Development of Advanced High Strength Steel (AHSS), Including for Automotive Parts, Stainless Steel and Structural Applications

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ABSTRACT
Safety and fuel efficiency are of utmost importance in the automotive industry. Over the past three decades, there has been a significant focus on enhancing the structural characteristics of motor vehicles. Advanced high strength steels have played a vital role in achieving these desired characteristics. Various types of advanced high strength steels, such as 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, as well as austenitic and ferrite grade stainless steels, have replaced many structural components due to their superior strength and ductility. In this context, the causes behind the development of these steels from conventional to third generation have been examined, along with the strengthening mechanisms employed in the development of advanced high strength structural steels. A review of the literature indicates significant progress has been made from a metallurgical standpoint in the last decade.

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

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

The modern automotive market demands improvements in fuel efficiency and reduction of greenhouse gas emissions by reducing vehicle weight. This is due to the stringent requirements for reducing greenhouse gas emissions worldwide [1]. In recent years, the requirements in the automobile industry have become more diverse. In addition to comfort, high fuel efficiency, emission control, and safety are also important aspects to consider when designing a vehicle. These goals can be achieved by reducing the vehicle's weight and simultaneously improving the crashworthiness of its body parts [2]. Therefore, the development of reliable advanced high-strength steels is necessary for manufacturing vehicle body parts. In the past three decades, aluminum, magnesium-grade steels, and conventional high-strength steel have been used for passenger safety in vehicles. However, the reliability of automotive parts can be enhanced by using advanced high-strength steel (AHSS). This type of steel has good formability and toughness. AHSS includes dual-phase steel, transformation-induced plasticity steel, complex phase steel, and martensitic steel. Advanced high-strength steel generally has a yield strength greater than 300 MPa and an ultimate tensile strength that is even higher. Using Advanced High-Strength Steels (AHSS) can reduce the weight of a vehicle by 25 percent, as reported in the ULSAB study [4]. AHSS is superior to High-Strength Steels (HSS) in terms of mechanical characteristics, such as tensile strength. When the tensile strength exceeds 780 MPa, it is called Ultra High Strength Steel [5]. Metallurgists have been working for the past four decades to develop advanced high strength and ductility steels for transportation and structural purposes. Some parts of sports cars are often made from aluminum and magnesium, which are low-density materials. Normal stainless steel has a yield strength of approximately 327 MPa, while high strength steel like grade S420MC has a yield strength of 440 MPa, TRIP700 steel has a yield strength of 495 MPa, and advanced high strength steels like DP1000 and MS1200 have yield strengths of 922 MPa and 1238 MPa, respectively [6]. There is a desperate need for more advanced high strength steels in automotive parts to further reduce vehicle weight [7]. One common example of an advanced high strength steel is TWIP (Twining Induced Plasticity Steel), which has a good combination of tensile strength and ductility due to the presence of austenite with a twins microstructure [8]. TWIP steel falls under the category of second-generation advanced high strength steels [9]. The current trend is to develop even better high strength and ductility steels for more efficient and lightweight vehicles. Please proofread this document and make it clearer and more fluid. Ductility refers to the ability of a material to deform under tensile stress without breaking. Third generation steel is a type of steel that is expected to be less expensive than second generation high strength steel, such as TWIP. One recent technique in the development of third generation advanced high strength steel is the use of quench and partitioning thermomechanical treatments. These treatments involve grain refinement with precipitation hardening. The resulting ultra grain refinement creates a steel structure with superior strength, good low temperature toughness, and high stretch formability. The grains in these structures are smaller than 100 nm. Researchers are targeting the development of even finer grain structures through thermomechanical treatments in order to achieve superior strength properties in future advanced structural grade steels. The strategic research agenda of the European Steel Technology Platform (ESTEP) emphasizes the need to develop advanced high strength steel with moderate ductility by the year 2030. This includes the development of austenitic stainless steel for future lightweight and safe vehicles, using thermomechanical treatments instead of costly alloying elements. The global demand for reduction in CO2 emissions has increased the need for high strength and ductile chassis and body in white (BIW) structures for automotive purposes. This has created a large market for austenitic grade steel, which is used in the manufacturing of transport vehicles and other automotive body components. The recent trend towards sustainability and reduction of greenhouse gases has led to an increased use of stainless steel in public transport systems, such as rail or metro rail. Stainless steel offers good corrosion resistance, excellent toughness, formability, and fatigue properties. These properties are essential for crashworthiness and car safety applications. As a result, there is a push to develop advanced high strength structural stainless steel, as well as other grades of steel, by reducing alloying elements and incorporating nitrogen content in austenitic grade steel. These developments also involve changing the microstructure through advanced thermomechanical treatments.

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

The European Commission for Steel Platform has set a target to develop high strength steel with moderate ductility by the year 2030. This is specifically aimed at meeting the needs of the automobile industry. Additionally, it is necessary to develop high strength austenitic stainless steel for structural and rail coach manufacturing in order to enhance human safety. In light of these goals, it is important to understand the various strengthening mechanisms used in the development of advanced high strength structural steels (AHSS). 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 greatly improved by inducing plasticity and introducing severe plastic deformation through metastable phase transformation [24]. Austenitic steel is known for its high ductility with low yield strength, and this is due to its low stacking fault energy. The low stacking fault energy causes dislocation dissociation into two Shockley partial dislocations, which require stress to collide before the united perfect dislocation can move through the slip plane. This results in a high strain hardening rate for this type of steel. Strain-induced hardening is achieved through the obstruction of movement for a large number of dislocations and the interaction of dislocations with the martensite phase that forms during severe plastic deformation. The formation of shear bands, which act as nucleation sites for the formation of α' martensite, is dictated by the stacking fault energy (SFE). In addition to developing a high hard martensitic phase, plastic deformation also improves the yield strength by forming twins, shear bands, dislocations, and Suzuki locking.

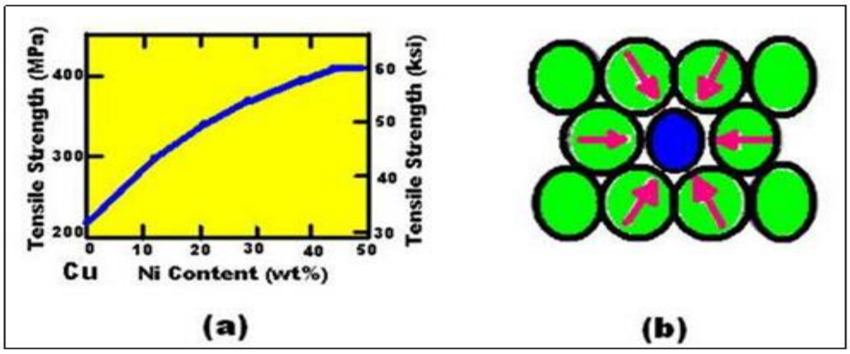

Figure 1. (a) Changes of Tensile Strength with increasing Ni content in the Copper- Nickel Alloy (b) Schematic diagram of generation of Lattice strain with incorporation of small substitutional element within the metal (Reprinted from [25])

Cold-worked metal contains more dislocations (approximately 1010 mm2) compared to annealed steel (which contains dislocations in the range of 104 to 106 per mm2) [22]. Strengthening through the incorporation of solute atoms inside the base metal: Solid solution strengthening is an important technique for developing high-strength metals by adding interstitial and substitutional impurity atoms into the base metal. Impurity atoms of large or small size can occupy interstitial positions or substitute for pure atoms, causing lattice strain within the metal and hindering dislocation movement. This leads to the high strength of the alloy metal, as observed in Figure 1 (a) and Figure 1 (b).

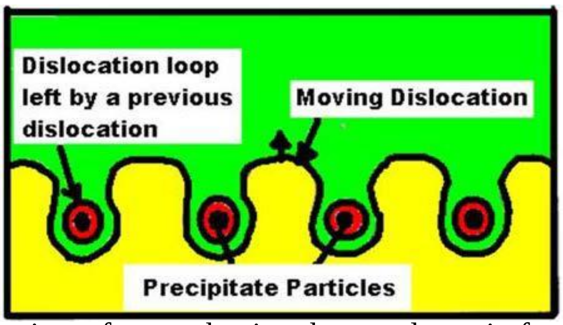

Figure 2. Orowan mechanism of strengthening the metal matrix from precipitates (Reprinted from [26])

Strengthening Metal through Strain Ageing Treatments: Bake hardening is a commonly used static strain ageing treatment that is applied to improve the tensile properties of various types of steels. Typically, the steel is heated below 2000C for a sufficient amount of time in order to enhance the yield strength, potentially up to 200 MPa [24]. It is important to note that strain ageing not only increases the yield strength, but also decreases the ductility. Nitrogen, due to its higher solubility and diffusion coefficient, is known to play a significant role in static strain ageing, as mentioned in the literature [22]. When undergoing static and dynamic strain ageing, the steel exhibits yield point phenomena, resulting in a stress-strain curve with serrated behavior. In some cases, the mechanical properties of the steel can be altered further, leading to the formation of twins and stress-assisted martensite. Precipitation Hardening of Steel: Another method of strengthening steel is through the precipitation of very fine second phase particles onto the base metal matrix.

During the ageing treatments, cementite particles precipitate from ferrite through a process of nucleation and growth [26]. This precipitation and dispersion strengthening mechanism significantly enhances the mechanical properties of the steel. Researchers have studied the role of the Orowan dislocation bypassing mechanism (shown in Figure 2) in this context [27]. Recovery, recrystallization, grain growth, and annealing are commonly used to strengthen austenitic grade stainless steels. After cold working, austenitic grade stainless steel is subjected to annealing at elevated temperatures (above 0.5Tm). This process involves short time annealing for stress relief through dislocation motion, followed by recrystallization to generate new strain-free grains, and finally, grain growth to form larger grains from the new strain-free grains.his annealing process is carried out at elevated temperatures for a long period [25,28,29,30].

3. Development of Conventional HSS:

Sheet steel technology has a long history of development in response to the reduction of CO2 emissions and simultaneously. Proofread this text and improve clarity and flow.Improving the rigidity of the vehicle, several high-strength steels have been used over the last two decades. Generally, conventional steel used for structural applications includes mild steel, IF (interstitial free) steel, BH (bake hardened) steel, and micro-alloyed or HSLA (high strength low alloy) steel. However, conventional steels have a major disadvantage in their heavy weight, which is a barrier to reducing fuel consumption [31].IF (Interstitial Free) Steel: This steel was first invented in Japan at the end of 1960 [32]. Interstitial Free steel is generally used to make rear floor pans, spare wheel wells, and front-rear door inners, as shown in Figure 3 [33]. The biggest disadvantage of this steel is its low tensile strength, which is less than 360 MPa [34]. However, improvements in tensile strength up to 450 MPa have been achieved through solid solution strengthening [35]. By adding 1.2% Cu, the yield strength and tensile strength values can be increased to around 460 MPa and 575 MPa, respectively, through precipitation hardening [36]. Recently, ultrafine grain structures have been achieved for this steel using the equal-channel angular extrusion/pressing (ECAE/P) method and annealing [37,38]. This thermomechanical method has shown tensile properties of 708-900 MPa with nearly 15%-10% ductility [39,40]. Furthermore, the toughness and elongation of this steel can be improved by achieving ultrafine grain structures through cold rolling, annealing, and bake hardening[41,42,43].

Bake Hardening Steel: This steel mostly has a ferrite microstructure. By using Bake Harden (BH) Steel, denting problems in automotive outer body panels can be avoided. Due to the lack of movement of dislocations by interstitial atoms, bake harden steels possess very high strength with superior ductility after painting or static strain aging. Through bake hardening treatment, the yield strength of a pre-strained, cold-rolled, continuous annealed steel can be improved by 10-54 MPa, and the work hardenability can be improved by around 17-82 MPa, depending on the panel location [44]. Normally, bake hardening treatment is given to low carbon steel and IF steel. However, nowadays, due to the great formability of IF steel, most panels are made from IF-BH steel.High Strength Low Alloy Steel (HSLA): This category of steel is extensively used for making body parts, wheels, ancillary parts, suspension and chassis components in vehicles, due to its yield strength being greater than 275 MPa [45]. HSLA steel was first developed in 1960 [46]. Different types of HSLA steels are available in the market, such as weathering steel, micro-alloyed steel, as-rolled pearlitic steel, low carbon bainite steel, dual-phase steel, and inclusion shape-controlled steel. A minimum yield strength of approximately 550 MPa can be achieved through precipitation hardening and ferrite grain refinement (less than 3 µm) [46,47]. Various alloying elements, such as Nb, Ti, V, and boron, have been added to improve the properties of HSLA steel.By incorporating TiN precipitates and increasing the percentage of fine bainite and uniformly distributed metal carbides in the matrix, a yield strength of 550 MPa and 20% elongation at room temperature can be achieved [48,49].Micro-alloyed Steels: This category of steel contains niobium, vanadium, titanium, zirconium, and boron.

It is used for discrete automotive parts like powertrain and suspension component systems, due to its excellent strength and toughness achieved through the formation of a fine grain size. Carbo-nitrides precipitate in the ferrite matrix through thermomechanical treatments, along with an accelerated cooling process. This results in a steel with a yield strength of around 400-800 MPa and an ultimate tensile strength of 500-1000 MPa, along with 23-26% elongation [50,51,52]. High-strength microalloyed steels, which account for approximately 60% of auto body manufacturing [53], are extensively used in heavy-duty truck wheel discs and wheel rims. Instead of conventional mild steel, hot-rolled microalloyed steel is widely used to provide high compressive strength and safety, with a composition of 90% 5µm polygonal ferrite and 10% pearlite. This steel has a yield strength of 570 MPa, tensile strength of 610 MPa, and elongation of 26% [54]. The addition of Nb to this steel improves its tensile strength from 970 MPa to 1200 MPa due to the pinning effect, but at the same time decreases its ductility by approximately 4% [55]. Thermomechanical treatments, along with the addition of 1%-2% Cu, further enhance the tensile properties of this steel to 1364-1403 MPa with 11%-14% ductility [56,57].

4. First Generation Advanced High Strength Steels for Vehicle Components Manufacturing:

In recent decades, metallurgists have been working on developing steel with higher strength and superior ductility compared to conventional high strength steel. This type of steel, called advanced high strength steel (AHSS), has a complex and multi-phase microstructure. Figure 4 (a) shows the percentage use of conventional high strength steel (HSS) and advanced high strength steel (AHSS) in 2007 and 2015. It can be observed that the use of AHSS is increasing for future steel vehicles, as depicted in Figure 4 (b).AHSS is generally produced by changing the chemical composition of steel and using advanced cooling treatments from the austenite phase or austenite + ferrite phase. Dual phase steel, which consists of ferrite and martensite microstructures, is widely used for manufacturing various automotive parts such as crumple zones, body structures, closures, hoods, doors, rails, beams, cross members, rockers, sills, cowl inners and outers, crush cans, shock towers, fasteners, and wheels. The yield strength and ductility of dual phase steel can be controlled over a broad range by adjusting the hot coiling and bake hardening temperature [5].In recent years, dual phase steel has replaced conventional HSLA steel in many automotive parts. Typical yield strength and tensile strength values of dual phase steels range from 210 MPa to 1150 MPa and 440 MPa to 1270 MPa, respectively, with elongation ranging from 35% to 10% for different grades [58,59]. Ultra high strength dual phase steels, with tensile strengths ranging from 750 MPa to 1300 MPa and elongation ranging from 25% to 10%, have been produced through thermomechanical treatments such as cold rolling or warm rolling and intercritical annealing treatments [60-66]. Researchers have also developed advanced high strength dual phase steel (with tensile strengths ranging from 780 MPa to 1600 MPa and ductility in the range of 22% to 13%) through cold rolling and intercritical annealing [67-73]. In the past decade, commercial simulation software has been used to develop safe high strength dual phase steel [74].

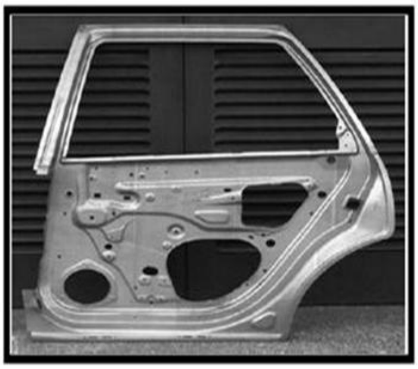

Figure 3. Inner door body panel for automobile from IF steel (Reprinted from [33])

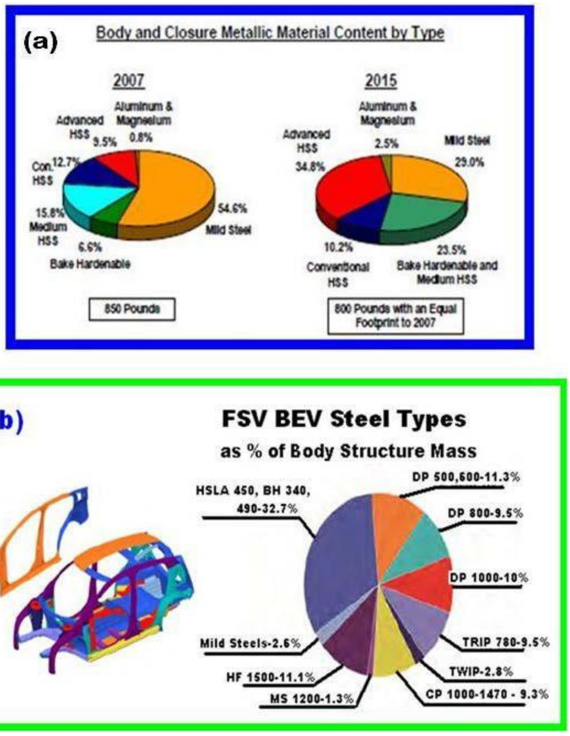

Figure 4. (a) Comparison of HSS and AHSS from past and present (b) Future Steel vehicle (FSV) & Battery Electric Vehicle (BEV) (Reprinted from [58])

5. TRIP (Transformation Induced Plasticity) Steel:

The development of advanced high-strength steel has been a challenge for the automotive industry over the past decade. The goal has been to create steel with a more complex microstructure that offers superior strength and ductility, in order to make vehicles more fuel efficient, emit less, and safer for passengers. Currently, commercially available dual-phase steel consists of a ferrite and martensite microstructure. On the other hand, TRIP steel exhibits a microstructure of ferrite-bainite-retained austenite and martensite. This steel contains a high amount of carbon and silicon, resulting in a mixture of 70% polygonal ferrite with a grain size ranging from 1.5-4 µm, approximately 20% retained austenite, and the remaining mixture of bainite and martensite [75]. TRIP steel is used in the production of various automotive components, such as frame rails, rail reinforcement, side rails, crash boxes, dash panels, roof rails, B-pillar uppers, engine cradles, front and rear rails, seat frames, and bumper cross members, as shown in Figure 5 [76]. The lamellar austenite with bainitic ferrite structure improves its mechanical properties, achieving a ultimate tensile strength (UTS) of 682 MPa and an elongation of 70% [77]. When intercritically treated at 630°C, this steel exhibits a strength of 800 MPa and a ductility of 29% [78]. TRIP steel has also been intercritically annealed at temperatures of 600°C and 650°C, resulting in true stress values of nearly 1200 MPa and 1400 MPa, respectively, with true strains of 0.3 and 0.1 [79]. High stretch-flangeability automotive components, such as reinforcement and sheet frames, were developed using NbC precipitation with TRIP effect, achieving UTS values ranging from 980-1470 MPa and elongation values of 25-10% [80]. A new type of TRIP steel, known as TBF steel (TRIP steel with a bainitic-ferritic matrix), exhibits high toughness values (100-120 J/cm²), as well as a low ductile-brittle transition temperature, ranging from -130°C to -150°C.

It also possesses an ultimate tensile strength of 1527 MPa and a ductility of 13.4% [81]. A steel with a strength of approximately 1000 MPa and an elongation of nearly 40% was produced by cold rolling it to 36% and then intercritically annealing it at 640°C for 1 hour [82]. By alloying it with molybdenum, niobium, and manganese, it has been possible to achieve ultra-high strength (1000 MPa-1400 MPa) and high ductility (35%-13%) in this steel [83,84]. However, the presence of tramp elements improves ductility but, at the same time, poses a critical problem of hydrogen absorption during white painting, which can lead to crack initiation in this advanced high-strength steel [85,86].

6. Complex Phase (CP) Steel: Complex phase steel is a fine-grain structure with a mixture of martensite, retained austenite, and pearlite within the ferrite-bainite matrix. It is used in the manufacture of various automotive components such as frame rails, chassis components, transverse beams, B-pillars, tunnel stiffeners, rear suspension brackets, fender beams, rear frame rail reinforcements, rocker outer, rocker panels, and bumper beams. It has a tensile strength ranging from 800-1470 MPa and an elongation of 15-5%, which is higher than DP steel [58,87]. Martensitic Steel (MS): Martensitic steel is a metallurgical innovation that consists of a small amount of ferrite-bainite mixture in a fully martensitic matrix. This steel possesses extremely high strength in the range of 1200 MPa to 1500 MPa with an elongation of approximately 8%-5%. It is mainly used for automotive parts such as cross-members, side intrusion beams, bumpers beams, bumper reinforcements, rocker outer, and side intrusion beams [58,88]. The high strength of this steel is caused by the auto-tempering of the lath martensite [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 [91,92]. The addition of Mo improves the mechanical properties of this steel as it promotes more bainite formation. The tensile strength of this steel is in the range of 1100 MPa-1200 MPa, with an elongation of 18-22%, whereas the base steel shows a tensile strength between 700-800 MPa and nearly 22% ductility [93]. Metallurgists have produced nanoscale (Nb,Ti)C precipitates for automotive wheel applications to enhance the bainitic hardening [94]. Cold rolled and continuously annealed carbide-free ferritic-bainitic steel is a new type of steel that shows greater formability than martensitic steel or dual-phase steel, with the same ultimate tensile strength (in the range of 1200-1500 MPa) [95]. The optimum bainitic structure typically consists 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 a total elongation over 10%. This structure is obtained by finishing rolling temperature (FRT) at 930°C followed by finishing coiling temperature (FCT) 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])

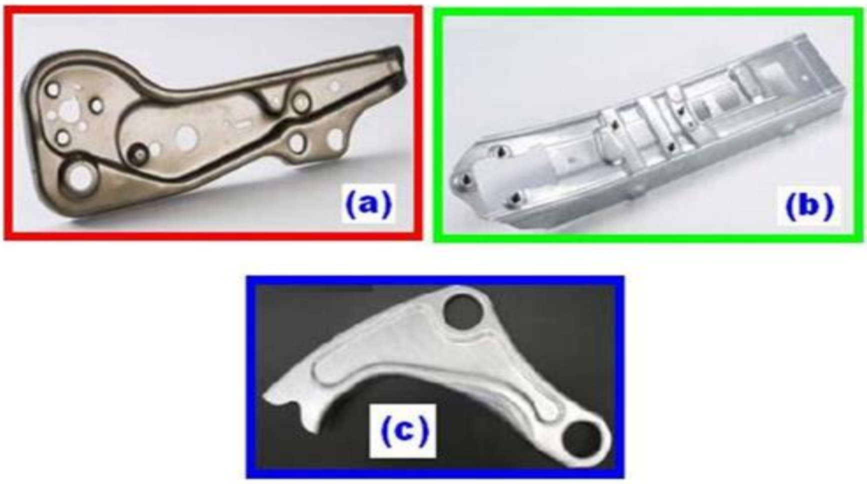

Figure 6. (a) Seat Flange, (b) tunnel stiffener and (c) suspension arm made by CP 600,800 Steel (Reprinted from [87])

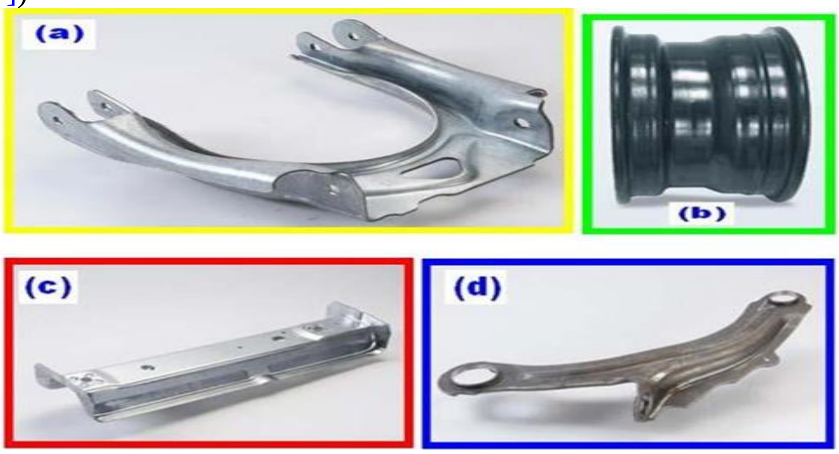

Figure 7. (a) FB 560 for suspension arm (b) FB 590 for wheel application (c) Front and rear under seat cross member made by FB 560 (d) FB 540 for uncoated suspension arm (Reprinted from [92])

Hot formed (HF) steel is commonly used in the manufacturing of structural and safety components for automobiles. This type of steel has a high tensile strength, approximately 1500 MPa, and offers ductility of nearly 6%. As a result, it allows for significant weight savings (around 30-50%) compared to conventional cold rolled grades. Currently, metallurgists are working on developing advanced hot formed (AHF) steel for the purpose of improving automobile crashworthiness. This is being accomplished through methods such as dynamic carbon partitioning (DCP), flash copper precipitation, and bake hardening. The goal is to achieve a tensile strength that is approximately... 1623 MPa with ductility around 13.7% and impact energy nearly 60-70 J [98,99,100].

7. Second Generation Advanced High Strength Steel (AHSS):

TWIP (Twin Induced Plasticity Steel): This steel contains deformation twins in an austenite matrix with an ultimate tensile strength in the range of 900 MPa to 1200 MPa and elongation within 20% to 50% due to soft phase austenite. The twin boundary acts like a grain boundary and is typically used for manufacturing various parts of a vehicle, including A-pillars, wheelhouses, front side members, lower control arms, front and rear bumper beams, B-pillars, wheel rims, floor cross members, and door impact beams [58]. The movement of dislocations is hindered by these deformed twins and the low stacking fault in this FCC alloy, resulting in high tensile and ductile properties [101, 102]. Nano-grained TWIP steel exhibits a yield strength of approximately 1195-1330 MPa and formability in the range of 20.1% to 13.7%, mainly used for anti-intrusion auto body parts [103]. Different percentages of cold reduction with annealing produce fine-grained TWIP steel with a grain size of approximately 8 µm to 10 µm, exhibiting a tensile strength of nearly 800 MPa and ductility close to 60% [104, 105]. TWIP steel containing Ni and Cr with high Mn and Si (0.61C–22.3Mn–0.19Si–0.14Ni–0.27Cr) shows an extraordinary high tensile strength of nearly 1702 MPa and high ductility of approximately 24% after severe plastic deformation by the Equal Channel Angular Pressing (ECAP) method with two passes at 300°C and 400°C. The as-received material shows a tensile strength of approximately 1000 MPa and ductility above 120%. This is due to the generation of deformation microbands (distance between two parallel microbands is ≈260±37nm) and nano twins within the primary twins or micro twins in the ultra-fine grains (0.3-0.6 µm compared to 34 ± 21 µm austenite grains for the as-received material), as well as the formation of stacking faults (around 50µm in size) within the subgrains, as shown in Figures 8 (a), (b), and (c) [106]. TWIP steel has sufficient ductility, making it extensively used for crash worthiness purposes to absorb impact energy. The generation of twins is important and is affected by deformation temperatures. It was found that the maximum quantity of twins is produced when deformed at room temperature rather than at high temperatures (like 400°C) or very low temperatures like -150°C or cryogenic temperatures (-196°C). Crash-resistant super ductility TWIP steel has a high value of specific absorption energy (0.5 j/mm3) compared to conventional deep drawing steel like IF steel, bake-hardening steel, and other thermomechanically treated steels due to the formation of extensive twins at high strain rates [107]. Recently, ferritic-austenitic duplex lightweight steel has shown a high tensile strength (734 MPa) and high elongation of around 77% due to the generation of deformation-induced martensite and twins within austenite grains simultaneously [108].

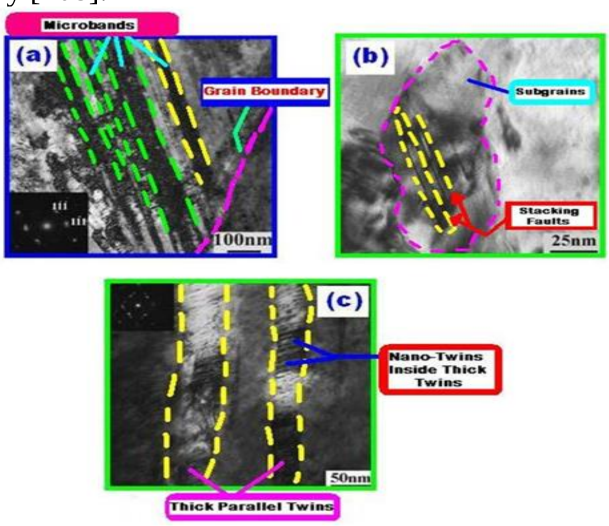

Figure 8. TEM Image of (a) Microbands (b) Stacking faults in Subgrain (c) Nano Twins within Thick

Twins (Reprinted from [106])

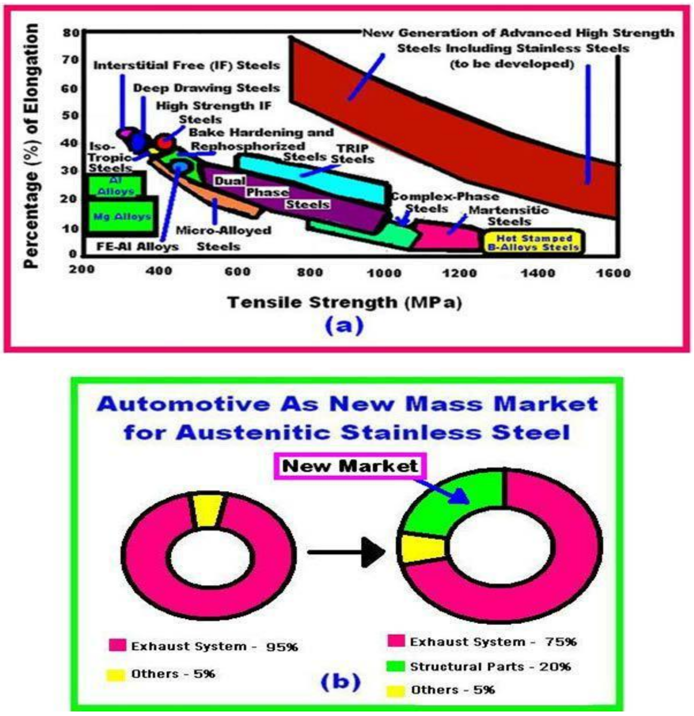

Figure 9. (a) The Red region of “Banana Curve” showing the strength and ductility required for Carbon Steel including stainless steel for future generation Automotive Purposes (Reprinted from [18]) (b) New Market for Austenitic Stainless Steel for Making Automobile Structural Parts (Reprinted from [19])

8. The Development of Future or third Generation Advanced High Strength Steel(AHSS):

The concept of third generation AHSS arose from the need to address the research gap in the development of first generation AHSS and second generation AHSS. Third generation steel is a combination of martensite and austenite, with austenite playing a crucial role in work hardening. Therefore, it is important to ensure the stability of austenite at room temperature through controlled thermomechanical treatments. In this regard, the "Q & P" treatment has been found to be instrumental in developing future generations of advanced high strength steel. The quench and partitioning process facilitates the formation of retained austenite interspersed with partitioned martensite [109]. Third generation AHSS consists of fine grain ferrite, carbide-free bainite, martensite, and retained austenite. A high volume percentage of stable retained austenite is necessary to create high strength and ductile materials. For example, a thermomechanical processing was carried out on Nb microalloyed steel containing 0.17% C, 3% Mn, 1.5% Al, 0.2% Si, and 0.2% Mo in the temperature range of 400°C-450°C. The processing was based on the DCCT (Deformation Continuous CoolingTransformation) diagram, resulting in a very fine grain bainite microstructure with nearly 20% stable retained austenite [110]. Similarly, a dual stabilization heat treatment (DSHT) was applied to a 0.3C-4.0Mn-2.1Si, 1.5 Al, and 0.5 Cr steel, using a five-stage cooling schedule. This treatment, which is different from quench and partitioning treatment, led to the formation of approximately 30 vol% stable retained austenite. As a result, the steel achieved a tensile strength of approximately 1650 MPa and a total elongation of 20% [111].Press hardened steel (PHS) is increasingly being used in automotive structural parts, but it tends to have low ductility.

However, through improvements such as a total elongation of 17% and a tensile strength of 1320 MPa, the ductility of PHS has been enhanced. The "Q & P" treatment at temperatures of 270°C and 400°C generates a high volume fraction of carbon-enriched retained austenite, resulting in increased strength [112]. In recent years, tempering has also been used in conjunction with quench and partitioning treatments to improve the formability and strength (nearly 2000 MPa) of boron-alloyed hot-rolled steel. This improvement is attributed to the formation of nano carbides and the annihilation of dislocation density during tempering [113].Another treatment method, known as "Q-P-T," has been applied to a composition of Fe-0.6C-1.5Mn-1.5Si-0.6Cr-0.05Nb, resulting in a high tensile strength of approximately 1950 MPa and high formability of around 12.4%. This is achieved through the formation of a high percentage of retained austenite, which absorbs dislocation intensity and provides a TRIP (Transformation Induced Plasticity) effect during deformation [114]. Furthermore, a multiphase steel composed of bainite, martensite, and retained austenite (13%) was successfully obtained through "Q & P" treatments applied to a Co-containing steel with the composition of 0.32 C, 1.78 Mn, 0.64 Si, 1.75 Al, and 1.20 Co (wt%). This resulted in a high tensile strength of approximately 1470 MPa and high total elongation of approximately 13% [115].In addition to the "Q & P" treatment, hot stamping with bake hardening (HS-BH) treatments have also been applied to a steel composition consisting of Fe-0.39C-1.56Si-1.54Mn-0.98Ni-1.01Cr -0.45Mo-1.40Cu-0.028Ti-0.0023B-0.025Al. This treatment yielded a tensile strength of nearly 2000 MPa and approximately 18% formability. The resulting microstructure consisted of film-like and blocky retained austenite, tempered lath-like martensite, and spherical nano-sized (approximately 15nm) Cu-rich precipitates [116].

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

For the past three decades, materials for vehicle parts have been developed in the narrow hyperbolic regions of the "Banana Curve" (bottom region of the curve) depicted in Figure 9 (a) [18]. The global demand for austenitic stainless steel grade has increased due to the need to reduce CO2 emissions in the automotive industry, as shown in Figure 9 (b) [19]. Therefore, it is necessary to investigate the mechanical properties of advanced high strength stainless steels for use in structural and automotive components. The thermal fatigue and high temperature strength of ferritic stainless steels have been improved by incorporating Nb-induced laves phase precipitation in exhaust engine components [117]. Ultra High Strength Stainless Steel is highly desirable in industries such as automotive, aerospace, nuclear, gear, and bearing industries. Therefore, alloy design is important, utilizing nano-particles along with lath martensite precipitation within the matrix [118]. A yield strength of 630 MPa and approximately 70% ductility was achieved in AISI 304 austenitic stainless steel through the use of gradient nanostructure and the formation of dense deformation twin boundaries as dislocation blockers, using the Ultrasonic Nano-Crystal Surface Modification technique [119]. In AISI 201 austenitic steel, containing 60% CR and annealed at 800°C for 10 seconds, yield strengths ranging from 450 MPa to 800 MPa and ultimate tensile strengths ranging from 900 MPa to 1100 MPa were achieved, with grain fineness at a level of 1.5 µm. The elongation was found to be 50% for fine grain structure and 70% for as-received coarse grain structure [120]. High nitrogen and enhanced Mo-containing super austenitic stainless steel are used to manufacture high-speed passenger craft. Additionally, duplex stainless steel is typically used for maintenance-free bridge columns and AISI 316L steel is frequently used for medical purposes [121]. The improvement of mechanical properties of stainless steels is a target of interest for many metallurgists. The High-Pressure Torsion (HPT) technique can produce tensile properties of approximately 1800 MPa and a ductility of nearly 10% in austenitic grade steel [122]. By applying Cryorolling to Fe-25Cr-20Ni grade austenitic stainless steel, tensile strengths of approximately 1500 MPa and a ductility of 6.4% were achieved [123]. After 95% cold rolling and annealing at 850°C for 30 seconds, AISI 201L steel with a grain size of 65nm exhibited a tensile strength of 1485 MPa and an elongation of 33% [124]. Researchers have observed that fine-grained austenitic stainless steels show excellent strength and ductility due to deformation twins, while coarse-grained structures show low strength but high ductility due to strain-induced martensitic transformation [125]. By increasing retained austenite to approximately 70% through cold rolling, a very high strength of nearly 2236 MPa with an elongation of 12.3% was achieved in high-nitrogen Ni-free austenitic steel [126]. Ultra-high strength with a yield strength of 1120 MPa and tensile strength of 1440 MPa, along with a formability of nearly 12%, was developed in AISI 304 stainless steel through three-stage cold rolling and annealing, resulting in the generation of ultra-fine austenite grains ranging from 80-150 nm [127]. Ferritic-austenitic stainless steel with ultra-high strength, yielding strengths ranging from 740 MPa to 1290 MPa, ultimate tensile properties ranging from 1003 MPa to 1415 MPa, and ductility ranging from 45.9% to 8.2%, was developed through the creation of a fine dislocation structure, grain refinement, and partial recrystallization [128]. Low-density duplex steel, after thermomechanical treatments, exhibits a unique combination of strength and ductility, with a tensile strength of 925.9 MPa and an elongation of 50.2% [129]. Pre-cooling was observed to induce high strength (1240 MPa) and high formability (42%) in high-manganese austenitic steel [130]. A new Ni-free austenitic stainless steel was designed, which possesses extremely high strength (2400 MPa) and extraordinary ductility (40%) due to slow martensite transformation with mechanical twins through solid solution and dislocation strengthening from high Mn and Nitrogen [131]. Sometimes, even cold deformation alone can produce yield strengths as high as 1257 MPa, ultimate tensile strengths of 1444 MPa, and elongation properties of nearly 2% [132]. Large strain severe plastic deformation applied to S304H austenitic grade stainless steel resulted in superior tensile properties, with a tensile strength of approximately 2050 MPa and an elongation of 5%-7%, in comparison to the as-received material, which had a tensile strength of 290 MPa and approximately 60%-61% formability, due to the generation of deformation twins and increased dislocation intensity [133]. Continuous heating of cold-rolled austenitic stainless steel resulted in a yield strength of 810 MPa, ultimate tensile strength of 1163 MPa, and an elongation property of nearly 26% [134]. Nano/ultrafine grain AISI201-type austenitic grade steel, alloyed with Nb, exhibited excellent tensile properties (~ 1200 MPa Y.S. and 1500 MPa U.T.S.) with an elongation of 35% [135]. (Y.S. - 790 MPa, U.T.S. - 1300 MPa, ductility – 28%) is produced by cold rolling and annealing [136]. Oxide dispersed bimodal ultrafine grain distributed high strength (1200 MPa yield strength) and moderate ductility (less than 10%) is developed by mechanical alloying and hot isostatic pressing (HIP) [137]. Around 1700 MPa tensile strength with 5% - 10% elongation is achieved with 19Cr duplex stainless steel formed by cold rolling, due to the generation of high dislocations pile up at twin grain boundaries [138]. A new ultra high strength maraging stainless steel shows 1649 MPa Y.S., 1928 MPa U.T.S., and 10% elongation, strengthened by Ni, Cr, Mo precipitates after aging [139]. Another super high strength newly developed lightweight austenitic stainless steel shows 1800 MPa tensile strength with 50% elongation due to containing low density Al and the generation of twins during the transformation of FCC austenite to BCC martensite at the time of tensile testing [140]. Cryorolling followed by annealing of AISI304L stainless steel austenitic grade exhibits 1295 MPa tensile strength and approximately 20% ductility, forming bimodal grains and twinning effect [141]. The drawback of AISI 301 austenitic stainless steel for structural purposes is its low yield strength (250 MPa – 350 MPa), which can be improved by grain refinement using repeated cold rolling and annealing thermomechanical treatments up to 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 exhibits nearly 1570 MPa U.T.S. and 15.7% elongation due to the formation of twinned martensite in the matrix [143]. Recently, ultrafine grain (270 nm) AISI 304 steel shows 1890 MPa Y.S. and 2050 MPa U.T.S. with 6% ductility [144].

10. Conclusion:

From the detailed literature study, it is clear that there is a high demand for advanced stainless steel with high strength and moderate ductility for future transportation and structural body manufacturing purposes. Over the past three decades, significant progress has been made in developing advanced high-strength steel. The first generation of these steels exhibits excellent tensile properties, with yield strengths in the range of 800-1000 MPa and ultimate tensile strengths of 1200-1600 MPa, along with 20%-13% ductility.

The second generation, known as TWIP steel, has ultimate tensile strengths ranging from 900-1700 MPa and approximately 20% ductility. The third generation of steels can achieve maximum ultimate tensile strengths of 2000 MPa and nearly 18.1% formability through hot stamping and bake hardening treatments. These advanced steels are commonly used in the production of automobile parts, body sheets, panels, crashworthiness components, and various accessories. In the past decade, attention has shifted towards austenitic grade steels, which have gained popularity in the structural and automobile markets due to their superior corrosion resistance properties and enhanced mechanical properties. The development of nano/ultra-fine grain AISI 201 steel, which has yield strengths as high as 1200 MPa, ultimate tensile strengths of 1500 MPa, and approximately 35.01% ductility, holds promise for the future. Additionally, a low-density austenitic grade steel with superior strength and ductility, achieving yield strengths of nearly 500 MPa, ultimate tensile strengths of 1800 MPa, and 50% elongation, has been developed through twin-assisted martensitic processes.

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