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Behind the Development of Advanced High Strength Steel (AHSS) Including Stainless Steel for Automotive and Structural Applications - An Overview

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Abstract Safety is paramount importance along with enhancing fuel efficiency of the transport car over the last three decades. Advanced high strength steels play a pivotal role towards achieving the desired structural characteristics of the motor vehicles. Many structural components have been replaced by advanced high strength steels like IF steel, Bake hardening steel, HSLA steel, Micro alloyed steel, Dual Phase steel, Ferrite Bainite steel, Martensitic steel, Hot formed steel, TRIP steel, TWIP steel etc. along with austenitic and ferrite grade stainless steels due to its superior strength and ductility. In the current context it has been attempted to see the causes behind the development of those mentioned steels from conventional to third generation as well the strengthening mechanisms employed towards the development of advanced high strength structural steels. It has been observed from literature study that substantial development have been progressed from metallurgical point of view in this matter over the last decade.

Keywords: *advanced high strength steel, automotive, strengthening mechanism, stainless steels*

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1. Background towards Development of Advanced High Strength Steel (AHSS) Including Stainless Steel

Modern Automotive market demand improvement of fuel efficiency and simultaneously reduction of green house gas emission by lowering the vehicle weight due to the stringent requirement of reducing green house gas emission throughout the world [1]. In recent years the function require in automobile industry is diverse. In addition to comfort, high fuel efficiency, emission control and safety are also important part to make a vehicle. These goals are possible to achieve by lowering the vehicle kerb weight and simultaneously improving the crash worthiness behavior of body parts of the automobile [2]. As a result development of more reliable advanced high strength steels are required to manufacture for body parts of vehicle. Over the last three decades aluminum and magnesium grade steels and conventional high strength steel use for passenger safety in the vehicle. Reliability of automotive parts can be enhanced by using advanced high strength steel (AHSS). Characteristics of this steel are good formability and toughness. Broadly dual phase steel, transformation induced plasticity steel, complex phase steel and martensitic steel are under AHSS. The advanced high strength steel generally have yield strength greater than 300 MPa and ultimate tensile strength will be greater than 600 MPa [3]. By applying AHSS merely 203 kg, 25 percent weight of the vehicle can be reduced by using thinner high tensile and formable steel as reported in ULSAB study [4]. The terms "High-Strength" and "Advanced High-Strength" steels are differ in the sense that AHSS steel is more superior in terms of mechanical characteristics than HSS (Interstitial free steel, Bake hardened steel, high strength low alloy steel). When tensile strength exceeds 780 MPa called "Ultra High Strength Steel" [5].

Over the last four decades metallurgists are trying to develop advanced high strength and ductility steels for transport and structural purposes. Some parts of the sports cars are frequently made by aluminum and magnesium like low density materials. Normal stainless steel exhibit tensile properties approximately 327 MPa yield strength, high strength steel like S420MC grade shows 440 MPa 0.2% offset yield strength, TRIP700 steel yield strength is 495 MPa and advanced high strength steel like DP1000 (Dual Phase steel) have 922 MPa, MS1200 (martensitic steel) have 1238 MPa yield strength properties respectively [6]. More advanced high strength contain steels are desperately use in many automotive parts to further reduce the weight of the vehicle [7]. TWIP (Twining Induced Plasticity Steel) steel is common example of advanced high strength steel which have good combination of tensile strength and ductility due to presence of austenite with twins microstructure [8]. It is under second generation advanced high strength steel [9]. Modern trend is to develop better high strength and ductility third generation steel which will be less costly than second generation high strength steel like TWIP [10]. Quench and partitioning thermomechanical treatments are recent techniques to develop third generation advanced high strength steel by grain refinement with precipitation hardening [11,12,13]. Ultra grain refinement exhibit advanced high strength steel structure properties like superior strength [14], good low temperature toughness [15] and high stretch formability [16]. These nano-crystalline structures produce grains lower than 100 nm [17]. It is targeted by the researchers to develop more ultra fine grains structure by thermomechanical treatments to get superior strength properties in the future advanced structural grade steels. In the strategic research agenda of European Steel Technology Platform (ESTEP) it was stated that advanced high strength steel with moderate ductility have to be developed within the year 2030 including austenitic stainless steel for future generation light weight and safe vehicle by thermomechanical treatments instead of incorporating costly alloying elements [18]. Gradually global demand CO_2 emission reduction more high strength and ductile chassis and body in white (BIW) structure is required for automotive purpose which has developed a big market for austenitic grade steel to manufacture transport vehicle along with many structural components of automotive body [19]. Recent market is moving towards sustainability and reduction of green house gases and less emission of other noxious gases by using stainless steel made public transport like rail or metro rail rather than extensive use of automotive vehicles due to its safety, less maintenance and consistently generating a green pollution free environment in the nature [20]. Along with good corrosion resistance of stainless steels (Austenitic and duplex stainless steel), it shows excellent toughness (25.9 – 38.0 J/g) as compared to other high strength steel like HSLA steel (12.5 J/g) and simultaneously produce good formability and fatigue properties which are essential for crashworthiness purposes for car safety applications [21]. So recent trend is to develop advanced high strength future generation structural stainless steel along with other grades of steels by decreasing alloying element by purposefully incorporating nitrogen content in the austenitic grade steel as well changing the microstructure by applying advanced thermomechanical treatments.

2. Role of Various Strengthening Mechanisms towards Development of Advanced High Strength Structural Steels (AHSS)

European commission of steel platform has set target to develop high strength with moderate ductility steel within the year 2030. According to commission high strength and moderate ductile steel have to be developed for automobile industry. Not only that high strength austenitic stainless have to be developed for structural and rail coach manufacturing purpose for better safe life of human being. In this regard it is essential to know various strengthening mechanisms to better understand the physics behind development of superior strength and elongation advanced high strength steel (AHSS).

Grain Boundary Strengthening by Generation of Ultra Fine Grains Structure: - Generation of ultra fine grain is a popular method to develop high strength steel. Not only grain refinement the increasing misorientation angle across grain boundaries increases the yield strength of the material [22]. A normal relation between grain size and yield strength proposed by Hall-Petch is as follows:-

$$\sigma_0 = \sigma_i + k(d)^{-\frac{1}{2}}$$

σ_0 – Yield Strength of Fine grain Material
σ_i – Friction Stress of the material or Initial yield Strength
k – Locking parameter due to hardening from grain boundary
d – Grain diameter (mm).

Hall Petch behavior has been explained by various models like pile up model, dislocation density model and composite model [23]. The basic thinking of pile up model is to consider the concentration of huge number dislocations along the grain boundaries causing retardation of dislocation movement and enhancement of yield strength property of the steel.

Dislocation Strengthening by Severe Plastic Deformation Particularly for Austenitic Grade Stainless Steels: - The yield strength of austenitic stainless steel can be drastically improved by generation of plasticity and metastable phase transformation introducing severe plastic deformation [24]. Austenitic steel generally posses' high ductility with low yield strength and has very good strain hardening property due to its low stacking fault energy. Due to low stacking fault energy the dislocation dissociated to two Shockley partial dislocations which require stress to collide those partial dislocations before movement of united perfect dislocation through slip plane which causes high strain hardening rate of this type of steel. Strain induced hardening is achieved due to obstacles of movement to large number of dislocations and interaction of dislocations with martensite phase which generate during severe plastic deformation. Stacking fault energy (SFE) dictate formation of shear bands which ultimately act as a nucleation site for formation of α' martensite. Plastic deformation not only develop high hard martensitic phase but simultaneously improve the yield strength due to formation of twins, shear bands, dislocations and Suzuki locking. The cold work metal contain more dislocations (approximately 10^{10} mm^2) as compare to annealed steel (contain in the range of 10^4 to 10^6 per mm2) [22].

Strengthening by Incorporating Solute Atoms Inside the Base Metal: - Solid solution strengthening is an important tool for developing high strength metals by additions of interstitial and substitutional impurity atoms inside base metals. Large or Small size impurity atom goes to interstitial position or substitute pure atom cause lattice strain within the metal and hinder dislocation movement which exhibit high strength of alloy metal as observed from Figure 1 (a) and Figure 1 (b).

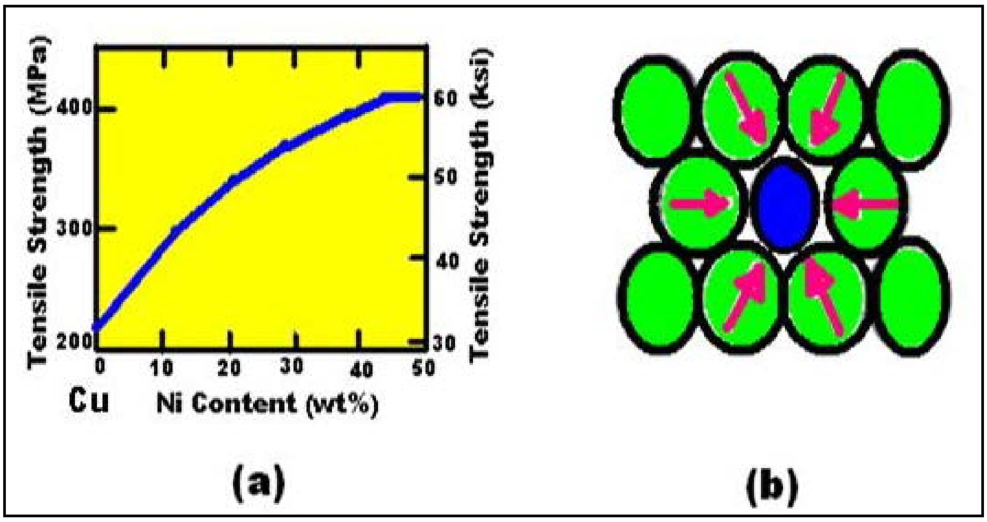

Figure 1. (a) Changes of Tensile Strength with increasing Ni content in the Copper- Nickel Alloy (b) Schematic diagram of generation of Lattice strain with incorporation of small substitutional element within the metal (Reprinted from [25])

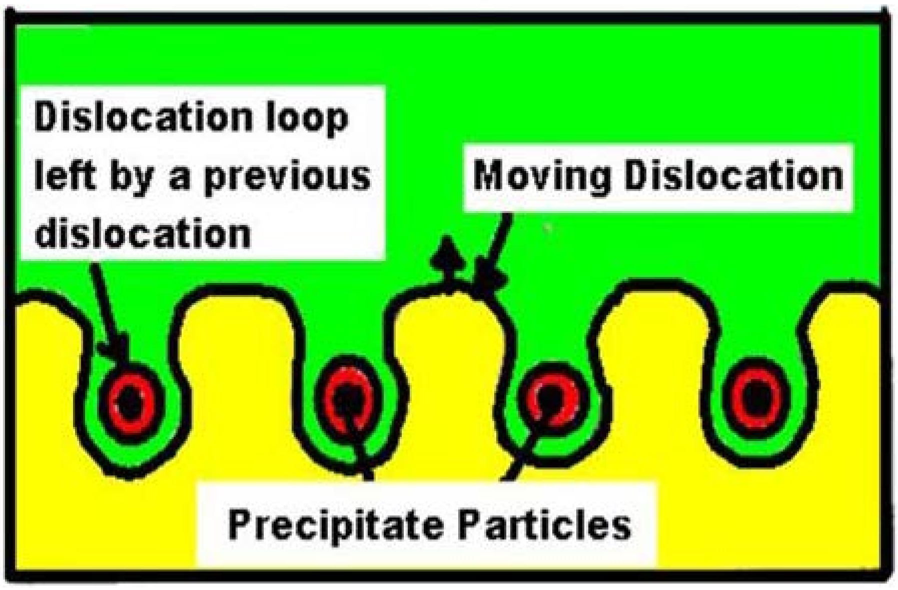

Figure 2. Orowan mechanism of strengthening the metal matrix from precipitates (Reprinted from [26])

Strengthening the Metal by Strain Ageing Treatments:- Bake hardening is a typical static strain ageing treatment which is generally applied to improve the tensile properties of all types of steels. Typically below 200^{0}C temperature with sufficient time heating are applied to cold work stainless, dual phase, transformation induced plasticity steel to improve the yield strength as high as maximum 200 MPa [24]. Strain aging increase the yield strength and simultaneously decrease the ductility also and nitrogen plays a pivotal role in static strain aging due to its higher solubility and diffusion coefficient as mentioned in the literature [22]. Yield point phenomena observed for static strain ageing and dynamic strain ageing produce serrated stress strain curve and sometimes generation of twins and stress assisted martensite also produced that behavior of mechanical properties of steel.

Precipitation hardening of Steel: - Very fine second phase particles precipitation on the base metal matrix improve the mechanical properties of steel. Precipitation of cementite particles from ferrite occurs during ageing treatments by nucleation and growth process [26]. Precipitation and dispersion strengthening mechanism has been studied by researchers and it is observed that Orowan dislocation bypassing mechanism (shown in Figure 2) play a pivotal role in this regard [27].

Recovery, Recrystalization, Grain Growth and Annealing mostly apply to strengthen austenitic grade stainless steels:- After cold working of austenitic grade stainless steel when subjected to annealed elevated temperature (above 0.5Tm) is undergone recovery (relieve of internal stress without application of any external pressure due to dislocation motion) for short time annealing, followed by recrystalization (generation of new equal size strain free grains) for certain period of annealing treatments and finally grain growth (formation of large size grains from new strain free grains) for long period of annealing at elevated temperatures [25,28,29,30].

3. Development of Conventional High Strength Steels

Sheet steel technology has long history for development. In response to reduction of CO_2 emissions and simultaneously improving the rigidity of the vehicle several high strength steels have been used throughout the last two decades. Generally conventional steel used for structural application are mild steel, IF (interstitial free) steel, BH (bake hardened) steel and micro alloyed or HSLA (high strength low alloy) steel. But conventional steels have major disadvantages is its heavy weight which is the barrier for reduce fuel consumption [31].

IF (Interstitial Free) Steel: - This steel was first invented in Japan at the end of the year 1960 [32]. The Interstitial Free steel generally used for making rear floor pan, spare wheel well and front-rear door inners which is shown in Figure 3 [33]. But the biggest disadvantage of this steel is its low tensile strength less than 360 MPa [34]. Upto 450 MPa tensile strength improvement has been achieved for this steel by solid solution strengthening [35]. By addition of 1.2% Cu the yield strength and tensile strength value around 460 MPa and 575 MPa respectively achieved by precipitation hardening [36]. Ultra fine grain structure using equal-channel angular extrusion/pressing (ECAE/P) method and annealing were applied for this steel recently [37,38]. 708-900 MPa tensile properties with nearly 15%-10% ductility observed for this steel by this thermomechanical method [39,40]. Ultrafine grain structure by cold rolling and annealing with bake hardening together improves toughness and elongation of this steel [41,42,43].

Bake hardening Steel: - This steel mostly has ferrite microstructure. Denting problems in automotive outer body panels can be avoided by uses of Bake harden (BH) Steel. Due to lack of movement of dislocations by interstitial atoms bake harden steels after painting or static strain aging posse's very high strength with superior ductility and after bake hardening of a pre-strain cold rolled continuous annealed steel it is possible to improve the yield strength 10 – 54 MPa and work harden ability around 17-82 MPa depending on the panel location [44]. Normally bake hardening treatment is given to low carbon steel and IF steel. But now a days due to great formability of IF steel most panel is made by IF-BH steel.

High Strength Low Alloy Steel (HSLA):- This category of steel extensively used for making body parts, wheels, and ancillary parts, suspension and chassis components in vehicle application due to its yield strength greater than 275 MPa [45]. The HSLA steel first developed in the year 1960 [46]. Different types of HSLA steels are available in market like weathering steel, micro alloyed steel, as-rolled pearlitic steel, low carbon bainite steel, dual phase steel and inclusion shape controlled steel. Minimum yield strength approximately 550 MPa was achieved by precipitation hardening and ferrite grain refinement (less than 3 µm) [46,47]. To improve the properties of HSLA steel various alloying elements has been added like Nb, Ti, V and boron. 550 MPa yield strength and 20% elongation at room temperature was possible to get by TiN precipitates and increase percentage of fine bainite and generation of uniformly distribute metal carbides in the matrix [48,49].

Micro-alloyed Steels: - It is basically containing niobium, vanadium, titanium, zirconium and boron is used for discrete automotive parts like power train, suspension component systems due to its excellent strength and toughness by formation of fine grain size with carbo-nitrides precipitate in the ferrite matrix by thermomechanical treatements along with accelerated cooling process shows around 400-800 MPa yield strength and 500-1000 MPa ultimate tensile strength steel along with 23-26% elongation [50,51,52]. High strength microalloyed steels are extensively (around 60%) used to manufacture auto body [53]. In heavy duty truck wheel disc and wheel rims instead of conventional mild steel hot rolled microalloyed steel is extensively using to take the high compressive strength with safety as 90% 5µm polygonal ferrite and 10% pearlite formed with 570 MPa yield strength, 610 MPa tensile strength and 26% elongation [54]. Due to pinning effect Nb improves the tensile strength of this steel from 970 MPa to 1200 MPa but simultaneously lower the ductility nearly 4% [55]. Thermomechanical treatments with 1%-2% Cu addition enhance the tensile properties to 1364-1403 MPa with 11%-14% ductility [56,57].

4. 1st Generation Advanced High Strength Steels for Vehicle Components Manufacturing

In recent decade metallurgists are trying to develop more high strength with superior ductility steel than the conventional high strength steel known as advanced high strength steel (AHSS). The microstructure of this type of steel is multi phase and complex in nature. The percentage use of conventional high strength steel (HSS) and advanced high strength steel (AHSS) for the year 2007 and 2015 is shown in Figure 4 (a) as well as it is observed that the use of AHSS will increase for future steel vehicle depicted in Figure 4 (b). Generally all types of AHSS produce by changing the chemical composition of steel and advanced cooling treatment from austenite phase or austenite + ferrite phase.

Dual Phase Steel: - Dual phase steel consists of ferrite and martensite microstructure. This steel is extensively used to manufacture crumple zone to body structure of a vehicle, closures, hood, doors, front and rear rails, beams and cross members, rocker, sill, cowl inner and outer, crush cans, shock towers, fasteners and wheel also as the yield strength and ductility of this steel can be controlled in a broad range by controlling hot coiling and bake hardening temperature [5]. In recent years most of the automotive parts are replaced by dual phase steel rather than use of conventional HSLA steel. Dual phase steels have typical yield strength and tensile strength value ranging from 210 MPa-1150 MPa and 440-1270 MPa with elongation nearly 35% -10% for DP 210/440 grade to DP 1150/1270 grade respectively [58,59]. Ultra high strength (750-1300 MPa tensile strength with 25-10% elongation) dual phase steels were produced by thermomechanical treatments like cold rolling or warm rolling and intercritical annealing treatments [60-66]. By cold rolling and intercritical annealing advanced high strength (780 MPa – 1600 MPa with ductility in the range of 22% - 13%) dual phase steel were developed by researchers [67-73]. Recent decade commercial simulation software help to develop safe high strength dual phase steel [74].

Figure 3. Inner door body panel for automobile from IF steel (Reprinted from [33])

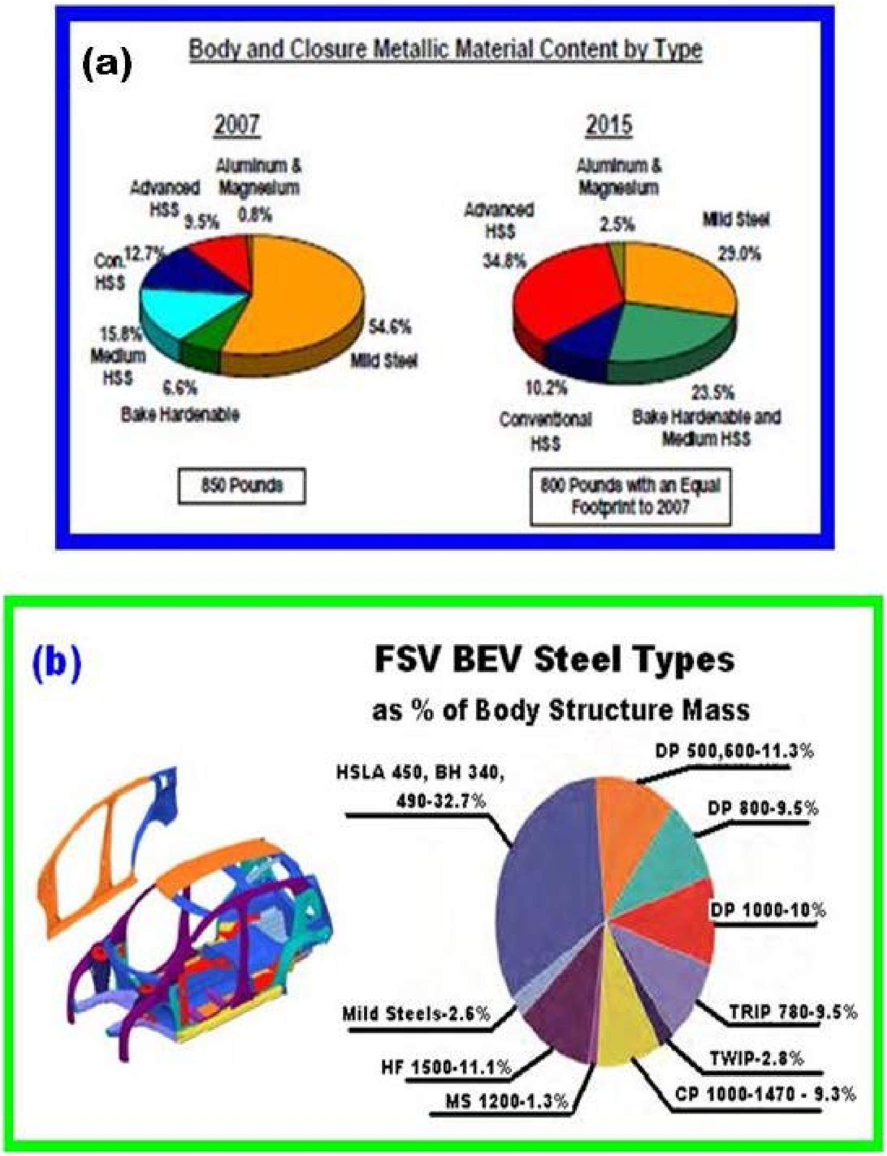

Figure 4. (a) Comparison of HSS and AHSS from past and present (b) Future Steel vehicle (FSV) & Battery Electric Vehicle (BEV) (Reprinted from [58])

TRIP (Transformation Induced Plasticity) Steel: - Development of advanced high strength steel is a challenge for automotive industry for making fuel efficient, less emission and safe vehicle for passengers over the past decade or so. It has been targeted by metallurgical researchers to develop more complex microstructure steel with superior performance in terms of strength and ductility. The commercially developed dual phase steel usually consists of ferrite and martensite microstructure which has been discussed earlier and on the other hand TRIP steel shows a ferrite-bainite-retained austenite and martensite microstructure. Due to presence of high amount C and Si, 70% polygonal ferrite with grain size in the range of 1.5-4 µm and nearly 20% retained austenite along with remaining bainite plus martensite mixture observed for this steel [75]. TRIP steel used for making frame rails, rail reinforcement, side rail, crash box, dash panel, roof rails, B-pillar upper, engine cradle, front and rear rails, seat frame, bumper cross member etc as depicted in the Figure 5 [76]. Lamellar austenite with bainitic ferrite structure improves the mechanical properties to UTS level 682 MPa and elongation 70% [77]. Intercritically treated at 630°C of this steel possess 800 MPa strength and 29% ductility [78]. TRIP steel was intercritically annealed at 600°C and 650°C which shows nearly 1200 MPa and 1400 MPa true stress with 0.3 and 0.1 true strains respectively [79]. High stretch-flangeability (UTS 980-1470 MPa and elongation 25-10%) automotive components like reinforcement, sheet frame were developed by NbC precipitation with TRIP effect [80]. A New TBF steel (TRIP steel with bainitic-ferritic matrix) shows high toughness value (100-120 J/cm^2) as well as low ductile-brittle transition temperature (range of -130°C to -150°C) and ultimate tensile strength of 1527 MPa, ductility 13.4% [81]. High strength (approximately 1000 MPa) with high elongation (nearly 40%) steel was produced by 36% cold rolled and intercritically annealed at 640°C for 1 hour [82]. By alloying Mo, Nb and Mn it has been possible to produce ultra high strength (1000 MPa-1400 MPa) and high ductility (35%-13%) of these steels [83,84]. Tramp elements improve ductility and simultaneously hydrogen absorption during white painting is a critical problem to crack initiation of this advanced high strength steel [85,86].

Complex Phase (CP) Steel: - The complex phase steel is a fine grain structure with mixture of martensite, retained austenite and pearlite within the ferrite-bainite matrix and applicable for manufacture of different automotive components like frame rails, chassis components, transverse beams, B-pillar, tunnel stiffener, rear suspension brackets, fender beam, rear frame rail reinforcements, rocker outer, rocker panels, bumper beams etc as its tensile strength within the range of 800-1470 MPa and elongation 15-5% which is higher than DP steel as embodied in Figure 6 [58,87].

Martensitic Steel (MS):- Martensitic steel is a great innovation of metallurgist which consists of small amount of ferrite-bainite mixture in fully martensitic matrix due to high cooling rate from quenching and posses extremely high strength in the range of 1200 MPa to 1500 MPa with elongation approximately 8%-5% which is mainly used for many automotive parts like cross-members, side intrusion beams, bumpers beams, bumpers reinforcements, rocker outer, side intrusion beams etc [58,88]. Auto tempering of the lath martensite is the cause of high strength of this steel [89,90].

Ferritic-Bainitic Steel: - Ferritic-Bainitic steel is a special case of application particularly for rim; brake pedal arm, seat cross member, suspension arm, lower control arm, bumper beam, chassis parts and rear twist beam etc as depicted in the Figure 7 [91,92]. Mo addition improves mechanical properties of this steel as it promotes more bainite formation which in the range of 1100 MPa-1200 MPa and 18-22% respectively whereas the base steel shows tensile strength in between 700-800 MPa and nearly 22% ductility [93]. Banitic hardening by nano scale (Nb,Ti)C precipitates produced by metallurgists for automotive wheel application [94]. Cold rolled and continuous annealing carbide free ferritic banitic steel is a new type of steel which shows a greater formability than the martensitic steel or dual phase steel with same ultimate tensile strength (in the range of 1200-1500 MPa) [95]. Cementite free optimum bainitic structure usually consist of upper bainitic-ferrite, carbon enriched retained austenite and some martensite with exceptionally high tensile strength (in the range of approximately 1600-1950 MPa) and total elongation over 10% obtained by FRT (finishing rolling temperature) at 930^{0}C followed by FCT (finishing coiling temperature) in between 550°C-650°C [96].

Figure 5. Typical application of TRIP steel for manufacturing B-Pillar reinforcement and Bumper cross member respectively (Reprinted from [76])

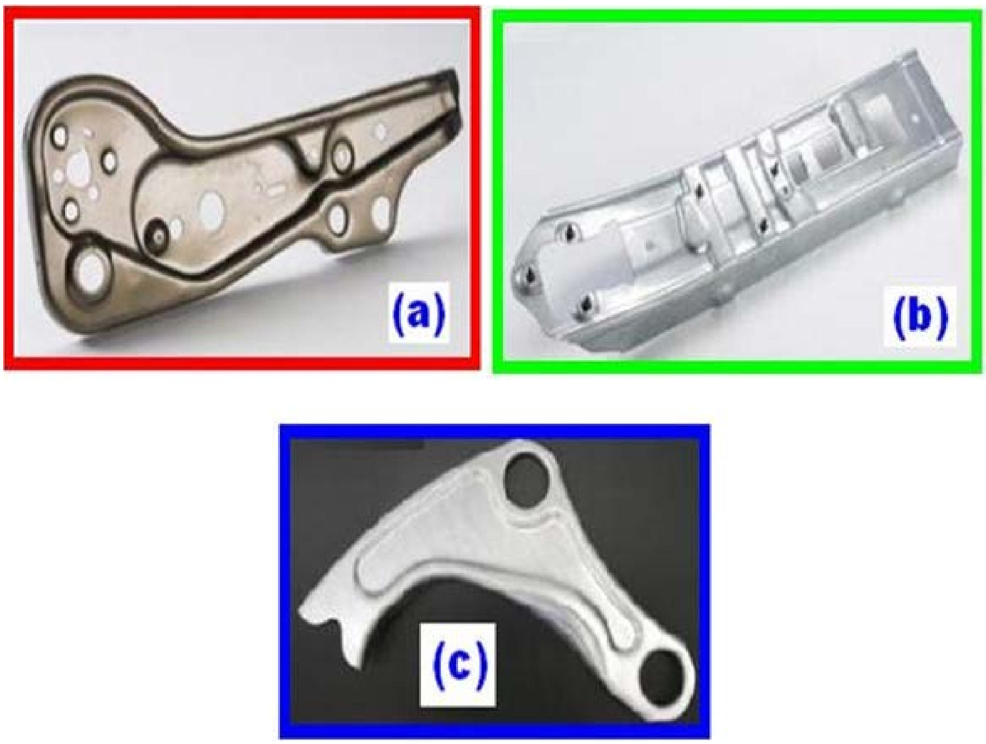

Figure 6. (a) Seat Flange, (b) tunnel stiffener and (c) suspension arm made by CP 600,800 Steel (Reprinted from [87])

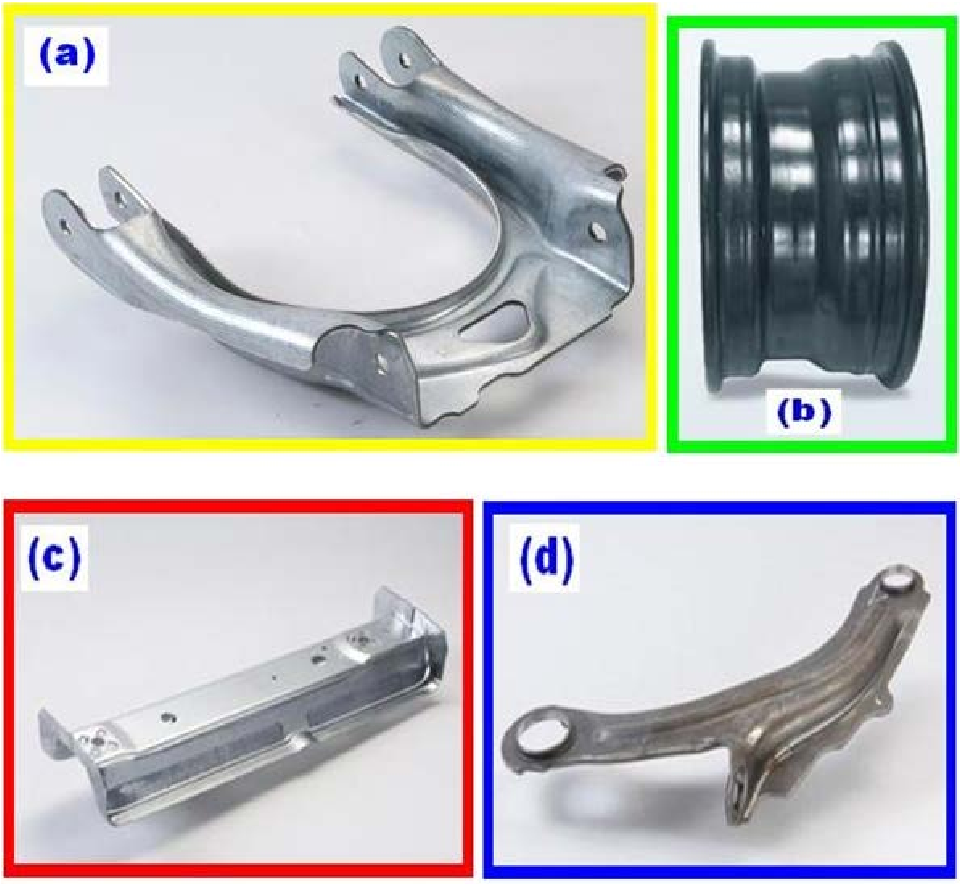

Figure 7. (a) FB 560 for suspension arm (b) FB 590 for wheel application (c) Front and rear under seat cross member made by FB 560 (d) FB 540 for uncoated suspension arm (Reprinted from [92])

Hot formed (HF) Steel: - This steel generally use for manufacturing automobiles structural and safety components due to its high tensile strength (approximately 1500 MPa) and ductility nearly 6% act as a high weight saving (30-50%) rather than use of conventional cold rolled grade [97]. Recently metallurgist are trying to develop advanced hot formed (AHF) steel for automobile crashworthiness purposes by dynamic carbon partitioning (DCP), flash copper precipitation and bake hardening method which exhibit a tensile strength approximately

1623 MPa with ductility around 13.7% and impact energy nearly 60-70 J [98,99,100].

5. Birth of 2nd Generation Advanced High Strength Steel (AHSS)

TWIP (Twin Induced Plasticity Steel):- This steel contain deformation twins in austenite matrix with ultimate tensile strength (in the range of 900 MPa – 1200 MPa), elongation within 20% – 50% due to soft phase austenite with twin boundary act like grain boundary and typically applicable for manufacture of A-pillar, wheelhouse, front side member, lower control arm, front and rear bumper beams, B-pillar, wheel rim, floor cross member, door impact beam etc of a vehicle [58]. The dislocations movements hinder from these deformed twins and low stacking fault this FCC alloy exhibit high tensile as well as ductile properties [101,102]. Nano grains TWIP steel shows approximately 1195-1330 MPa yield strength and formability in the range of 20.1-13.7% respectively mainly used for anti-intrusion auto body parts [103]. Different percentage cold reduction with annealing produce fine grain (nearly 8 µm – 10 µm grain size) TWIP steel exhibit tensile strength nearly 800 MPa and ductility close to 60% [104,105]. An extra ordinary high tensile strength (nearly 1702 MPa) with high ductility (approximately 24%) were observed for TWIP steel containing Ni and Cr with high Mn and Si (0.61C–22.3Mn–0.19Si–0.14Ni–0.27Cr) after deform severe plastically by Equal Channel Angular Pressing (ECAP) method by two passes at 300°C as well as 400°C (as received material shows closely 1000 MPa tensile strength and ductility above 120%) due to generation of deformation microbands (distance between two parallel microband is ≈260±37nm) and nano twins within the primary twins or micro twins in the ultra fine grains (0.3-0.6 µm as compare to 34 ± 21 µm austenite grains for as received material) as well as the formation of stacking faults (around 50µm in size) within the subgrains as embodied in the Figures 8 (a), (b) and (c) [106]. TWIP steel has enough ductility so it is extensively use for crash worthiness purpose for absorbing impact energy. The generation of twin is important with deformation temperatures. It was found that it produce maximum quantity of twin with deformation at room temperature rather than at high temperature (like 400^{0}C) and very low temperature like -150°C or cryogenic temperature (-196°C) and crash resistance super ductility TWIP steel has high value of specific absorption energy (0.5 j/mm^3) than the conventional deep drawing steel like IF steel, bake hardening steel, other thermomechanically treated steels due to formation of extensive twins at high strain rate [107]. Recently ferritic-austenitic duplex light weight steel exhibit high tensile strength (734 MPa) and high elongation around 77% for generation of deformation induced martensite and twins within austenite grains simultaneously [108].

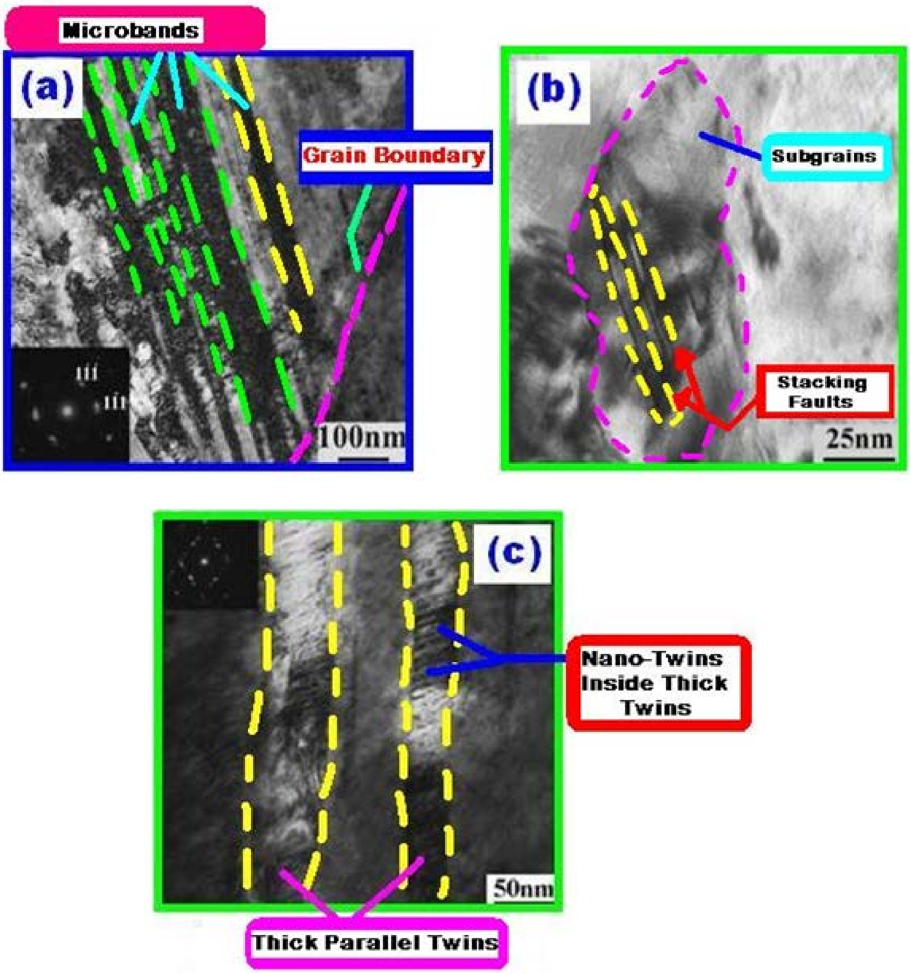

Figure 8. TEM Image of (a) Microbands (b) Stacking faults in Subgrain (c) Nano Twins within Thick Twins (Reprinted from [106])

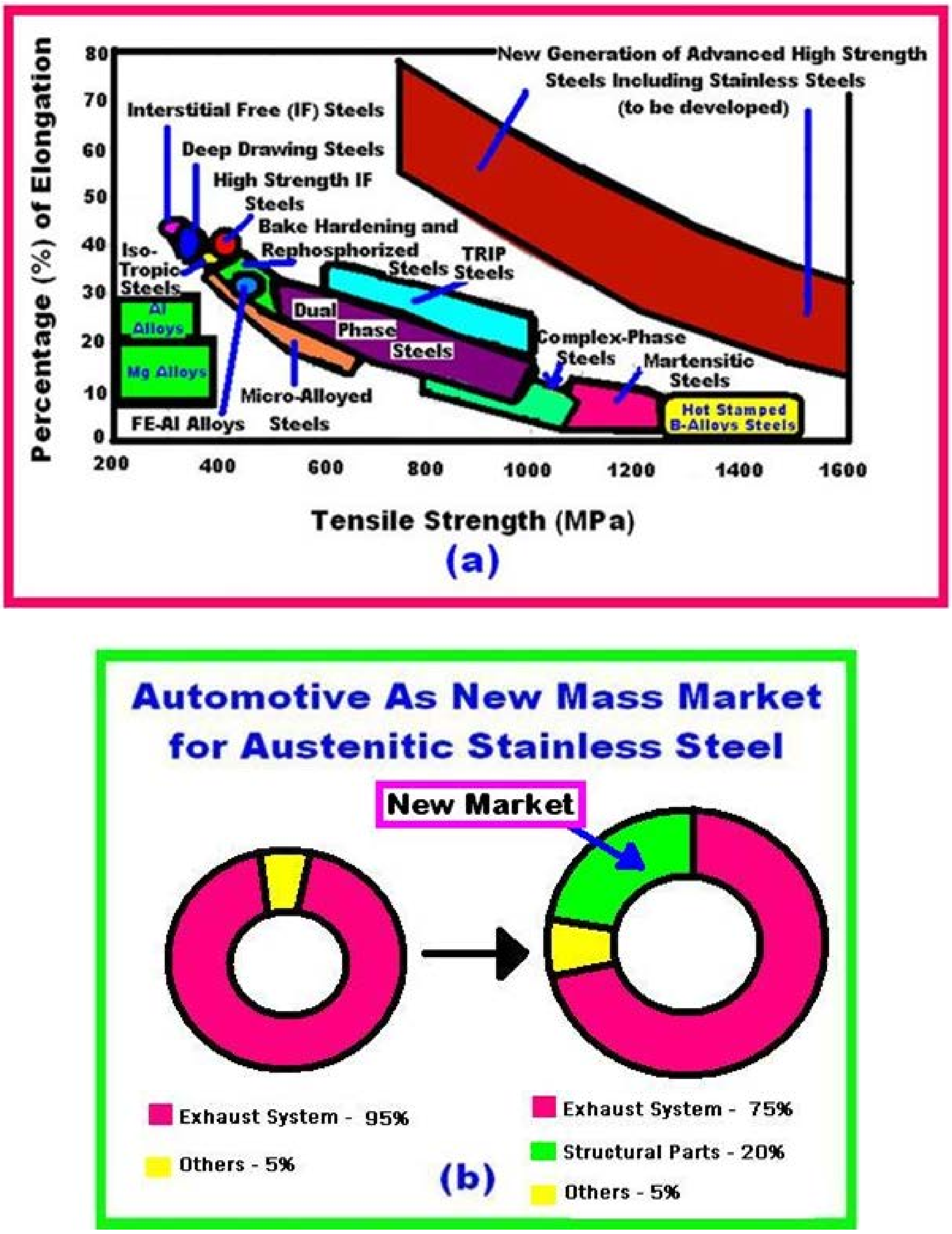

Figure 9. (a) The Red region of "Banana Curve" showing the strength and ductility required for Carbon Steel including stainless steel for future generation Automotive Purposes (Reprinted from [18]) (b) New Market for Austenitic Stainless Steel for Making Automobile Structural Parts (Reprinted from [19])

6. Towards Development of Future or 3rd Generation Advanced High Strength Steel (AHSS)

Third generation AHSS concept came from the research gap found to develop 1st generation AHSS and 2nd generation AHSS. The third generation steel consists of a mixture of martensite and austenite as austenite plays an important role in work hardening. So austenite stability at room temperature is important by controlling thermomechanical treatments. In this point of view "Q & P" treatments has play an important role to develop future generation advanced high strength steel. Quench and partitioning process controlled formation of retained austenite interspersed with partitioned martensite [109]. Third generation AHSS consists of fine grain ferrite, carbide free bainite, martensite and retained austenite. High volume percentage stable retained austenite is required to develop high strength and ductile materials. Nb microalloyed 0.17% C, 3% Mn, 1.5% Al, 0.2% Si, 0.2% Mo steel were thermomechanically processed in the temperature range of 400°C-450°C on the basis of DCCT (Deformation continuous cooling transformation) diagram which exhibit very fine grain bainite microstructure with nearly 20% stable retained austenite [110]. Approximately 1650 MPa tensile strength and total elongation 20% achieved when 0.3C-4.0Mn-2.1Si, 1.5 Al, and 0.5 Cr steel is subjected to dual stabilization heat treatment (DSHT) which is basically a five stage cooling schedule act as a paraequlibrium carbon partitioning (different from quench and partitioning treatment) due to formation of approximately 30 vol% stable retained austenite [111]. Press hardened steel (PHS) increasingly use in automotive structural parts posses low ductility which has been improved to 17% total elongation with 1320 MPa tensile strength by “Q & P” treatments at 270°C and 400°C respectively due to generation of high volume fraction carbon enriched retained austenite [112]. In recent decade along with quench and partitioning treatments, tempering were also applied to boron alloyed directly hot rolled steel to enhance better formability with high strength (nearly 2000 MPa) which has been attributed due to formation of nano carbide with dislocation density anhilation during tempering [113]. Quench partition and tempering treatment (“Q-P-T”) also applied to a steel of composition Fe-0.6C-1.5Mn-1.5Si-0.6Cr-0.05Nb hot-rolled high-carbon steel which exhibit high tensile strength (approximately 1950 MPa) and high formability (around 12.4%) due to formation of high percentage retained austenite which absorb dislocation intensity and provide TRIP effect during deformation [114]. A multiphase steel contain microstructure mixture of bainite, martensite and improved retained austenite (13%) were achieved by “Q & P” treatments to a Co containing steel (composition 0.32 C, 1.78 Mn, 0.64 Si, 1.75 Al, and 1.20 Co all in wt%) which shows high tensile strength ≈1470 MPa and high total elongation ≈ 13% [115]. Instead of “Q & P” treatment hot stamping with bake hardening (HS-BH) treatments were applied a steel composition like Fe-0.39C-1.56Si-1.54Mn-0.98Ni-1.01Cr-0.45Mo-1.40Cu-0.028Ti-0.0023B-0.025Al shows nearly 2000 MPa tensile strength and approximately 18% formability due to formation of film like and blocky retained austenite with tempered lath like martensite and spherical nano size (≈ 15nm) Cu rich precipitates [116].

7. Focus to Develop Advanced High Strength Stainless Steel for Future Transport Purpose

For the last three decades materials for the various parts of the vehicle have been developed in the narrow hyperbolic regions of the “Banana Curve” (bottom region of the curve) depicted in Figure 9 (a) [18]. Globally decrease CO_2 emission is required for automotive purpose which has increased the demand of austenitic stainless steel grade in the world market which has been depicted in the Figure 9 (b) [19]. So it is necessary to look behind the developed advanced high strength stainless steels mechanical properties for use of structural and automotive components.

Thermal fatigue and high temperature strength of ferritic stainless steels were improved by Nb incorporated laves phase precipitation in exhaust engine components [117]. As Ultra High Strength Stainless Steel is highly desirable for automotive, aerospace, nuclear, gear and bearing industries so alloy design is important by nano-particles along with lath martensite is precipitation within the matrix [118]. 630 MPa yield strength and ductility approximately 70% AISI 304 austenitic stainless steel was developed by gradient nanostructure and dense deformation twins’ boundaries formation for dislocation blocker by Ultrasonic Nano-Crystal Surface Modification technique [119]. 60% CR and annealed at 800°C for 10 sec of AISI 201 austenitic steel shows 450 MPa to 800 MPa Y.S. and 900 MPa to 1100 MPa U.T.S. due grain fineness to 1.5 µm level as well as elongation found 50% for fine grain and 70% for as received coarse grain structure [120]. High nitrogen and enhanced Mo contain super austenitic stainless steel is used to make high speed passenger craft as well as duplex stainless steel typically used for making maintenance free bridge column and repeated use of AISI 316L steel for medical purposes [121]. So mechanical property improvement of stainless steels are target by many metallurgists. High pressure torsion (HPT) technique produces approximately 1800 MPa tensile and nearly 10% ductility property of austenitic grade steel [122]. 90% Cryorolling was applied to Fe-25Cr-20Ni grade austenitic stainless which exhibit approximately 1500 MPa tensile strength and 6.4% ductility [123]. Nano-crystaline (grain size 65nm) with tensile strength 1485 MPa and elongation 33% AISI 201L was formed after 95% cold rolling and annealing at 850°C for 30 seconds [124]. It is observed by the researchers that fine grains austenitic stainless steels shows excellent strength and ductility due to deformation twins and on the other hand coarse grain structure shows low strength with high ductility from strain induced martensitic transformation [125]. Increased retained austenite (approximately 70%) after cold rolling produce very high strength (nearly 2236 MPa with 12.3% elongation) austenitic grade high nitrogen Ni-free steel [126]. Three stages cold rolling and annealing were applied to develop ultra high strength (yield strength-1120 MPa and tensile strength-1440 MPa) with formability nearly 12% AISI 304 stainless steel due to generation of ultra fine austenite grains in the range of 80-150 nm [127]. Ultra high strength (yield strength-740 MPa to 1290 MPa and ultimate tensile properties-1003 MPa to 1415 MPa and ductility 45.9% to 8.2%) ferritic-austenitic stainless steel was developed by fine dislocation structure, grain refinement and partial recrystalization [128]. Thermomechanical treatments of low density duplex steel exhibit a unique property of strength and ductility (tensile strength-925.9 MPa and elongation- 50.2%) [129]. It was observed that pre-cooling induce high strength (1240 MPa) and high formability (42%) of high manganese austenitic steel [130]. A new Ni-free austenitic stainless steel was designed which posses’ extremely high strength (2400 MPa) and extraordinary ductility (40%) due to slow martensite transformation with mechanical twins by solid solution and dislocation strengthen from high Mn and Nitrogen [131]. Sometimes only cold deformation also produce as high as 1257 MPa yield strength, 1444 MPa ultimate tensile strength and nearly 2% total elongation [132]. Large strain severe plastic deformation applied to S304H austenitic grade stainless steel which exhibit superior tensile properties (nearly 2050 MPa) and elongation 5%-7% as compared to 290 MPa tensile strength with approximately 60%-61% formability of the as received material due to generation of deformation twin and dislocation intensity [133]. Continuous heating of the cold rolled austenitic stainless steel produce 810 MPa yield strength, 1163 MPa ultimate tensile strength and nearly 26% elongation property [134]. Nb alloyed nano/ultrafine grain AISI201 type austenitic grade steel shows excellent tensile and ductility (~ 1200 MPa Y.S. and 1500 MPa U.T.S. with elongation 35%) [135]. Nanocrystalline advanced high strength austenitic steel

(Y.S. - 790MPa, U.T.S. - 1300 MPa, ductility – 28%) produced by cold rolling and annealing [136]. Oxide dispersed bimodal ultra fine grain distributed high strength (1200 MPa yield strength) and moderate ductility (less than 10%) developed by mechanical alloying and hot isostatic pressing (HIP) [137]. Around 1700 MPa tensile strength with 5% - 10% elongation contain 19Cr duplex stainless steel formed by cold rolling due to generation of high dislocations pile up at twin grain boundaries [138]. New ultra high strength maraging stainless steel shows 1649 MPa Y.S., 1928 MPa U.T.S. and 10% elongation, strengthen by Ni, Cr, Mo precipitates after ageing [139]. Another super high strength newly developed light weight austenitic stainless steel shows 1800 MPa tensile strength with 50% elongation due to containing low density Al and generations of twins during transformation of FCC austenite to BCC martensite at the time of tensile testing [140]. Cryorolling followed by annealing of AISI304L stainless steel austenitic grade exhibit 1295 MPa tensile strength and approximately 20% ductility form bimodal grains and twining effect [141]. The drawback of AISI 301 austenitic stainless steel towards use for structural purpose is its low yield strength (250 MPa – 350 MPa) which can be improved by grain refinement using repeated cold rolling and annealing thermomechanical treatments upto as high as 1970 MPa [142]. Quenching and Partitioning (Q&P) is a relatively new technique applied to AISI 420 martensitic stainless steel grade which exhibit nearly 1570 MPa U.T.S. and 15.7% elongation due to formation of twined martensite in the matrix [143]. Recently ultra fine grain (270 nm) AISI 304 steel shows 1890 MPa Y.S. and 2050 MPa U.T.S. with 6% ductility [144].

8. Inferences

From the detailed literature study it is readily observed that there is a vast demand of high strength and moderate ductile advanced stainless steel for future transport as well structural body manufacturing purpose. last 3 decades significant contribution exerted for developing advanced high strength steel like 1st generation steels which exhibit best tensile properties in the range of 800-1000 MPa yield strength, 1200 – 1600 MPa ultimate tensile strength with 20%-13% ductility. 2nd generations TWIP steel has 900-1700 MPa ultimate tensile strength and approximately 20% ductility. 3rd generation steels produce mechanical properties like maximum 2000 MPa ultimate tensile strength and nearly 18% of formability by hot stamping and bake hardening treatments. These advanced developed steels are frequently used for making automobile parts, body sheets, panels, and crash worthiness and for making several accessories. In recent decade austenitic grades steels make attention to the steelmaker for capturing structural and automobile market due to its superior corrosion property and subsequently enhanced mechanical properties. Nano/ultra fine grains AISI 201 steel which produces as high as 1200 MPa Y.S., 1500 MPa U.T.S. and approximately 35% ductility as a future steel. Low density austenitic grade steel with superior strength and ductility (nearly 500 MPA Y.S., 1800 MPa U.T.S. and 50% elongation) developed by twin assisted martensitic transformation. European commission has targeted to develop new generation advanced high strength steel by 2030 which have strength and ductility within the so called banana curve.

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