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Tensile Deformation Behaviour of Dual Phase Steel Under Various Processing Conditions: A Review

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Abstract

Present paper presents a progressive overview of DP (dual phase) steels which are extensively used materials for manufacturing of automotive parts/components. These materials have high ratio of strength-to-weight and optimum ductility which make them outstanding characteristics compared with other traditional steels. The uni-axial tensile deformation behavior of DP steels is presented which are tested under various heat treatment conditions at ambient temperature and elevated temperatures. Mechanical properties have been evaluated under static and dynamic conditions as well as different strain rates. The results reported by the several investigators are presented as a consolidated summary and compared various material properties such as ultimate tensile strength (UTS), yield strength (YS) and total elongation.

1. Introduction

Dual phase (DP) steels are widely used in automobile industry wherein a large number of parts / components such as roof outer, door outer, body side outer, floor pane etc. require engrossing large amount of mechanical energy during impact. Interestingly, DP steels offer a good combination of continuous yielding behavior, low yield stress-to-tensile strength, high strength, high strain hardening rate and good formability. The continuous low yield and high tensile strengths are associated with two phase microstructures i.e. soft ferrite and hard martensite phases of the DP steels, respectively. The list of dual phase steels alloys along with chemical compositions is given in Table 1. DP steels are microstructurally engineered strength materials having two phases i.e. ferrite and martensic. These are basically lower medium carbon steels that are produced from a transformation that lies in between A1 and A3. The distinguishing microstructural attributes of DP steels are volume fraction and morphology (size, aspect ratio, orientation relationship between ferrite and marteniste phases, interoviality etc.) and grain size of the continent phases alloying with the carbon content. Apart from the carbon continent, the other alloying elements are having both the martensitic and ferritic phase strengtheners.

Production of DP steels involves complex processing routes: (1) thermo-mechanical processing trailed by control cooling, and (2) continuously annealing followed by cold rolling [1]. Both types of processes are characterized by producing the DP steels. The processing route-1 for the production of DP steel is shown in Fig. 1. This involves the hot rolling of the strips in the austenite formation temperature region (Ac3 + 40°C) then after slow cooling allowing the steel to transform from austenite to desired amount of ferrite. Further, to achieve a fully martensitic structure during the ferrite transformation, the enrichment of carbon content in the austenite phase is essential. This enrichment enhances the hardenability of the austenite while simultaneously lowering the martensitic start (Ms) temperature. Following this, the strip undergoes rapid cooling to a temperature below Ms temperature, known as the coiling temperature. The equation (1) is utilized to determine the critical cooling rate necessary to ensure the formation of a complete martensitic phase in the second stage of transformation:

$$\text{Log(CR)} = 5.36 - 2.36\text{Mneq}$$

$$\text{Mneq} = \text{Mn} + 0.45\text{Si} + 1.15\text{Cr} + 2\text{P} \qquad (1)$$

Where both the CR and Mneq are the critical cooling rate and Mn equivalent of the alloying elements present in the DP steel, respectively. Production of Dual phase steels following the processing route 2, additionally involves cold rolling followed by the annealing continuous enduringly hot-dip galvanising. The variation in temperature at the time of annealing process is represented in Fig. 1. While performing the annealing process, sheet is heated slightly above the lower critical temperature (Ac1). During this stage, around 15% of the microstructure composed of pearlite and ferrite transforms into austenite. Subsequently, the sheet is quenched for the transformation of austenite phase to martensite phase. Therefore, the finally transformed microstructure consists of primarily martensite and ferrite phases in appropriate proportions.

Table 1 *Dual phase steels along with their chemical compositions. (in wt.%)*

DP Steel Grade	Composition													Reference
	C	Si	Mn	P	Cr	Ni	Al	Co	Nb	Cu	V	S	Fe	
500	0.12	0.6	1.2	0.025	0.5	1.1	-	-	-	-	-	0.015	Balance	[8], [19]
600	0.13	0.2	1.5	0.01	0.02	0.039	0.04	0.019	0.015	-	-	-	Balance	[7], [9], [18], [19]
700	0.11	0.18	0.44	0.023	0.97	2.68	-	-	-	-	-	0.03	Balance	[8]
780	0.138	0.2	1.52	0.011	0.03	0.04	0.038	-	0.014	0.01	0.02	0.138	Balance	[19]
800	0.13	0.2	1.49	0.03	0.02	0.037	0.04	0.019	0.016	0.008	0.02	-	Balance	[7], [9]
980	0.09	0.6	2.15	-	-	-	-	-	-	-	-	-	Balance	[14]
1000	0.16	0.5	1.48	0.04	0.02	0.036	0.06	0.019	0.02	0.005	0.014	-	Balance	[7]

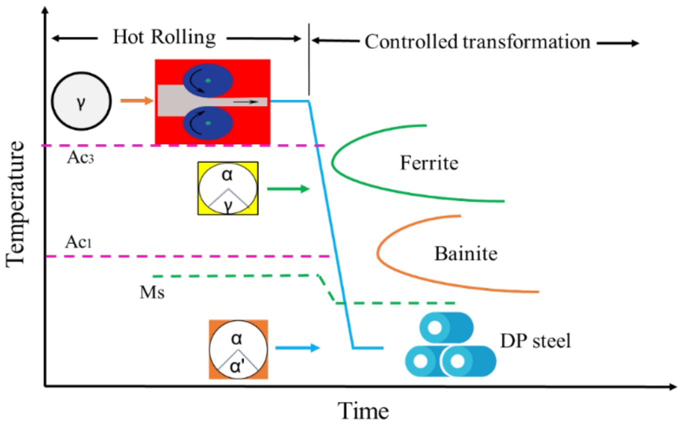

Fig. 1 *Processing of DP steels by hot rolling [1]*

The microstructures of DP steels are produced using the above-mentioned processing routes 1 and 2. Usually, the typical microstructures of the DP steels consist of a martensite phase scattered into a ferrite matrix. The hard martensitic phase adds strength, while the soft ferritic matrix provides ductility to the material. The combination of the microstructural attributes of two constituent phases makes DP steel outstanding from those of the other conventional steels in terms of strength and formability.

In the past, researchers like Sodjit and Uthaisangsuk have worked on these steels including different volume fractions of ferrite phase and martensite phases [3]. They have found that the overall volume percentage of martensitic phase and strength of dual phase steel are directly proportional, and the ductility of material depends on the ferritic phase. The investigation has been performed on deformation behaviour of DP steel to study the effect of a volume fraction with 20% of martensite having homogenously and non- homogenously distributions in ferrite matrix [4]. It has been observed that the DP steel with more uniformly distributed martensite has deformed more slowly than the non-uniform distributed martensite phase. The effect of ultra-fine ferrite phase on the deformed behaviour of DP steels for the volume fractions of martensite ranging from 6.8 to 31.4% with a step of 6.8%, and at different ferrite grain sizes of 3, to 60 μm using micromechanical modelling of cells has been investigated by Al-Abbasi [5]. It has been observed that the finer ferrite grain size provides more restriction for deformation. The impact of ferrite grain size and martensite in several DP steels has been investigated by Bergström et al. in terms of deformation behaviour of DP-500, DP-600, DP-800 and DP-980 graded DP steels [6].

Present paper is thus concerned to present an up-to-date review of the DP steels covering materials processing, uniaxial tensile behaviour and employed heat treatments to engineer microstructural attributes. Consolidated summary of literature on the deformation behaviour and material properties of DP steels tested under heat treated conditions are also presented.

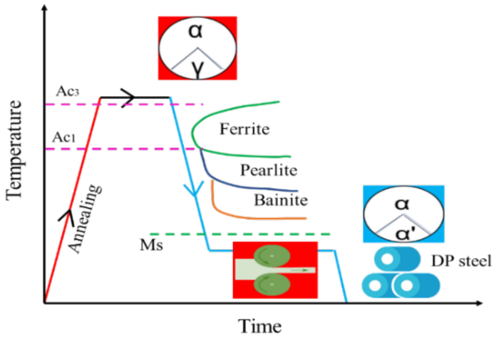

Fig. 2 *Processing of DP steels by cold rolling [2]*

2. Uniaxial Tensile Deformation Behaviour

2.1 Under Ambient and Elevated Temperatures

Uni-axial tensile tests were conducted at room temperature at a strain-rate of 0.0025 */s* [7]. The more martensite content and lesser initial volume fraction of active ferrite have yielded an appreciable rate of hardening. The tensile tests were conducted within the temperatures ranging from -100 to 235°C with strain-rates feed of 10^{-3} to 1250 s^{-1}. Finally, it has been noticed that the DP steels are insensitive in the employed temperature range while sensitive toward strain rates. The behaviour of DP800 steel under uniaxial tensile was characterized by qin et al. [8]. They have strained the sample to 3.5% by annealing with 180°C of temperature for duration of 30 *min*. The tensile tests conducted at temperature range of -60 to 100°C with the strain rates of 0.0001-100 s^{-1} which are generally experienced by the material during crash / impact situations. Material properties like YS, UTS and elongation are evaluated. Although the DP material exhibits steady yielding behaviour, the pre-strained (PS) and super imposed BH (bake hardening) materials have resulted in the re-appearance of a definite yield point. Compared to the as-received material, the PS + BH and PS have shown an improvement of both the YS and UTS of the material in the range of 5 to 10% at +20°C temperature and all studied strain rates.

The uniaxial deformation behaviour of the as received and tempered DP980 steel is investigated by Das et.al, [12]. Wang et.al., [7] have investigated the effect of volume fractions of constituent phases and related morphologies on the dynamic properties of DP steels (DP-600, DP-800 and DP-1000) and Mild steel (MS1200). They have found that the tensile strength of DP steels increases at immense strain rates of static condition while the MS steel, smaller than the static condition. Energy absorption of DP steel is similar in dynamic condition and MS steel has excellent potential energy absorption. Break elongation (BE) of DP 600 and DP800 steels drops sharply under high strain. On the other hand, break elongations of DP-1000 and M-1200 behave differently. It rises with increases in strain rate. Similarly, breaking elongation of MS 1200 steel is nearly two times higher under high strain-rate than that of the under quasi-static condition. The energy absorption conditions of all the steels investigated in the study reflected similar behaviour. The deformation of ferritic phase dominates in DP-600 and DP-800 steels under both the quasi-static as well as dynamic conditions. The materials DP-1000 and MS-1200 display the deformation under quasi-static condition. This has been ascribed to increase in BE as well as fracture mode transition.

Qin et.al., [8] have studied DP steels of 700 and 500 and performed a tensile test of quasi static testing with 0.001/s strain-rate on split Hopkinson's tensile bar (SHTB) testing. They have noticed that the DP 700 steel has high value of strength and low ductility of material as when compared with DP 500 steel under dynamic loading. Due to this, dislocations in DP steel increase the strength when compared with quasi-static results. Kundu and Field have investigated DP 590 steel (received from TATA steel) [9]. The specimens were polished with silicon carbide, the diamond paste of grit sizes 6, 3 and 1μm to make the specimen completely scratch free and etched with 2% of nital solution. Microstructures of ferrite and martensite phase of DP590 steel are fine and coarse grain structures, respectively. Most of the geometrical necessary dislocations (GNDs) are formed at the interfaces of ferrite and martensite phases. The average density of GNDs increases with increasing the plastic deformation.

The uniaxial tensile test in the servo-hydraulic universal testing machine was performed at a strain rate of 0.001s-1. Pandre et al., [10] have investigated the influence of strain rate and temperature on the tensile flow behaviour and mechanical properties like YS, UTS, % elongation and strain hardening exponent of DP590 steel. The testing was conducted in the temperature range of RT to 700 °C and at strain rates of 0.0001, 0.001 and 0.01 s-1. Finally, it has been concluded that the flow stress decreases with increase in the temperature and a drastic reduction is observed above 400°C. They have also found that the observed elongation is higher at lower strain rate (0.0001 s-1) compared to that of the higher (0.01 s-1).

Pandre et.al., [11] have also worked on the prediction of the flow stress behaviour using different constitutive models and addressed the variation in the mechanical properties by performing EBSD analysis. They have shown that the changes in the fraction of low and high angle grain boundaries appear to be responsible for the change in the strength and percentage elongation of the DP590 steel. Das et.al., [12] have worked on DP 600 and DP 800 steels and evaluated tensile properties at different conditions: (i) at the quasi-static method, at the strain rate of ≤1/s and (ii) at the high-speed servo-hydraulic test with velocity up to 20 m/s. They have noticed an increase in strength and decrease in ductility in DP 800 compared to the DP 600. The microstructure of dual phase steel exhibits the deformation in the ferrite grains by making the deformation more uniform across the grain volume when it is increased from quasi-static to high strain rates. The evolution of local misorientation primarily depends on the martensite fraction of the steels.

2.2 Heat Treated Conditions

The effect of strain rates and tempering temperatures (at 250 and 400°C for 60 minutes) on the deforming behaviour of DP steels have been investigated elsewhere [24]. It has been found that the UTS and strain hardening exponent of the tempered DP980 steel at 250°C is decreased by 11.18 % and 21.90% compared to the as-received DP980 steel. While at 400°C, it is reduced by 11.98% and 29.52%. The deformation behaviour of DP steel with different microstructures has been analysed by Torkamani et al. [25]. The microstructures are produced by inter-critical heat treatment (IHT) at 750 and 800°C followed by the quenching process. The tensile tests were conducted at RT at a strain rate of 5 × 10-4 *s-1*. The results have shown that, by increasing the IHT temperature, the YS values of the DP steel increase to770 MPa from 493 *MPa*, and UTS to 1080 MPa from 908 MPa. On the other hand, the total elongation values decrease from 9.8 to 4.5%.

The flow behaviour of the commercially available DP steel has been investigated by Bayramin et al. [26] with wide ranges of strain rate (0.0001 to 1 s-1) along with temperatures (100 to 400°C). They have observed the occurrence of the DSA phenomenon in 200 to 300°C of temperature range. This is attributed to the reduction in the overall ductility of the material. Dai et.al., [27] have performed the heat treatments of DP980 steel grade by rapid annealing method at temperature of 800°C. Subsequently, they have conducted uniaxial tensile tests and found that the elongation and UTS values have raised up to 16.7% with 1200 MPa. Das et al. [12] have investigated the influence of martensite morphology on the work hardening behaviour of low carbon (with 0.08 wt. %) DP steel treated with different heat treatments. This involves namely, step Quenching (SQ), inter-critical annealing (IA) and intermediate Quenching (IQ) which have resulted in three different morphologies of martensite phase. The fine and fibrous, banded and island type morphologies are observed at IQ, SQ, and IA samples, respectively. These microstructures have shown three work hardening stages for IQ and IA specimens whereas two work hardening stages for SQ sample. The IQ treated sample has demonstrated the best combination of strength and ductility. In addition, IQ samples have shown lowest yield ratio and highest work hardening magnitude. AI sample exhibits low strength and intermediate elongation while the SQ sample reveals high and low strength and elongation values, respectively among all the three types of heat treatments. The microstructures of SQ and IA samples reveal the presence of microcracks and micro-voids in martensite and ferrite phases, respectively. Radwanski et al., have conducted heat annealing (780 to 810°C) and tempering (240 to 460°C) on DP steel and evaluated tensile properties [29]. They have estimated YS and UTS using Perlade model. The discrepancy between experimental and calculated results is less than the 10%. Evin et al. [30] have investigated the effect of annealing (740-840°C) on DP 600 grade steel and assessed tensile properties. They have predicted mechanical properties using regression analysis based on the volume fraction of the secondary phase and grain size, following the annealing temperature. Calcagnotto et al., [31] have worked on ageing method on DP steel having 30% martensite coarse grain (CG) at room temperature, fine grain (FG) at 700°C, ultra-fine grain (UFG) at 500°C and bake hardening (BH) at 170°C. They have observed that in FG and UFG samples, fracture occurs in martensite phase. The YS and UTS values increase with decrease in grain size. It enhances the ductility and UTS slightly in BH while the uniform elongation is constant in CG, FG and UFG samples. The elongation and reduction in area increase to 2.5% and 22%, respectively in BH sample. The reduction in area is maximum in FG and CG samples. In contrast, the total elongation is low in UFG specimen.

Table 2 *Consolidated summary of literature on the deformation behaviour and material properties of DP steels tested under ambient and elevated temperature conditions*

Authors & Year	Material used	Tests Availed	Test Temperature (^oC)	Strain Rate (s-1)	Flow Stress	Strain Hardening Behavior	Microstructural Studies	Material Properties Determined						
Huh et.al, 2013 [14]	DP780, AHSS	Tensile Test	RT	0.001-100	×	×	✓	**m**	**n**	**%El**	**BS**	**CS**	**UTS**	**YS**
Srivastava et.al, 2016 [16]	DP980 DF140T	Uniaxial tension	RT	0.009	✓	✓	✓	×	✓	×	×	×	✓	✓
Cheng et.al, 2016 [18]	DP980	Uniaxial Tension	250, 400	0.001	✓	×	✓	✓	✓	×	×	×	✓	✓
Gronostajski et.al, 2017 [20]	DP600, TRIP690	Uniaxial Tension	RT	0.001–5000	✓	×	✓	×	✓	×	×	×	✓	✓
Liao et.al., 2017 [21]	DP500, DP600, DP780	Uniaxial Tension	RT	0.001	✓	✓	✓	×	×	✓	×	×	✓	✓
Alvarez et.al, 2020 [23]	DP Steel	Tensile	700	0.001	✓	×	✓	×	✓	✓	×	×	✓	✓
Wang et.al., 2013 [7]	DP-600,800,1000	Tensile	RT	0.001	✓	×	✓	✓	✓	✓	×	×	✓	✓
Qin et.al., 2013 [8]	DP-500,700	Tensile	RT	0.001	✓	×	✓	×	×	✓	×	×	✓	×
Kundu and Field 2016 [9]	DP-590	Tensile	RT	0.001	✓	×	✓	×	×	×	×	×	✓	×
Das et.al., 2019 [12]	DP 600, 800	Tensile	RT	1	✓	×	✓	×	×	×	×	×	×	×

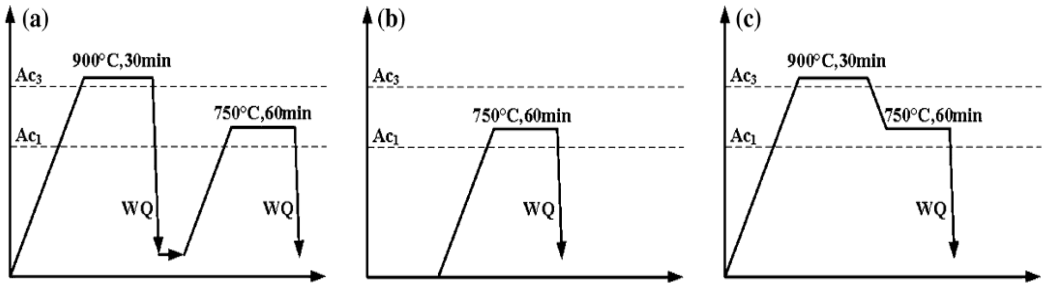

Fig. 3 *Schematics representation of three heat-treatment studied: (a) IQ; (b) IA; (c) SQ. WQ (water quenching) [27]*

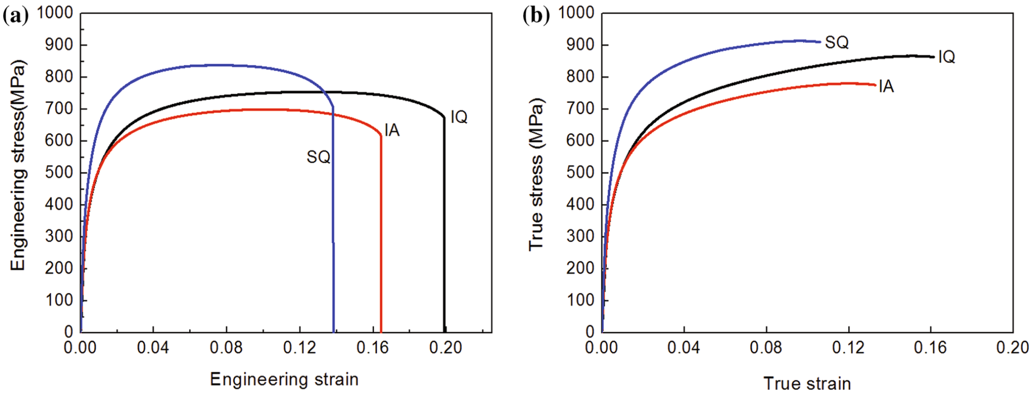

Fig. 4 *(a) Engineering stress; (b)True stress–strain curves for investigated steels [27]*

Gao et al., [32] have investigated on the inter-critical annealing 780 - 840°C on mechanical properties of DP steel. They have observed an increase in YS and UTS values and decrease in uniform elongation 7% at 840°C due to a higher degree of warm rolling and annealing temperature 780-840°C. Ayres et al., [33] have conducted heat treatment of inter-critical annealing and soaking at temperatures (750-850°C) on DP steel and evaluated tensile properties. They have observed that both the volume fraction and grain size of martensite phase increase with increasing the soaking temperature. The highest UTS value is found at low inter-critical temperatures, achieving 935 MPa whilst the highest elongation value (21%) is achieved at the higher inter-critical temperatures. Ramazani et al., [34] have investigated the effect of Bake hardening (BH) on DP 600 and TRIP 700 steels and evaluated the tensile properties. They have observed that the DP steel shows continuous YS of 400 MPa with low yield stress to tensile strength ratio and thus a UTS value higher than the 600 MPa in the basic state.

Di et al., [35] have performed a tensile test of annealed (715-760°C) DP 780 steel. It has been reported that the tensile strength decreases with an increase in YS and elongation values. This has been extended to investigate the microstructures in different annealed conditions. Singh et.al., [36] have evaluated the microstructure and mechanical properties of DP steel at inter-critical annealing 800°C. They have noticed a UTS value 1375±35MPa in comparison to the parent steel with UTS of 510±15MPa. Interestingly, this is nearly 2.7 times higher. Raj et al., [37] have worked on heat treatment of annealing and quenching at a temperature of 775°C on SPFH590 and DP steel and evaluated the microstructures. They have performed a formability test and observed that the DP600 steel undergoes bake hardening which has increased YS by 55MPa. Centeno et al., [38] have investigated inter-critical annealing at 700-730°C on DP steel and evaluated uniaxial tensile test properties at room temperature and microstructure after heat treatment. They have observed the increase in tensile strength and decrease in total elongation with increasing temperature of 710-730°C. Deng et al.,[39] have worked on inter-critical annealing at a temperature of 820°C on DP590 steel. They have evaluated microstructure and tensile properties. It has been observed that both the UTS and total elongation values improve from 656 to 706 MPa and 22.4% to 25.0%, respectively. Hasbi et al., [40] have worked on annealing and quenching at temperatures of 760-840°C, tempering at 450°C on DP steel and evaluated hardness using a rock-well hardness test. They have observed that the increase in hardness value at temperature 840°C, lower hardness at temperature 740°C and decreasing of hardness value in tempered condition. Liao et al.,[41] have worked on inter-critical annealing of DP steel at a temperature 800 ° and evaluated the tensile properties in air cooling (sample A) and water quenching (sample B) conditions. The samples A and B exhibit UTS values 1047 and 1127 MPa, respectively and YS 480 and 983MPa. The total elongation values of samples A and B are 15.5 and 7%, respectively. The sample B exhibits superior mechanical properties than that of the A.

Table 3 *Consolidated summary of literature on the deformation behaviour and material properties of DP steels tested under heat treated*

Processing conditions			Test Conditions	Strain Rate (s-1)	Flow Stress Behavior	Microstructuraltudies	Other parameters studied	Material Properties		
Authors & Year	Temperature (°C)	Heating Technique						%El	UTS	YS
Curtze et.al [24]	250 - 400	Tempering	Tensile test	0.001	×	✓	Strain hardening exponent	×	✓	×
Torkamani and Raygan [25]	750 and 800	Inter-critical heat treatment	Tensile test	5×10^{-4}	✓	✓	-	✓	✓	✓
Bayramin et.al., [26]	100 - 400	Heating	Tensile test	0.0001 to 1		✓	-	×	✓	×
Dai et.al., [27]	800	fast-annealing	Tensile test	10^{-4}	×	✓	-	✓	✓	×
Radwanski et.al.,[29]	780 – 810 & 240 - 460	Annealing	Tensile test	-	×	✓	Work hardening	×	✓	✓
Evin et.al., [30]	740 - 840	Annealing	Tensile test	0.001	✓	✓	Strain hardening	×	×	×
Calcagnotto et.al.,[31]	170 - 700	Ageing	Tensile test	0.4 - 4	✓	✓	Bake hardening	✓	✓	✓
Gao et.al.,[32]	780 - 840	Inter-critical annealing	Tensile test	$3*10^{3}$	✓	×	Strain hardening	✓	✓	✓
Ayres et.al., [33]	750 - 850	Inter-critical annealing	Tensile test	0.00025 to 0.0067 mm	×	✓	Bake hardening	✓	✓	×
Ramazani et.al.,[34]	60, 170 & 220	Bake hardening	Tensile test	4 mm/min	✓	✓	-	×	✓	✓
Di et.al., [35]	715 - 760	Annealing	Tensile test	-	✓	✓	-	✓	✓	✓
singh et.al., [36]	717 - 840	Inter-critical annealing	Tensile and Vickers hardness	0.001	✓	✓	Hardness	✓	✓	×
Raj et.al.,[37]	775	Annealing and quenching	formability test	0.001	✓	✓	Bake hardening	×	✓	✓
Centeno et.al.,[38]	700 - 730	Inter-critical annealing	uniaxial tensile test	0.005	✓	✓	-	✓	✓	×
Deng et.al., [39]	820	Inter-critical annealing	tensile test	3 mm/min	✓	✓	Work hardening	✓	✓	×
Hasbi et.al.,[40]	760 - 840 , 450	Annealing and Tempering	rock-well hardness	-	×	✓	Hardness	×	✓	✓
Liao et.al.,[41]	800	Inter-critical annealing	tensile test	3 mm/min	×	✓	-	✓	✓	✓

3. Concluding Remarks

The state-of-the-art overview of DP Steels consisting of martensite and ferrite phases is presented. The variation in uniaxial tensile properties under static and dynamic conditions and different strain rates are discussed. The effect of heat treatments (quenching and tempering) has been presented to bring out the evolution of microstructural attributes of DP steels which in turn govern the mechanical properties.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

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