NIPES Journal of Science and Technology Research 3(2) 2021 pp. 125-139 pISSN-2682-5821, eISSN-2682-5821

NIPES

Journal of Science and Technology Research

Journal homepage: www.nipesjournals.org.ng

Review of the Applications, Properties and Processing Parameters of Dual Phase Steels

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Article Info

Received 08 May 2021
Revised 21 May 2021
Accepted 22 May 2021
Available online 04 June 2021

***Keywords*:**
dual phase steel, mechanical properties, processing parameters, ferrite-martensite.

https://doi.org/10.37933/nipes/3.2.2021.15

https://nipesjournals.org.ng

Abstract

A critical and comprehensive review of the applications, properties and processing parameters of dual phase steel has been presented in this paper. Existing literatures ascertained that dual phase steels possess mechanical properties superior to that of conventional high strength low alloy steels and ordinary plain carbon steels, with a high yield to strength ratio and good formability. It has been noted that the synergy between the soft ferrite (matrix) phase and the dispersed hard martensite or bainite phase is responsible for the enhanced mechanical properties. Automotive industries were identified to be the major consumers of dual phase steels, particularly in the manufacture of its body structural components. However, its application has been extended to other sectors like production of precision tubes, large diameter pipes for conveying petroleum products etc. The review revealed that though steel with two phases were mentioned in the 1930s and 40s, fundamental and detailed research on it did not commence until about 20 years later and first breakthroughs being recorded in the 1970s. Cooling rate, microalloying elements, temperature, deformation and strain rate has been recognised to be the processing parameters that may affect the mechanical properties of dual phase steel. Economic reasons and the quest for safer and sustainable environment were identified to be the major driving forces responsible for the development and subsequent transformations and innovations that have occurred in dual phase steels since its advent in the steel industry.

1. Introduction

Dual phase products were first marketed in the USA at commercial level [1]. The product was vanadium contained low alloyed steel, plus an intercritical annealing process commonly encountered in the 1970's. Dual phase (DP) steels are mainly of low carbon content (~0.05 to 0.25 %) Advance high strength steel (AHSS) grades, which apart from Si and Mn which are usual constituents, also have some microalloying elements as added. The microstructure usually consists of 5 – 30% martensite [2], however, higher amounts are obtainable in practice. Little quantity of acicular ferrite, retained austenite or bainite, could also be present in microstructure [3,4,5,6]. In general, dual phase steels sometimes called dual phase low alloy steels (DPLA), have mixture of martensite islands distributed along the grain boundaries in a ferrite matrix, with retained austenite and bainite possibly being included.

Today, DP steels have become one of the most preferred and versatile material in the automotive industry. They have presently substituted conventional high strength low alloy (HSLA) steels in many structural applications. According to US Steel, reduction in weight, high resistance to fatigue failure, good crash energy absorbing capacity and improved formability are responsible for this substitution.

They have also found tremendous use in producing pipes for the transportation of petroleum products due to its good weldability as a result of relatively low content of alloying element, especially those with low carbon level. In addition, because of the increasing demand for larger diameter pipes, steels of higher yield stress have become a choice candidate material for use in order to limit excessive wall thickness. They exhibit "no yield discontinuity but work harden rapidly so as to be just as strong as the conventional high strength low alloy steels when both have been deformed by about 5%. In contrast to ferrite - pearlite steels, the work hardening rate of dual-phase steels increases as the strength increases. The absence of discontinuous yielding in dual-phase steels is an advantage during cold pressing operations and this feature combined with the way in which they sustain work hardening to high strains makes them very attractive materials for sheet-forming operations". Honeycombe and Bhadeshia (1995) [7], reported that duplex structure can be obtained through intercritical annealing of the steel in the (α+γ) region, preferably at 790^0C for some minutes so that austenite could form in the ferrite, and then quenching at a high rate which enables the austenite phase to transform to martensite.

1.1. Microstructures Present in DP Steels and their Effect on Mechanical Properties

Microstructures and the exact amount of each phase present in DP steels are dependent on heat treatment and composition [8]. The relative amount of each phase present may affect mechanical and corrosion behaviour of dual phase steels. Some microstructures present in dual phase steels include ferrite-austenite, ferrite-bainite and ferrite-martensite.

a. Ferrite – Austenite dual phase steels: This is typical of duplex stainless steels (DSS) which is composed of ferrite/austenite phases in its microstructure. Though some sigma and chi phases may be present, but in very small quantities [9,10,11]. Labanowski *et al* (2014) [10] reported that austenite content increased with increasing annealing temperature, while Guo *et al* (2014) [11] reported an inverse relationship between the austenite content and increasing annealing temperature. However, Labanowski *et al* (2014) [10] observed that amount of austenite increased more remarkably as time increases at 700^OC than 500^OC. They also reported that the amount of precipitated sigma phase becomes larger with extended time.

The usefulness of duplex (austenitic-ferritic structure) stainless steel has been acknowledged by many branches of industry such as petrochemicals, pulp and paper etc. As a result, so many researches [8,10,11,12] have been conducted to examine the effect of microstructure on mechanical properties. Martins and Castelatti (2005) [12] observed that impact toughness is favoured by high volume fraction of austenite (58%). Similarly, Na *et al* (2012) [8] reported that alloy with equal amount of each phase has optimum mechanical properties. However, a direct relationship was reported between mechanical properties (UTS, yield strength and ductility) and austenite volume fraction [11]. They attributed this to grain size in line with Hall-Petch relation that a smaller average grain size results in a higher strength material [13]. It has equally been observed that the hardness value of super duplex stainless steel increased as volume concentration of the sigma phase increases [12]. They observed that the absorbed energy was not much affected by variation in the concentration of sigma phase.

In the words of Sieurin (2006) [14], the dual phase structure (austenite and ferrite) harmonizes the advantages of the two phases and makes the steel attain good toughness and high strength via the ferrite phase and austenite phase respectively.

b. Ferrite-Bainite DP steels: the class of DP steels associated with this microstructure comprising of soft ferrite phase and hard bainite phase and most times with some amount of retained austenite and martensite is found with mostly medium carbon steels and plastically induced transformation (TRIP) steels. This class of steel is developed by a two stage thermal treatment. First, annealing at (α+ϒ) region and quenching to the bainitic region followed by soaking at this region to allow the austenite (ϒ) from the first stage treatment to transform to bainite and then cooled to ambient temperature.

This class of steels are however, more often classified as complex phase (CP) steels because in most cases the presence of other phases like retain austenite and martensite are prominent. Again, it is not a popular class of advance high strength steel because of its low weldability compared to ferrite/austenite and ferrite/martensite dual phase steels because of its high carbon content.

The soft ferrite provides for the ductility, bainite or bainite/martensite contributes to the high hardness and strength while the synergy between the hard phase(s) and the soft ferrite phase provides for the improved impact toughness.

c. Ferrite – Martensite DP Steels: this is composed of essentially soft ferrite phase as matrix with dispersion of hard martensite phase. However, little amount of carbide or retained austenite could be included in the microstructure. This class of dual phase steels is mostly associated with low carbon micro alloy steels.

In recent times, this class of dual phase steels have attracted the attention of many researchers [15,16,17,18,19,20,21,22,23] because of its optimum combination of high strength, impact toughness and ductility as well as its good formability and weldability. It has found wide application in the automotive industry as a result of its advantage in weight reduction which translates to high fuel economy, improved crash safety due to its high impact toughness, ease of fabrication and low cost of production.

Majority of the researchers mentioned above have reported a direct relationship between martensite volume fraction (MVF) and intercritical annealing temperature (IAT). They have also worked extensively on the influence of intercritical annealing temperature on mechanical properties. Also, improvement in properties of DP steels over conventional HSLA steels and carbon steels have been widely reported.

The enhancement of properties in ferrite/martensite DP steels over the conventional HSLA steels and plain carbon steels is a function of composition, relative amount of each phase and other processing parameters. The effect of the above mentioned parameters on the behaviour of ferrite/martensite DP steels shall be discussed in detail subsequently.

1.2.History of Ferrite-Martensite Dual Phase Steels

In the 1950s and 60s, the major material for automotive applications was the High Strength Low Alloy (HSLA) Steels. Though they possess good mechanical properties, but their formability and ductility were not good enough for the production of press-formed car components. The advent and development of DP steels provided solution to this problem [24,25,26,27].

Despite some patents and studies mentioning the utilization of steels with two phases in the 1930s and 40s, detailed and more fundamental study on DP steels did not commence until 20 years later [24]. They used ferrite-martensite strip in their study as a substitute for rephosphorized grades for use in tinplate applications.

Two relevant breakthroughs were recorded in the 1970s on the development of dual phase steels: a relationship between the martensite volume fraction (MVF) and strength was established, and discussion on the properties of ferrite-martensite steels processed by continuous annealing was presented. It was at this juncture that such steels were first called “dual phase” steels [24,26,27].

Dual phase products were first marketed in the USA at commercial level [1]. The product was vanadium contained low alloyed steel, plus an intercritical annealing heat treatment process commonly encountered in the 1970's. It exhibited tensile and yield strengths of 650MPa and 350MPa respectively with total elongation of over 27%. Dual phase steel was mainly used in reinforcements of bumper and some other parts of automotive such as passenger car wheels [24,26,27,28].

Today, DP steels have become one of the most versatile and preferred material in the automotive industry. They have presently substituted conventional HSLA steels in many structural applications. According to US Steel, reduction in weight, high resistance to fatigue failure, good crash energy absorbing capacity and improved formability are responsible for the substitution. Today's applications of dual phase include back panels, bumpers, door intrusion beams, crush cans, S-rails, rocker reinforcements, cross members, B/C pillar reinforcements, front and rear rails [29,30,31].
In referring to commercial grades of dual phase steels, a number is usually attached, which is an indication of the ultimate tensile strength of the material in mega pascal (MPa); e.g., DP600 is a DP steel with UTS of 600MPa. The most common and available DP steels are of the range between DP500 and DP1000, depending on the steel producer [32].

1.3 High Strength Steel (HSS)

Since the manufacture of the first car, materials used by the automotive industries have undergone tremendous improvements and innovations. Today’s automotive sector has utilized wild range of materials from ceramics to highly developed composites, metals as well as so many kind of polymers; contrary to the initial limitation to a combination of wood and plain carbon steel. On the contrary, wood which was the main material used for the frame and body structure of the first car is now limited to aesthetic decoration of the interior design of luxury cars.
In the history of automotive industry, steel is the most developed enhanced and transformed material. In order to enhance the properties of steel, a lot of research effort and time have been put into the study of combination of various alloying elements and heat treatment. Modification of steel for specific applications and optimization of conditions have been the focus of many researchers for over 200 years. However, since the last 35 – 45 years specifically, the development and transformation that have taken place in steel have given birth to what is today referred to as High Strength Steel (HSS). As the name implies, HSS are characterized by strength superior to that of normal plain carbon steels.
However, it is worthy of note that increasing strength of steel has a repercussion of decrease in ductility, which makes the material brittle and not suitable for many applications. Hence, compromise and optimization between ductility and strength results to a wide range of HSS as depicted in Fig. 1. These and other grades of steel, including other metals (e.g. aluminium) have presently been commonly deployed in the production of the body structure of cars. Specific body parts of car have been made with range of materials from low carbon steels to high carbon steels depending on the requirements – Fig. 2

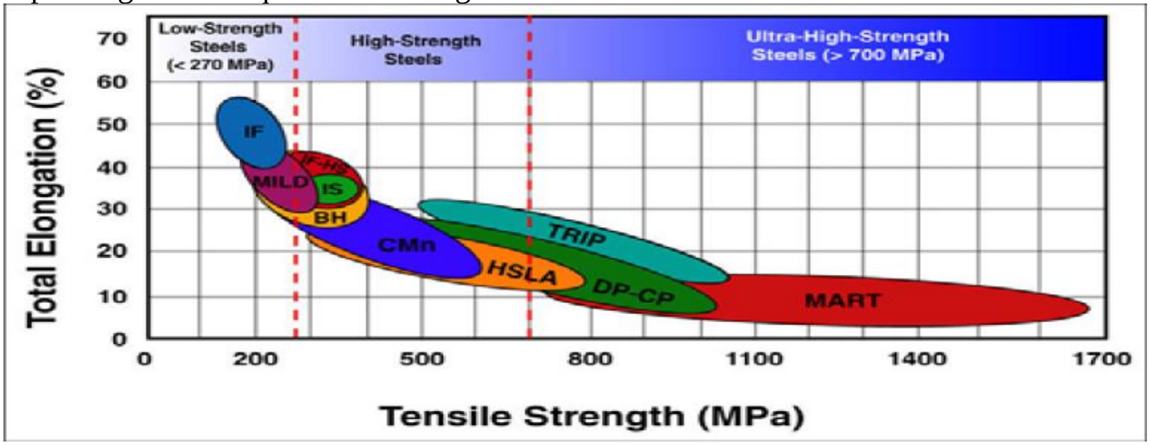


Fig. 1: Formability chart of steels types based on strength and elongation [33,34].

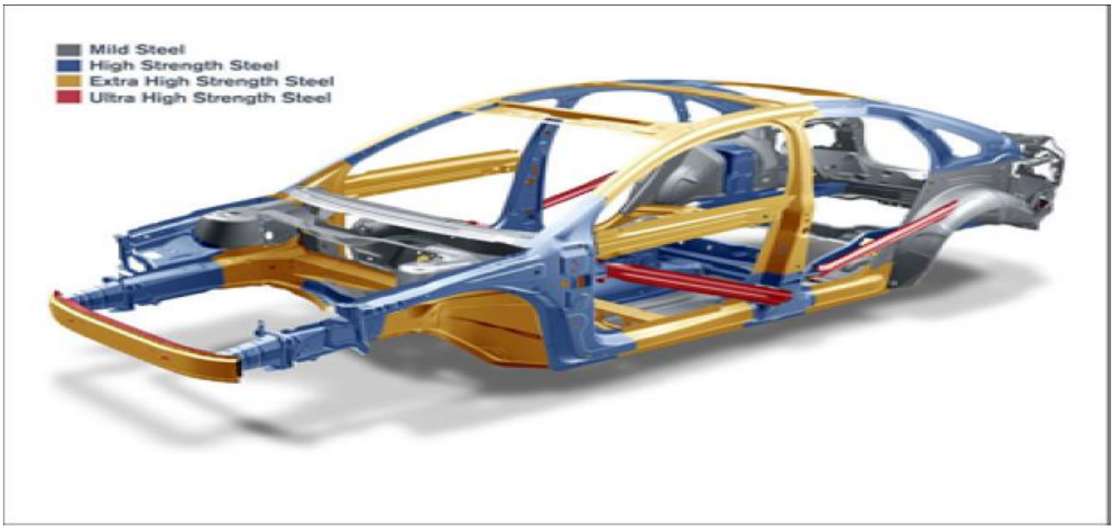


Fig. 2: Different types of steel in a typical frame of a modern automobile [33,34].

1.4 Microstructure and Properties of DP Steels

Generally, expansion in volume due to the transformation from austenite to martensite has been attributed to be the reason behind the continuous yielding, high rate of strain hardening and low elastic limit of DP steels [19,35,36]. Strains developed because of the transformation create residual stresses in the neighbouring ferrite [37,38]. It was observed that martensite accommodates larger proportion of the stress compared to ferrite which accommodates greater proportion of the deformation in the microstructure following stress approximately equal to 0.1 – 1MPa in ferrite compared to 1 – 4MPa in martensite [23].

Transmission electron microscopic study revealed that the change in volume causes the ferrite grains to be deformed plastically and as such produces high density of mobile dislocations in the surrounding martensite [1,39,40,41]. “In order to avoid decohesion at the ferrite/martensite (F/M) interfaces this expansion must be accommodated by microplastic deformation of the surrounding ferrite grains. This leads to the generation of mobile dislocations, i.e. there is an increased dislocation density next to F/M interfaces than inside the ferrite grains” [1,42]. “The dislocation density in the interior of ferrite grains is about 6·1012 m^{-2} and at the F/M interface about 30·1012 m^{-2}” [43]. The F/M DP mixture behaves as a composite with particle reinforcement. The rule of mixture as represented in eq. (1) can be used to estimate the composite’s tensile strength [33]:

$$\sigma_{DP} = V_M \sigma_M + V_F \sigma_F \qquad (1)$$

Where, σ = tensile strength, V = the volume fraction of phases presents in the microstructure DP = composite dual phase structure, M and F = martensite and ferrite phases respectively.

A lot of theoretical models have been propounded to describe the deformation characteristics of DP steels [44,45]. Majority of these models look at each phase present in the microstructure as a continuum, and assume that the mechanical properties of each phase does not depend on the other constituents of the microstructure. Again, most of these models assume that both ferrite and martensite deforms almost equally. Nevertheless, the outcome of many investigations revealed that there is inhomogeneity in deformation of dual phase steel, with ferrite accommodating most of the strain than martensite [33,46,47]. Ashby (1971) [48] and Ballinger and Gladman (1981) [46] proposed that pile-up of dislocations which do not deform uniformly to be the reason for high rate of work hardening in a typical dual phase steel. Furthermore, other versions of deformation models are of the assumption that both martensite and ferrite phases in dual phase steels are ductile, with equivalent strain in the two phases and obey the Ludwig relationship (Eq. 2) [49,50]:

$$\sigma = k.\phi^{\,n} \qquad (2)$$

Where φ = true strain, σ [MPa] = true stress, n = a work hardening coefficient and k [MPa] = the strength coefficient.

A simple parabolic function cannot approximate the stress-strain characteristics of DP steels over the entire strain range (i.e. DP steels have more than one n values), which is contrary to most steels [1]. Evaluation using constitutive equations has shown that the stress-strain graph of DP steel could be split up to three strain regions, describing each of them by a different n value or parabolic function [51]. Grain size and martensite volume fraction are some of the microstructural parameters that determines the number of stages or regions and the behaviour of stress-strain curve of DP steels [1]. The presence of more than a single stage suggests that work hardening behaviour at all strains cannot be explained by one work hardening mechanism.

Dual phase steels possess both moderate ductility and high tensile strengths, perfect for auto applications, e.g. wheel rims produced by cold pressing [52,53]. Apart from high strength, DP steels also show high bake hardening (BH) potential.

Some characteristics of DP steels are summarized as outlined below [54].

a) They show rapid initial and high work hardening rate.
b) They show no yield point elongation (YPE).
c) They have good formability because YPE is absent and higher work-hardening rate.
d) Spring-back can easily be controlled in DP steels than in the normal HSLA steels because of consistent behaviour during stamping.
e) They have very good ability to bend.
f) Strength: They have higher ultimate tensile strength, which ranges from 500 – 1200Mpa.
g) They have good shelf life (i.e. dual phase steels do not display aging at room temperature).
h) They have crash energy management because of higher yield to tensile ratio as compared to regular HSLA steel.
i) The fatigue performance of dual phase steel is superior to that of equivalent conventional high strength low alloy steel.
j) They exhibit good weldability and particularly they meet automotive application weldability needs.
k) They show high bake hardening potential.

2. Applications of Dual Phase Steels

The quest for cleaner environment and Economic reasons are the driving forces in the development of enhanced lightweight transportation systems; ranging from heavy duty haul trucks to cargo ships, automotive vehicles and even aircrafts [55,56]. Reduction in weight translates to decrease in fuel consumption and emission of gases from the exhaust. Utilization of steel components having lower thickness is a sure means of achieving reduction in the dead weight of car bodies. However, for safety reasons and structural integrity, mechanical properties must be maintained or improved upon. This can be actualized by the application of Ultra High Strength Steels (UHSS). The attractive synergistic effect between manufacturability and strength on the newly invented grades of UHSS has helped in the significant reduction in weight with little or no impact on cost ang structural integrity. DP steel is one of the most common grades [57,58].

As earlier highlighted, the major consumer of DP steel grade is the automotive sector. Depending on the customer by nature and at times the producer, DP steel grades are used to make various components of the automotive vehicle (car), which are presented in Table 1. According to SSAB, Tata Steel and Arcelor Mittal, who are major steel producers, demonstrated the use of DP steels in car structural components with the aid of Fig. 3. Nevertheless, dual phase steels are also gaining relevance in other sectors such as heavy construction units, farm equipment and machine building. Apart from the automotive sector, DP steels have also found application in the underlisted areas.

a. Train seats
b. Precision tubes
c. Pipes for conveying crude and petroleum products
d. Liquid Petroleum Gas (LPG) cylinders
e. Yellow goods (quarrying equipment, earth moving equipment, fork lift trucks and construction materials)

Table 1: Range of automotive components build from dual phase steels (from different Manufacturers) [24]

Producer	Component
General Motors	Wheel discs and rims, bumper reinforcements, face bars, jack posts, water pump pulleys, Steering coupling reinforcements
Hoesch-Estel	Wheel discs
Inland Steel	Plate brake backing (grinding), Panel for doors, deck (boot) lids, centre pillars, windshield frames, wheel houses
Jones and Laughlin	Bumper face bars, bumper reinforcements, rear suspension, wheels, alternator fan blades, steering column reinforcements
Kawasaki	Stylised wheel discs, door and hood panels and fenders
Nippon Steel	Bumper stay/facing door impact bars, frame sections
NKK	Outer and inner panels, door, beam and bumper reinforcements
Sumitomo Metal Industries Ltd	Outer body panels
Toksid Accial	Stylised wheel discs
US Steel	Parts in cars, trucks, buses, farm equipment, industrial handling units, heavy construction units

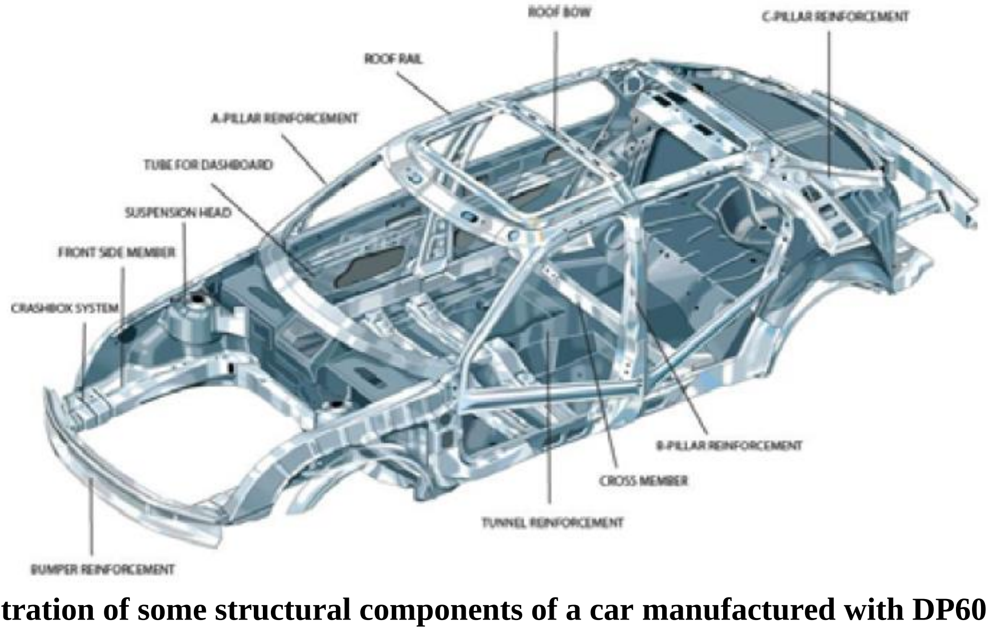
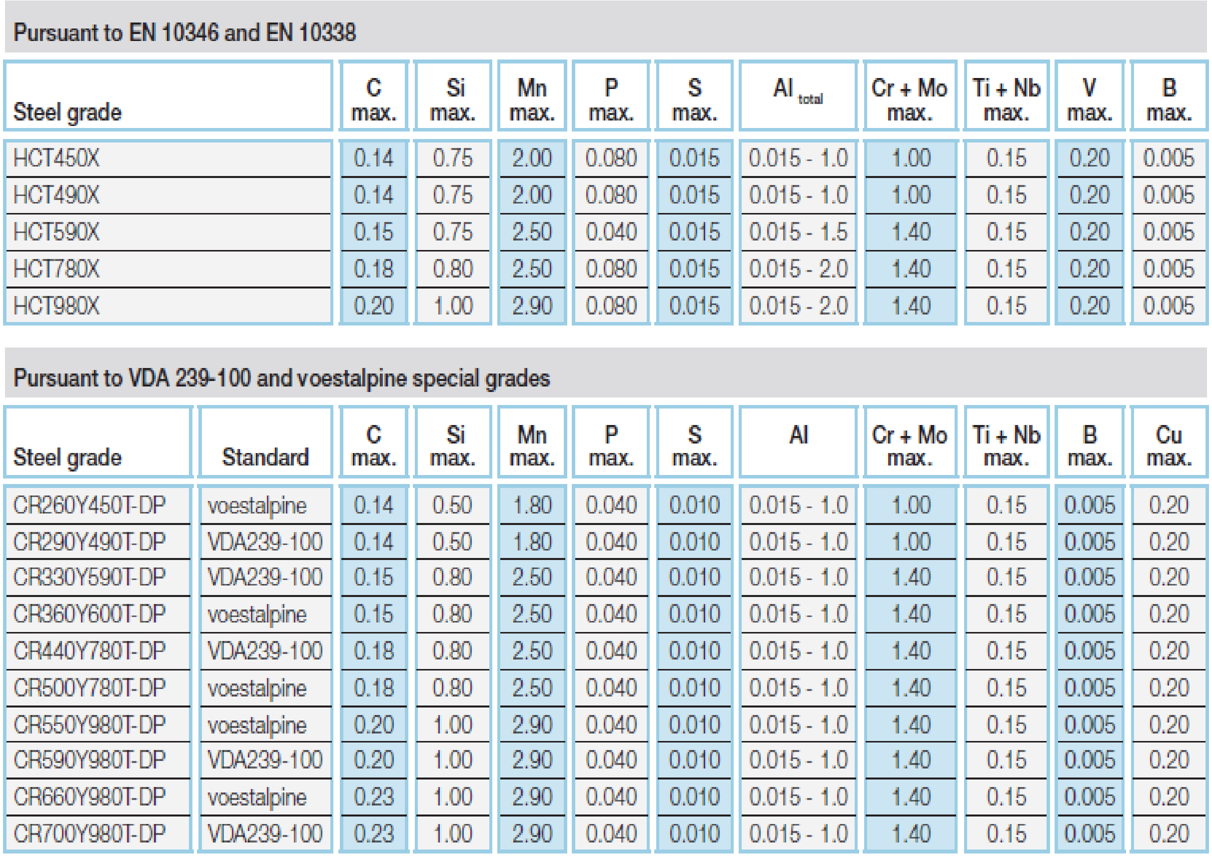


Fig. 3: Illustration of some structural components of a car manufactured with DP600 [59]

3. Dual Phase Steel and its Alloying Elements

Dual phase steels are of the low alloyed steels origin, with Si, Mn and C as the major alloying elements. Carbon shifts formation of bainite and martensite towards longer times [60]. It has the greatest influence on the hardness of the martensite in advance high strength steel. Manganese is a major austenite stabilizer. Mn increases the solubility of carbon in austenite [4] and lowers the pearlitic reaction, which permits cooling rates over a wide range. However, precipitation of carbide in austenite can be promoted by excess amount of Mn [61]. Si raises the temperature for eutectoid transformation because it is not an austenite stabilizer and therefore decreases carbon's activity in ferrite [5]. The solubility of Si in cementite is low; as a result, cementite can hardly be accommodated in a steel of high silicon content [62,63,64]. Nevertheless, high amount of Si tend to promote the formation of adherent oxides which are not easily removed from the surface during continuous annealing or rolling [65]. Mahieu *et al.* (2000) [66] reported that this effect can be attributed to the segregation of Si to the surface and the development of complex oxides of Mn-Si that resist wetting by the zinc bath. Phosphorus reduces carbide formation, thus allowing more C to be segregated to austenite in solution. Little amount of carbide was noticed to be present in steels alloyed with phosphorus compared to phosphorus-free alloyed steels [67]. Chromium delays formation of pearlite and bainite phase fields and effectively extends the austenite field [68]. Cr tends to increase strength, but reduces retention of austenite and ductility [65]. This could be advantageous in the production of advance high strength steel better ductility than dual phase material, but this may be at the expense of strengths which are not necessary. Mintz (2001) [69] noted that the influence of Cr on precipitation of carbide is like that of P, Al and Si, but galvanizing becomes poor when Cr content exceeds 0.5%. Chemical composition of conventional DP steel is shown in Table 2.

Table 2: Chemical Composition of Conventional DP Steels [70]



Pursuant to EN 10346 and EN 10338

Steel grade	C max.	Si max.	Mn max.	P max.	S max.	Al total	Cr + Mo max.	Ti + Nb max.	V max.	B max.
HCT450X	0.14	0.75	2.00	0.080	0.015	0.015 - 1.0	1.00	0.15	0.20	0.005
HCT490X	0.14	0.75	2.00	0.080	0.015	0.015 - 1.0	1.00	0.15	0.20	0.005
HCT590X	0.15	0.75	2.50	0.040	0.015	0.015 - 1.5	1.40	0.15	0.20	0.005
HCT780X	0.18	0.80	2.50	0.080	0.015	0.015 - 2.0	1.40	0.15	0.20	0.005
HCT980X	0.20	1.00	2.90	0.080	0.015	0.015 - 2.0	1.40	0.15	0.20	0.005

Pursuant to VDA 239-100 and voestalpine special grades

Steel grade	Standard	C max.	Si max.	Mn max.	P max.	S max.	Al	Cr + Mo max.	Ti + Nb max.	B max.	Cu max.
CR260Y450T-DP	voestalpine	0.14	0.50	1.80	0.040	0.010	0.015 - 1.0	1.00	0.15	0.005	0.20
CR290Y490T-DP	VDA239-100	0.14	0.50	1.80	0.040	0.010	0.015 - 1.0	1.00	0.15	0.005	0.20
CR330Y590T-DP	VDA239-100	0.15	0.80	2.50	0.040	0.010	0.015 - 1.0	1.40	0.15	0.005	0.20
CR360Y600T-DP	voestalpine	0.15	0.80	2.50	0.040	0.010	0.015 - 1.0	1.40	0.15	0.005	0.20
CR440Y780T-DP	VDA239-100	0.18	0.80	2.50	0.040	0.010	0.015 - 1.0	1.40	0.15	0.005	0.20
CR500Y780T-DP	voestalpine	0.18	0.80	2.50	0.040	0.010	0.015 - 1.0	1.40	0.15	0.005	0.20
CR550Y980T-DP	voestalpine	0.20	1.00	2.90	0.040	0.010	0.015 - 1.0	1.40	0.15	0.005	0.20
CR590Y980T-DP	VDA239-100	0.20	1.00	2.90	0.040	0.010	0.015 - 1.0	1.40	0.15	0.005	0.20
CR660Y980T-DP	voestalpine	0.23	1.00	2.90	0.040	0.010	0.015 - 1.0	1.40	0.15	0.005	0.20
CR700Y980T-DP	VDA239-100	0.23	1.00	2.90	0.040	0.010	0.015 - 1.0	1.40	0.15	0.005	0.20

4. Martensite in Dual Phase Steels

The amount and morphology of martensite in DP steels have much influence on its properties. Consequently, the influence MVF as a hard phase in DP steels has been studied by many researchers [47,52,71,72]. The growth of the martensite volume fraction leads to higher tensile and impact strengths of DP steels. In the words of Bag *et al* (1999) [73] and Tavares *et al* (1999) [74], this effect could only be observed up to martensite volume fraction of about 55%. Above this martensite volume fraction values, they reported decrease in strengths which they attributed to reduced concentration of carbon in martensite. Majid (2010) [75] reported that equal amount of martensite and ferrite in dual phase steels has outstanding mechanical properties. However, Smallman (1995) [76] and Rashid (1980) [26] observed an optimum combination of ductility and strength at martensite volume fraction between 10 to 20%. Almost all the researchers aligned to the fact that martensite volume fraction has a direct relationship with temperature.

Formation of martensite can occur at temperatures that even the diffusion of interstitial atoms are not expected over the duration of the experiment. Generally, in steels the transformation of martensite is taken to be a function of time. It is a thermal process, which begins at a temperature, M_S (i.e. martensite-start) and continues upon cooling at temperature lower than this (M_S). In steels, kinetics of martensite transformation is controlled by nucleation as growth rate of martensite is extremely rapid [77].

Martensite is of two types: plate and lath. Lath martensite is usually associated with steels of lower carbon concentrations (≤ 0.5 wt. %) [78]. In laths, their structure units are usually demarcated by low angle boundaries, grouped into packets. Generally, lath type of martensite is in dual phase steels. Several dislocation cells make up each martensite lath with an average width of 2500 Å [79]. Dislocation densities are approximated to be 0.3 to 0.9·1012 cm^{-2} [80]. The substructure has superficial resemblance with that developed by heavy cold in work [81]. Plate martensite is a property associated with steels of very high carbon contents (> 1.3 wt. %) [82]. The structure is composed of units of lenticular plate martensite, each comprising of fine twins with a separation distance of about 5 nm [83]. These twins slowly aggregate into well-ordered arrangement of dislocations close to the plate's periphery. For steels of carbon content between 0.5 and 0.8 wt. %, their microstructure is complex, with plate and lath martensite coexisting with non-transformed residual austenite [84].

Martensite undergoes structural transformation even at very low temperatures because it is a metastable structure. Over the years, tempering has been used to describe the process of heating martensitic steels to elevated temperatures in order to improve their ductility. Ageing on the other hand is used to describe the process that takes place at room temperature during martensitic storage. For over 60 years, a lot of intensive investigation has been conducted on the behaviour of iron-carbon martensite on tempering and ageing, and their literatures are well and widely documented [85,86,87,88,89]. Research has revealed that the processes of decomposition have several overlapping phenomena that are complex. Composition, heating rate and structural details determine the temperature range at which they occur. They are summarized as follows [90,91,92]:

a) Between 115 and 215 K, part of the retained austenite is transformed into martensite.
b) Near and slightly above room temperature, redistribution of Carbon atoms occurs as follows:
i) Carbon atoms segregate to lattice defects.
ii) Carbon atoms migrate to c octahedral interstices from a/b octahedral interstices.
iii) Formation of C enrichments in the matrix for the predominant part of the C atoms.
c) Transition carbides are precipitated between 355 and 455 K as the first stage of tempering.
d) Retained austenite decomposes into ferrite and cementite between 475 and 525 K as the second stage of tempering.
e) Between temperature range of 525 and 625 K, the third stage of tempering occur with precipitation of the stable carbide, cementite.

f) Within the temperature range of 600 to 900k, grain growth, cementite sphereoidization and recovery of dislocation substructure takes place.

5. Processing Parameters that Affect Properties of Dual Phase Steels

5.1 Cooling Rate

The rate of cooling to the bainite, martensite or ferrite formation region from the intercritical area has strong effects on the final properties of the steel. Sakuma *et al* (1991) [93] observed that higher values of total elongation and yield strength in bainitic steels are obtained by increasing rate of cooling, although increasing to the highest rates (≥ 100 K/s) reduces these values steadily. Minote *et al* (1996) [94] in their studies reported that high volume fraction of epitaxial ferrite produced in TRIP steels at a slow rate of cooling (≈3 K/s) is higher than faster rates of cooling. This resulted to stronger partitioning of carbon to the austenite which is advantageous to mechanical properties.

Speer and Matlock (2002) [6] in their investigation, clearly highlighted the effect rate of cooling could have on epitaxial ferrite formation in dual phase steels. At about 1000 K/s quenching, formation of epitaxial ferrite may be little. At 12 K/s, most of the austenite formed during intercritical annealing is lost to epitaxial ferrite, resulting to very low martensite volume fraction. Sakuma et al (1991) [93] observed that cooling rates between 20 and 60 K/s has almost negligible effect in bainitic steels. However, at 80 K/s, they observed that uniform elongation reduced slightly. No explanation was offered by them on the mechanism that produced this result, but loss of C rejection from epitaxial ferrite could be responsible for this.

5.2 Microalloying Elements

Carbon is the principal alloying element that controls the phase transformations, final microstructure and mechanical properties of DP steels; it equally aids the stability of austenite which upon cooling results to martensite formation [95]. Apart from carbon, other constituent elements of DP steel also play vital roles in the process. For example silicon promotes ferrite formation. Mn enhances formation of martensite by retarding bainite and pearlite development when cooling from the intercritical temperature. In addition, aluminium and/or phosphorus (in some cases with chromium) may be substituted for silicon to prevent difficulties during coating and hot rolling. Again, vanadium and niobium are added to inhibit grain growth leading to effective strengthening. Boron, molybdenum, and titanium are also present in smaller percentage. Proper mix of these elements, play pivotal role in having adequate and effective control of specific annealing parameter(s) and obtaining various strength requirements [24,27,95,96]. Additionally, limitation of martensite fraction and restriction of carbon concentration in martensite phase helps to maintain high ductility in dual phase steels. Lath martensite forms at lower carbon contents (<0.4wt %), compared to twinned martensite associated with high carbon content. Deformation of lath martensite to a limited degree makes it desirable because this delays formation of void at ferrite/martensite interfaces when the material is subjected to strain [24]. In the as rolled condition, tensile strengths between 550 – 650MPa is typical of dual phase with the above composition, with approximately 15% martensite volume fraction. This strength is as a result of grain refinement and carbon concentration [52,97,98,99]. Ti, Nb or V as microalloying elements can also be included in the production of dual phase [39,100]. Addition of little quantity of them retards recrystallization [101]. Cuddy (1982) studied the effect of microalloying elements on recrystallization behaviour of a 0.07 C - 1.40 Mn - 0.25 Si (wt. %) steel and noted that Nb acts more effectively to raise recrystallization temperature. Again, at higher temperatures, recrystallization is impeded with little additions of Niobium. Multi-pass deformation was used by Cuddy in his investigation with a total reduction of about $\phi = 0.5$. In [102], "the temperature during reheating the slabs is chosen in a way that the microalloying elements are in solution. For rolling, the temperature is reduced, so niobium forms carbides, nitrides and/or carbo-nitrides which effectively slow down recovery and recrystallization leading to finer austenite grains". Numerous ferrite nucleation sites are provided by highly work hardened austenite during the subsequent transformation which gives very fine ferrite grains.

5.3 Temperature, Deformation and Strain Rate

Alaneme *etal* (2010) [2], observed that the best combination of tensile and fatigue properties were noticed at 760°C and 780°C than 740°C. They attributed this improvement in properties to increased martensite volume fraction. Majid (2010) [75] reported that equal amount of ferrite and martensite in DP steels have outstanding mechanical properties. He also observed that martensite volume fraction increased as a function of temperature. Many researchers were of the view that optimum intercritical annealing temperature lies between 760°C and 790°C depending on the steel's composition. Calcagnotto *et al* (2008) [103] examined the effect of large strain warm deformation on the microstructure of dual phase steels. The researchers noticed that the developed microstructure comprised of islands of martensite dispersed in an ultrafine grained polygonal ferrite matrix. Average grain size of 1-2 μm was obtained. Improved strain hardenability was observed by introducing martensite as a second phase. Little amounts of retained austenite could further enhance strain hardenability. Little quantities of retained austenite (< 1 μm) were finely dispersed. The results obtained by other researchers were in alignment [104]. Hanzaki et al. (1995a, 1995b, 1997) [105,106,107] analysed the impact of different thermo-mechanical complex phase routes on the final characteristic of the developed TRIP steels. This class of steels were processed by deforming to various degrees after soaking in austenite region, followed by intercritical annealing and cooled to room temperature after constant temperature bainitic transformation. The high temperature deformation was done in one step with $\varphi = 0.3$ or a double reduction with two passes, each at the same strain rate of 0.3. This led to the development of materials with different sizes of austenite, the higher the degree of deformation, the finer the austenite grain size.

Hanzaki *et al* (1997) [107] examined the influence of the deformation finishing temperature on the mechanical properties of TRIP steels. The deformation temperatures of the steels were 1000 °C and 1050 °C. They reported that the steel displayed a slight increase in ductility and reduced strength at 1050 °C. The same group of researchers [105] varied the strain rate (ϕ) to obtain both, dynamically and statically recrystallized samples. Two different temperatures (1000 and 1050 °C) were selected for deformation of and the second of the double hit analysis were conducted at $\phi = 0.1\ s^{-1}$ (still static recrystallization, SRX) and at $\phi = 0.001\ s^{-1}$, resulting in dynamic recrystallization (DRX). The lower deformation temperature produced a lower fraction of retained austenite for both strain rates. The amount of retained austenite was the same for both strain rates at 1050 °C, and the dynamic process gave slightly higher fraction of retained austenite at 1000 °C. They proposed that the dynamically recrystallized dislocation substructure will be of higher capacity for austenite retention, without giving an argument. Reduced magnitude of precipitation could be responsible. From the forgoing, it is obvious that temperature, deformation and strain rate has influence on microstructure, which imparts on the mechanical properties of high strength steels which DP steels belong.

6.Conclusion

A comprehensive review of the applications, properties and processing parameters of DP steels has been attempted in this presentation. It has been shown that DP steels have their origin from HSLA steels. The automotive industry was identified as the major consumer of DP steels, before its application was extended to other areas such as precision tubes, pipes for transporting crude products etc. The microstructure of DP steels consists of either ferrite – martensite, ferrite – austenite or ferrite – bainite. Though mention was of steels with two phases in the 1930s and 40s, fundamental and detailed studies did not commence until about 20 years later. However, breakthroughs were only recorded in the 1970s and since then DP steels have passed through several transformations, innovations and developments. This review has also revealed that the synergy, compromise and optimisation between the soft ferrite (matrix) phase and the hard martensite or bainite phase imparts on it special property of high strength, good ductility and hardness resulting to material having excellent toughness. Cooling rate, alloying elements, temperature, deformation and strain rate were identified to be the processing parameters that can affect the properties of DP steels. It can be concluded that economic reasons and the quest for safer and sustainable environment were the driving forces that led to the development of this class of high strength steel – DP steels.

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