios led to greater displacement, while increasing bending depth reduced displacement at the same speed ratio. These findings are consistent with previous literature.

Based on these results, the evaluation of CBT-processed material was performed using tensile tests. For this purpose, a new set of samples was processed by CBT without reaching fracture, stopping the tests at 75% of the maximum number of cycles recorded previously. The conditions of these tests are summarized in Table 3. The results, presented in Fig. 4, show good repeatability for the same bending depth, with slightly higher forces observed for higher speed ratios. In Continuous Bending under Tension (CBT), increasing the bending depth reduces the axial stress required to deform the specimen. A higher bending depth increases the contact length between the specimen and the bending rolls, resulting in a smaller bending radius. Consequently, the material experiences more intense repeated bending and unbending, leading to increased local plastic deformation. As a result, for the same applied uniaxial displacement, the measured axial force is lower than that observed at smaller bending depths.

Table 2. Description of the CBT test conditions for samples tested to fracture. (*imposed parameters).

	P2_R_L1	P2_R_H1	P3_R_L1	P3_R_H1	P4_R_L1	P4_R_H1
P [mm]* (see Fig. 2b)	2	2	3	3	4	4
Velocity ratio (v_t/v_b)*	R_L 0.0088	R_H 0.0118	R_L 0.0088	R_H 0.0118	R_L 0.0088	R_H 0.0118
Number of cycles	25	20	18	17	16	16
Displacement [mm]	63	67	48	52	38	48.5

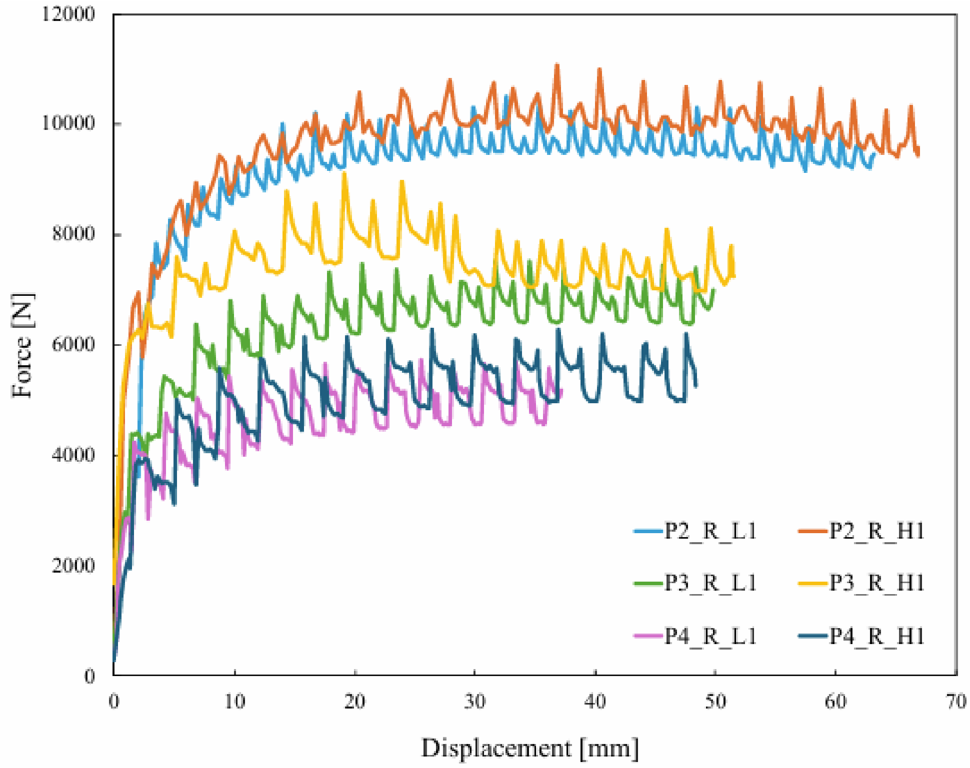

Fig. 4. Mechanical behaviour of DP1000-LY under CBT conditions, tested at two velocity ratios and three bending depths (2, 3, and 4 mm) up to fracture.

Table 3. Description of the CBT test conditions prior to fracture, up to 75% of the total cycles. (*imposed parameters).

	P2_R_L2	P2_R_H2	P3_R_L2	P3_R_H2	P4_R_L2	P4_R_H2
P [mm]*	2	2	3	3	4	4
Velocity ratio (v_t/v_b)*	R_L 0.0088	R_H 0.0118	R_L 0.0088	R_H 0.0118	R_L 0.0088	R_H 0.0118
Number of cycles*	19	15	13	13	12	12
Displacement [mm]	51.5	50	32.7	43.5	30	40

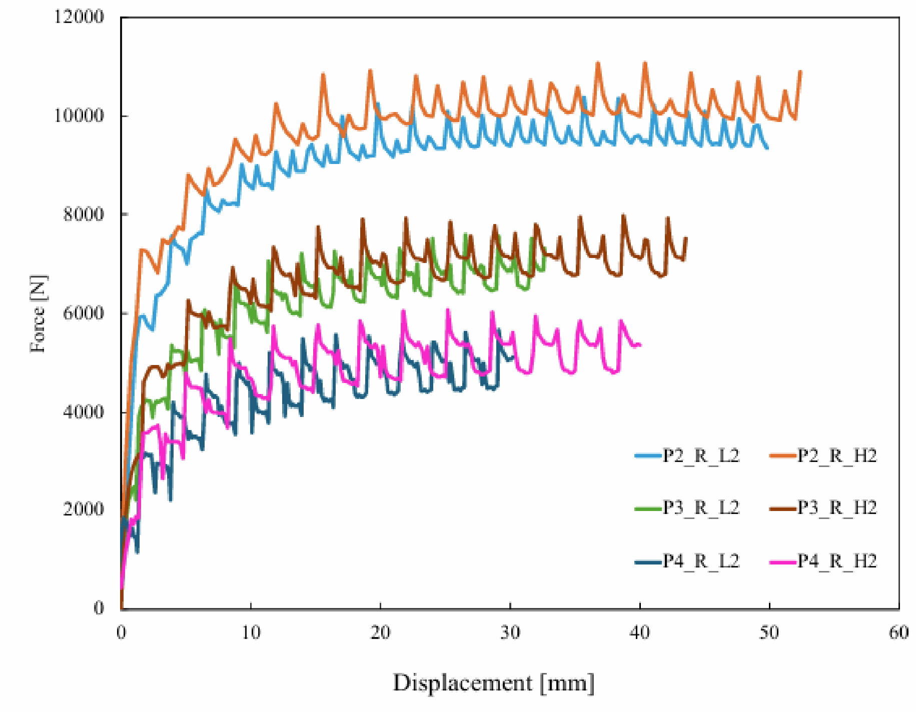

Fig. 5. Mechanical behaviour of DP1000-LY under CBT conditions at two velocity ratios and bending depths of 2, 3, and 4 mm, before fracture.

The tensile test results after CBT are shown in Fig. 5. As expected, the highest strength was observed for the lowest bending depth, which also exhibited the highest force during CBT, while the lowest strength corresponded to the highest bending depth. For a bending depth of 2 mm, no significant difference in strength was observed between the two speed ratios. For the other bending depths, higher speed ratios tended to produce slightly higher strength. In all cases, the strain was significantly reduced compared to the as-received material, reflecting the large amount of accumulated plastic deformation during CBT.

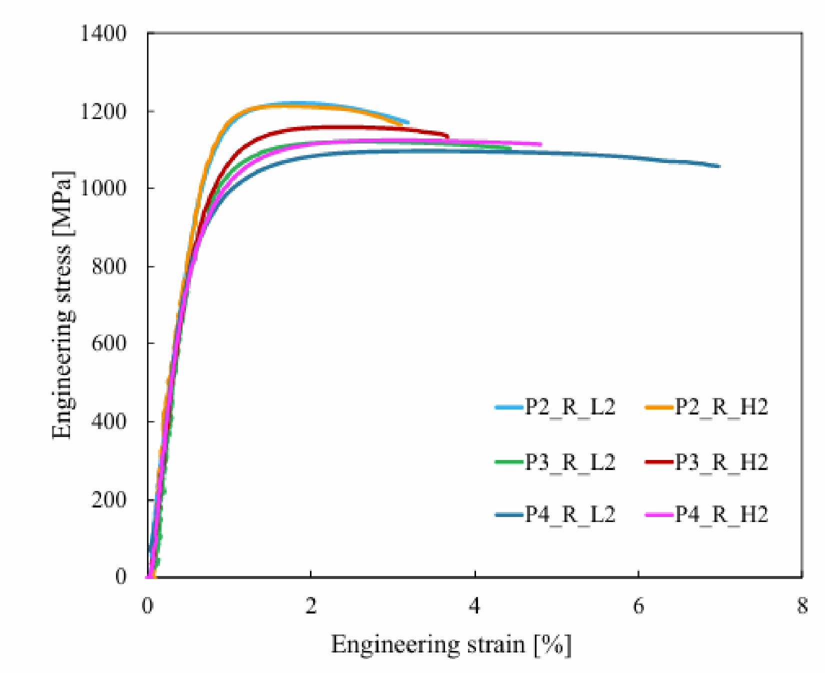

Fig. 6. Tensile stress–strain curves of material after CBT processing.

The hardness of both surfaces in contact with the bending rolls was also investigated to assess whether contact with one or both rolls had a differential effect. The Vickers hardness of the original DP1000-LY material was approximately 317 HV. CBT samples exhibited increased hardness, ranging from 325 HV to 390 HV, representing up to a 25% increase over the undeformed material. This increase is attributed to work hardening induced by CBT and is consistent with the observed increases in yield and ultimate tensile stresses. The initial material had an average yield stress of 705 MPa and ultimate tensile stress of 1002.7 MPa, whereas post-CBT specimens exhibited yield stresses between 835.5 MPa and 1052.6 MPa and ultimate stresses between 1100.5 MPa and 1222.6 MPa. These results demonstrate a clear correlation between surface hardness and mechanical strength, highlighting the significant impact of CBT on material properties. Despite the geometric asymmetry during loading, hardness values were similar between the two faces, with no clear trend of one face consistently exhibiting higher hardness than the other. This suggests that the effects of CBT on surface work hardening are approximately symmetrical.

Summary

CBT processing of DP1000-LY steel significantly influenced deformation and tensile behavior. Lower bending depths allowed greater total deformation before fracture and higher tensile forces, while higher speed ratios caused earlier failure. Tensile tests on partially processed samples confirmed that increasing bending depth reduces strength, and higher speed ratios accelerate failure. Both surfaces of the specimens showed similar mechanical behavior, indicating that contact with one or two rolls has minimal effect. Overall, CBT enhances material strength, with deformation and failure strongly dependent on bending depth and speed ratio.

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