2021, VOL. 27, NO. 3, 152-156



# **RESEARCH PAPER**

# STRAIN HARDENING AND STRETCH FORMABILITY BEHAVIOUR OF TRIPLE PHASE (TP) STEEL STRIPS

Maha El-Meligy<sup>1)\*</sup>, Taher El-Bitar<sup>1)</sup>

<sup>1)</sup> Central Metallurgical R&D Institute (CMRDI), Plastic Deformation Department, Egypt

\* Corresponding author: dr.mahaelmeligy@gmail.com, 1st Elfelazaat St., Eltebeen, 11722 Helwan, Egypt

Received: 07.07.2021 Accepted: 12.08.2021

#### ABSTRACT

The current work explores the strain hardening and stretches formability behaviour of the developed Triple Phase (TP) steel. Double quenched TP steel strips posse three distinguished stages of strain hardening on tensile forming. A 1st stage represents the highest n-value reflecting resistance to homogeneous deformation, where steel can be safely stretched. A 2nd and 3rd stage reveals lower n-values, where localized thinning exists. On Erichsen testing, the relationship between punch forming force and punch stroke exhibits two forming regions. The 1st region is delineated by a straight line showing an ultra-high strain-hardening rate, which represents a reversible elastic stretch forming. The 2nd forming region continues to a higher Erichsen punch stroke than that of the 1st region and presents the permanent plastic stretch forming behaviour. It is found that bainite and martensite clusters created, by double quenching, in TP-steel exaggerated the elastic stretch forming limit 10 times higher than the as-hot rolled condition. 7 min. holding time of strips in the salt bath is considered the most effective for the creation of a useful volume fraction of the bainite phase. However, 21 min. holding time in salt bath grows martensite laths through the bainite aggregates, affecting negatively on stretch formability.

Keywords: Triple Phase (TP) steel; Bainite, martensite, ferrite TP Steel; double quenching treatment; Strain Hardening rate; Stretch Formability

## INTRODUCTION

Triple phase (TP) steels have a combination of favourable properties such as high tensile strength, high strain hardening rate at early stages of plastic deformation combined with a reasonable ductility. These properties are related to the special microstructure of the TP steel in which, the soft ferritic network provides a reasonable ductility; while bainite and martensite phases play the load-bearing role. The increased strengths of these steels were achieved usually at the expense of ductility and formability [1]. High initial strain hardening rate results in a high n-value, which provides better resistance to local thinning under the forming conditions of drawing and stretching [2, 3].

Properties such as continuous yielding behaviour, uniform plastic deformation and reasonable elongation are important features of TP- steels. Recently, production sites are looking for processing high-strength TP-steel sheets with reasonable formability to be used in automotive body frames to improve crashworthiness and to reduce automobile emissions [4-5]. The developed steel sheets have an elongation approximately twice that of a conventional DP-steel sheet [5]. The applications of ultra-high-strength steel (UHSS) sheets in the automotive industry were restrictedly used in simple shape parts, such as door impact beams or bumper reinforcements. Recently, however, UHSS is used for the press-formed complicatedshape-parts, such as seat frames or B-pillars, because of the growing demand for the weight reduction of automobiles [5, 6].

TP-steel sheets revealed a regular unexpected shear fracture in die bending operations and during flanging operations [7],

where the strain is highly localized due to severe dislocation pile-up in individual ferrite grains leading to delaminating at the boundary between ferrite and hard phase or to cracking of hard phase islands [7]. Dislocation pile-up, which causes micro-damage under the condition of localized straining cannot be principally avoided in DP-steel containing martensite. However, successful attempts were done through DP-steels containing bainite [8] or through microstructure grain refining to reduce the grain size of both ferrite and hard phases [8]. Consequently, the size of initial damage can be reduced raising the critical stress for crack propagation [2]. Microstructure homogenization is also essential to avoid the formation of hard-phase clusters as these provide an easy path for crack propagation. Fast cooling after the last rolling pass further refines the microstructure by delaying the austenite-to-ferrite transformation [7]. A secondary advantage of the refined hot strip microstructure is an accelerated nucleation rate of newly transformed phases during the intercritical annealing [9] since the new phases preferably nucleate on the grain boundary, which is significantly exaggerated by refining [7].

The strength of TP-steels is a function of the volume fraction of the constituent phases and their strength. The increasing volume fraction of hard phases has two contradicting effects on the tensile strength. An increase of hard phase volume fraction raises tensile strength. On the other hand, the carbon content of the martensite phase decreases with the increasing volume fraction of the martensite itself, as the strength of the martensite is mainly determined by its carbon content [10].

The strain hardening exponent (n) expresses the rate at which the material strain hardens. A material with a high n-value is usually preferred for processing sheet metal cold forming to

suit the automotive parts. A material having a considerable nvalue can deform before instability and can be stretched further before necking starts [3]. Steel that contains < 50% of martensite volume fraction (Vm) has a linear relationship between the true stress (ln  $\sigma$ ) with true strain (ln  $\varepsilon$ ). This is evidence that strain hardening of these steels reveals one stage strain hardening behaviour [11]. However, nonlinear variations of (ln  $\sigma$ ) with (ln  $\varepsilon$ ) for steels containing Vm > 50% indicate that the strain hardening behaviour of this steel reveals two stages of strain hardening mechanisms [11]. The strain hardening exponent (n) of the first stage is usually higher than the second one, where the first stage is related to the plastic deformation of ferrite, while the second stage can be related to the codeformation of both ferrite and martensite [12]. The maximum ultimate strength was obtained at 50% Vm [13]. However, a study emphasized that the relation between  $\sigma u$ , and Vm is not linear [11]

Recent work was dealing with triple-phase steel sheets containing both bainite and martensite beside a ferrite matrix. The steel sheet revealed high spring back action and low stretch flange ability [14]. The strength and toughness of bainite, martensite and ferrite triple-phase steel are superior to single martensitic dual-phase steel. The lath shaped bainite, which is separated from the prior austenite grains refined the subsequent transformed martensitic laths enhancing the strength and toughness of steel for fatigue based components [15]. During the early stage of bainite transformation, retained austenite forms from or between the bainite laths. Si inhibits the precipitation of cementite in Si-containing steel. Bainite that containing films of retained austenite instead of cementite is referred to as carbide-free bainite [15].

The current work is dealing with steel, which is considered a value-added steel grade. The steel sheets possess mechanical properties that can fulfil the requirements of processing automotive parts due to their high strength, which secures the safety of passengers during crashing. Furthermore, the high strength property reduces the automotive weight, which reflects positively on reducing fuel consumption.

#### MATERIAL AND METHODS

The steel alloys under investigation are hot rolled 3 mm thickness strips. The strips were containing 0.13% C, 0.55% Si and 1.1% Mn, while alloy 1 contains 1.0 %Cr varies and alloys 3 was containing 1.8 %Cr.

The steel strips were heated to the two-phase (ferrite and austenite) region before rapid cooling to 450 °C in a salt bath and isothermally hold for a time 7, 14, and 21 min. [16], to enhance the transformation of different amounts of bainite [17]. A subsequent final water quenching process to room temperature was directly followed, for martensite transformation. Detailed processing conditions were published elsewhere [16].

The hot-rolled, as well as the double quenched steel strips, were investigated by optical and SEM microscopes. The strips were mechanically evaluated by tensile testing at room temperature (23 °C) with a crosshead speed of 10 mm/min in accordance with DIN 50125-E3X8X30 (flat specimens). In addition, the strips were subjected to Erichsen testing (in accordance with ISO 20482:2003(E)) in which the punch height at failure defines the overall stretch formability of the material [18].

#### **RESULTS AND DISCUSSION**

The flow behaviour of the alloy can be described by equation  $\sigma = K$ .  $\epsilon^{n}$ , where K is a strength coefficient and n is a strain hardening exponent. The engineering stress-strain curves can

be numerically converted to true stress - true strain, as presented in Fig. 1 (a-d). The true stress - true strain curves can be split into stages according to the changes of curve slope due to the existence of different strain hardening mechanisms. Each curve slop can be characterized by linear equations, where the slope of the line represents the strain hardening exponent (n). It can be noticed that alloy (1-a) at the hot rolling condition exhibits two-stages strain hardening mechanisms, which is confirmed by the work done E. N. Birgani and M. Pouranvari [11]. I<sup>st</sup> stage possesses a high strain hardening rate, where n = 1.36. On the other hand, the 2<sup>nd</sup> stage shows a lower strain hardening exponent than the 1<sup>st</sup> stage, where n = 0.22. The two strain hardening mechanisms are due to the existence of 34% ferrite matrix with 66% martensite, which is previously published by ref. [16].

Furthermore, the true stress - true strain curves of triple-phase (TP) double quenched steel strips show three stages of strain hardening mechanisms.  $1^{st}$  stage represents forming of the ferrite phase and presents the highest strain hardening rate with (n) ranging between 1.4 and 1.5. The  $1^{st}$  stage reflects homogeneous cold formability, where the steel can be safely stretched [3]. The  $2^{nd}$  stage shows lower rates of strain hardening where n is ranging 0.94, 0.71, and 0.54. The n-value is inversely proportional to the amount of created bainite in the steel (as stated below in Table I). The bainite phase is sharing the ferrite phase tases of strain hardening, as n is ranging 0.24, 0.21, and 0.16. Finally, TP steel shows continuous deformation, where martensite starts cold forming cooperatively with the other existing phases.











(1-d) 21- min holding in the salt bath **Fig. 1 c, d** True stress – true strain relationship of strips from alloy 1 for different holding times in a salt bath.

 
 Table 1 summarizes the volume fraction of different phases transformed by double quenching heat treatment and the calculated strain hardening exponent (n).

 Table 1 Volume fraction of created Phases & calculated Strain hardening exponent for Alloy 1

Holding	The volu	ime fracti	on of created	Calculated strain hardening		
time in a	Phases %, [16]			exponent		
salt bath				(n-value)		
at 450 °C	_			Strain hardening stage		
	Ferrite	Bainite	Martensite	1 <sup>st</sup>	2 <sup>nd</sup>	3 <sup>rd</sup>
as hot	34	0	66	1.36	0.22	0
rolled						
7- min	31	39	30	1.46	0.94	0.24
14- min	35	45	20	1.47	0.71	0.21
21- min	31	58	11	1.43	0.54	0.16

Fig. 2 presents the results of the Erichsen test, where Erichsen punch forming force per unit strip thickness is presented against the punch stroke for different strips, which were taken from alloy no. 1. The punch forming force represents the resistance of TP-steel strips to cold formability, while the punch stroke represents the stretch formability.

The curve of the hot-rolled strips, without heat treatment, reflects a continuous increase of the punch forming force with the increase of punch stroke. The curve represents a continuous strain hardening phenomenon, which is reasonable for stretch forming of medium carbon steel sheets [19].

On the other side, the curves represent strips, which were subjected to different holding times at 450 °C in the salt bath, possess two identified regions. The 1<sup>st</sup> region is delineated by a straight line showing ultra-high strain hardening rate. This part of the curve expresses a reversible (elastic) stretch forming region. The high strain hardening rate may be urged to creation of bainite phase aggregates and martensite colonies in addition to the ferrite matrix. The 1<sup>st</sup> forming region expresses the spring back action of the steel strips, which may exert severely on the forming dies [14]. The TP-steel strips having spring back action can be usefully used for reinforcing of the sedan cars sides. It can be noticed that the elastic stretch forming phenomenon continues up to 0.38 - 0.4 mm of the punch stroke. The hard phases transformation, due to double quenching treatment, in TP-steel exaggerated the elastic stretch forming (spring back action) limit 10 times higher than the ashot rolled condition.

The 2<sup>nd</sup> region is represented by a straight line with a lower strain hardening rate. The 2<sup>nd</sup> forming region continues to a higher Erichsen punch stroke than that of the 1<sup>st</sup> region, which would encourage the automotive manufacturer to use the current TP-steel in press-formed complicated-shape-parts, such as seat frames or

B-pillars, to cope with the growing demand for the automobiles weight reductions [6].

Prolonging of holding time from 7 to 14 min. does not effectively enhance the punch stroke, which confirms that 7 min. holding time at the salt bath is effective for creation sufficient useful volume fraction of bainite [16]. Further increase of holding time in the salt bath to 21 min. would create massive amount of bainite, which would affect negatively on stretch formability and exert severely on the forming dies [14].



Fig. 2 Punch forming force at different heights of punch stroke for alloy 1

Fig. 3 shows a microstructure investigation for TP steel – strips from alloy 1. The strips were hold in the salt bath at 450 °C for 7, 14, and 21 min. Micrographs (3-a) and (3- b) show creation of bainite and martensite in the ferrite matrix with different volume fractions (as stated in the table 1). Micrograph (3 - c) represents specimen that was hold 21 min. in the salt bath. It is clear that the amount of bainite created has been massively increased, which affects negatively on the stretch formability [11, 14], and the punch force is remarkably increased.

Fig. 4 represents the microstructure of TP- steel alloy 3 at highmagnifications (4000 X & 10000 X). Both micrographs are focusing on details of the bainite aggregates created after holding 21 min. in a salt bath and followed by water quenching. The elliptical shapes drawn on both micrographs demonstrate martensite laths grown through the massively created bainite aggregates in a ferrite phase matrix. The grown of martensite laths through the bainite aggregates may imbed the deformability properties of the bainite phase. The grown martensite laths phenomenon is used to explain the loss of stretch formability after 21 min. holding time in the salt bath. Numerous previous works were dealing with the creation of martensite laths between the bainite aggregate in triple-phase steel [20-22] different magnifications (B-bainite, M- martensite, F- Ferrite).



(3-a) 7 min. holding at 450 °C



(3-b) 14 min. holding at 450 °C



(3-c) 21 min. holding at 450 °C Fig. 3 Micrographs of heat-treated TP- steel strips for 7, 14, and 21 min. holding time in the salt bath at 450 °C

Fig. 5 compares the results of the Erichsen tests for both alloys 1 and 3. Strips of both alloys at the hot rolled condition prevail continuous increase of punch force with the increase of punch stroke (strain hardening). However, the punch stroke (stretch formability) of alloy 3 is lesser than alloy 1, as a result of its higher Cr content (1.8%), [16]. In all cases, alloy 3 has a similar behaviour as that of alloy 1. However, alloy 3 shows lower stretch formability and higher strain hardening rate than that of alloy 1, as a result of further alloying with Cr [23, 24].



**Fig. 4** Microstructure of alloy 3 (21 min. holding at 450 °C) at different magnifications (B-bainite, M-martensite, F-ferrite)



Fig. 5 Comparison of Erichsen test results between alloys 1 and 3  $\,$ 

### CONCLUSION

 Double quenched TP-steel strips show three stages of strain hardening on tensile forming. Ist stage reveals the highest nvalue reflecting resistance to homogeneous deformation, where steel can be safely stretched. 2nd and 3rd stages possess lower n-values, where localized thinning would exist.

2. The punch forming force - punch stroke relationships exhibit two forming regions on Erichsen testing. The 1st region is delineated by a straight line showing ultra-high strainhardening rate, and representing a reversible (elastic) stretch forming (spring back action). 2nd forming region continues to a higher Erichsen punch stroke than the 1st region.

3. Bainite and martensite creation in TP-steel exaggerated the elastic stretch forming limit 10 times higher than the as-hot rolled condition.

4. 7 min. holding time in the salt bath at 450 oC is the most effective to transform a reasonable useful volume fraction of the bainite phase.

5. 21 min. holding time in the salt bath is leading to growing martensite laths through the bainite aggregates, affecting negatively on stretch formability.

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