IRON AND STEEL THROUGH THE AGES AND THE CURRENT SCENARIO

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ABSTRACT

The paper provides a broad overview of the changing scenario that the iron and steel industries have witnessed over the ages as well as in current times in terms of the technology of manufacture and applications. It has been emphasized that with the great strides taking place in the fabrication and design of automobiles and sophisticated engineering machines and structures, there is a great demand on engineered materials such as iron & steel to change appreciably. Fortunately, the steel industry has responded very well to the progressively tighter demands of affordability, superior performance and environmental responsiveness. Therefore, it is envisaged that iron and steel will continue to play a major role in the future industrial evolution of the human civilization as in the past.

INTRODUCTION

It is well known that iron and steel materials have been playing a crucial role in shaping the human civilization. The origin of iron, although obscure in accurate historical terms, had a beginning perhaps in Egypt/China/ India some 4000 years ago. From the ancient rudimentary implements, then the famous Damascus swords of long ago ,steel has moved into the manufacture of sophisticated transportation systems; machines ; special constructions (building as well as bridges); large thermal, hydro or nuclear power stations; aggressive chemical industries ; and so on. Indeed the spectrum is so wide that a comprehensive list of applications alone could cover a few hundred pages. In terms of volume, steel production has topped 930 m. tones in the year 2002 in the world and is second only to concrete as the most voluminous engineered material on the globe today. Therefore, tracing the history of this material and bringing it update is as fascinating as it is daunting. The paper would attempt to provide some features of the Iron and Steel technology in the ancient period, subsequent developments in mass production and quality and then focus on the status of new developments in recent times, particularly in the auto sector.

HISTORICAL BACKGROUND

It is generally believed that the bronze age provided the discovery of iron which was an act of serendipity since iron ore was used as flux for bronze making. However, the early civilization realized the superiority of iron over bronze in terms of the ease of fabrication and soon iron / steel making took the status of a wide spread industry.

In India iron was being produced during the pre-historic vedic period as it is mentioned in the scriptures. Elaborate description is found on iron & steel in the Vedas & other scriptures (e.g 'Rasa Ratna Samucca,' ~ 100AD). The latter named source documents the classifications of iron/steel (e.g. 'Kanta Loha Soft Iron ; 'Tikshna Loha' high carbon material etc.). In ancient times iron was primarily used for making rudimentary implements and agricultural tools and later in the manufacture of weapons.

Damascus Swords

The use of iron base material (e.g. 'Wootz' metal) for producing high class weapons such as Damascus swords has, through the ages attracted a number of researchers. Yet, a complete understanding of the process by which the steel was made and heat treatment given by the artisans did not unfold until only three years ago for explaining the intricate patterns ('damask') on the smooth surface of the sword. Prof. Verhoeven of Iowa State University, has now been able to replicate the patterns with the help of small quantities (~0.04% of V) in the ore. Interestingly, in many ways it also represented a precursor to the sophisticated field of superplasticity in the high - carbon steels as Prof. O Sherby of Stanford has established. Some references to Damascus steel during various periods is indicated in the Table 1. It is also known that apart from India, the technology flourished also in a few other countries. The famous Damascus swords still continues to thrill the modern scientists.

Table 1 : Source of information on Damascus Steels

- Adze blade, Al Mina coast of Turkey (about 400BC)
- The time of Alexander the great (about 323BC)
- Earliest description available since 540 AD
- Europeans first encountered this steel during the crusades
- Best blades believed to have been forged in persia from Indian 'Wootz', also used for shields and armours
- In medieval Russia called 'Bulat'
- In Japan the recorded history shows the making of swords around 700AD (technology also available in China) known as 'UWAGANE', made from 'Kera' steel.
- Since the ancient times Samurai valued Japanese swords for its form(sugata), hardened zone (yakiba) ,beautiful pattern (Hamon) and sculpture (Chokoku)
- Work of Michael Faraday in 1919 (before he invented electric motor), Robert Breant in 1821 (of Paris Mint) and Pavel Anosoff in Russia 1841.
- Work of Prof. O Sherby in Stanford & Prof. Verhoeven of Iowa State Univ. contributed extensively to the understanding in the field.

Delhi's Iron Pillar

This is again a fine example of India's great heritage in iron making. Recent work on the same has shown the presence of a layer of the hydrated iron hydrogen phosphate ($FePO_4$,H3PO_4,$4H_2O$) layer & then an amorphos S-FeOOH layer over the base metal that greatly resisted corrosion / oxidation of the pillar.

Iron Making through the Ages

Man possibly came across iron, 'accidentally' some 4000 years ago that had originated through the impact of meteorites. Iron also appeared as a by-product of bronze smelting during ancient times. During the period 2500 BC to about 1000 AD, iron was produced through direct reduction mostly in small furnaces, blooms were produced through repeated heating & forging. In China, cast iron is documented to have appeared around 400 BC. The invention of tilt hammer in the 12th century marked an important turning point in the history of iron making enabling man to be replaced by mechanical systems. Similarly the early 14th century brought in further advantage with the emergence of water-powered bellows; the 14th century also saw the development of cast iron (for direct casting) using inherent phosphorus (that leads to low melting point). The invention of printing press in the 16th century contributed to the dissemination of knowledge ("De Re Metallica" by German Agricola,1546) and the production of iron through blast furnace became widespread by the middle of the 16th century; large scale production led to reduction in the manufacturing cost. The use of puddling process for producing low carbon wrought iron by blowing air into pig iron (H. Cort and P. Onion, 1784) marked another important milestone. Here, the reverberatory furnace was used and up to the 19th century this remained as the only method for producing good quality steels. It may be noted that all the steels used in the famous Eiffel Tower of Paris was through this route. In the 18th century (work of Darby in England), charcoal was replaced by coal in the Blast Furnace and later on , in secondary refining furnaces. This was a step towards protection of forests and paved the way for the development of metallurgy as is known today.

The modern period of iron-making practically started in 1850 and never looked back. In this period, the first development was the Bessemer Converter (1856); thereafter, the Siemens-Martin (Open Hearth, 1865), Thomas Basic Bessemer (1877) and finally the Oxygen blown LD (1950) converters brought the steel making to its present state. One must also mention the introduction of electrical steel-making in 1930 which has made rapid strides since and accounts for around 40 percent of the world's total steel production. Apart from the main process of steel making, the secondary processes (e.g. vacuum treatment etc) have also contributed to development of newer grades of steel (e.g. interstitial free with 25-30ppm carbon) and led to the improvements in performance of existing grades through enhanced cleanliness. The major stages of development is shown in Table 2.

Table 2 : The major stages in the history of carbon steels

4000 BC	**"Accidental" iron**
	Meteorites
	By product of bronze smelting
2500 BC	**Direct reduction**
	Small furnaces, production of blooms requiring repeated heating and forging
-500	Partially decarburized blooms : Noricum steel
-400	Discovery of cast iron in China
100	Iron appears in Gaul
1100	Invention of the tilt hammer
1300	**Cast iron**
	Larger furnaces, production of pigs, remelted and refined in an air blast
1300	Invention of water-powered bellows
1550	Printing influences dissemination of knowledge (e.g. De Re Metallica)
1760	Replacement of charcoal by coal
1784	Invention of the puddling process
1850	**Modern metallurgy**
1856	Bessemer converter
1865	Siemens-Martin (open hearth) furnace
1877	Thomas (basic Bessemer) process
1900	Production of converter steel overtakes wrought and puddle iron
1950	Oxygen-blown converter
1930	**Electric steelmaking**

Development in the Fe-C Diagram

Apart from the developments in steel making processes, the understanding of iron-carbon phase diagram (developed over a period) contributed to the basic knowledge and led to the design of several new steels. At the end of the 18th century, the work of Lavoisier, Bergman, Berthollet and Morge explained the exact role of carbon and established Fe-C diagram which serves as the foundation of the modern developments in steel making and heat treatment. Subsequently, Tchernoff (1808), Souveur (1896), Roberts –Austen(1897), Roozeboom (1900) and Honda(1920) all contributed to the refinement of the phase diagrams in one way or the other. There has not been any major change since then except for some correction in solid solubility of carbon in the gamma phase from 1.7% to 2.08% (1948).

CURRENT SCENARIO OF STEEL MAKING

The production of steel in the world has risen steadily over the years and more so with the advent of the rapid steel making process, viz. the LD-process. The world steel production along with that of population is shown in fig.1.

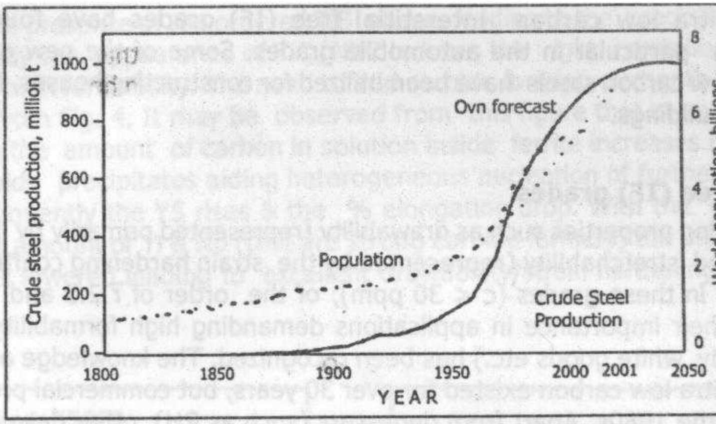

Fig. 1: Comparison of world population and worldwide crude steel production

The world steel production during the year 2002 topped 930 m tones & is predicted to grow further. The global per capita also grew to a peak of about 170 kg / head around 1980 and currently this figure is around 130 kg / head. Incidentally India, which has a production figure of around 30 m tones per year of steel, has a per-capita consumption of only 23 kg / head; therefore there is a substantial potential for increase in consumption in India and in similar developing countries. Along with the facilities for rapid steel making in oxygen blown converters & increase in the volume, steel scenario also experienced qualitative improvements with the introduction of a variety of degassers. In Fig.2, one would find that in the 90s, carbon & nitrogen in steel can be dropped to as low as 25-30 ppm and in recent times, carbon content has come down to 10-15 ppm with the introduction of RH-OB.

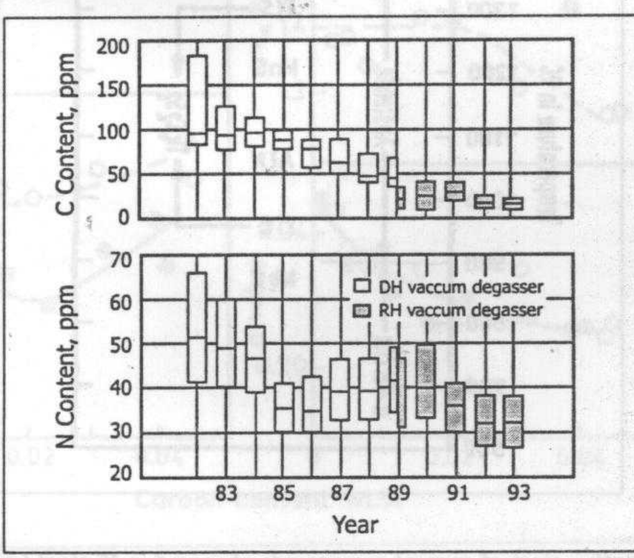

Fig. 2 : Development of carbon and nitrogen contents of IF steels

These ultra low carbon interstitial free (IF) grades have found wide applications, in particular in the automobile grades. Some of the new grades of high strength low carbon steels have been utilized for constructing houses, including the high-rise buildings.

Interstitial Free (IF) grades

The forming properties such as drawability (represented primarily by Lankford parameter r) and stretchability (represented by the strain hardening coefficient, n) are quite high in these grades (c < 30 ppm); of the order of $\bar{r}$ 2.3 and n > 0.2. Consequenly, their importance in applications demanding high formability (i.e. in automotive body, white goods etc.) has been recognized. The knowledge about the advantage of ultra low carbon existed for over 30 years, but commercial production started only in the 1980s. Apart from degassers (such as RH), other developments viz. continuous annealing (CAL) practice and hot dip galvanizing facilities contributed to their rapid spread. Broadly, in these steels the sequence of precipitation is very different (Fig. 3) as the S:C:N is around 1:1:1 (as opposed to 1:10:10 in more conventional low-carbon steels).

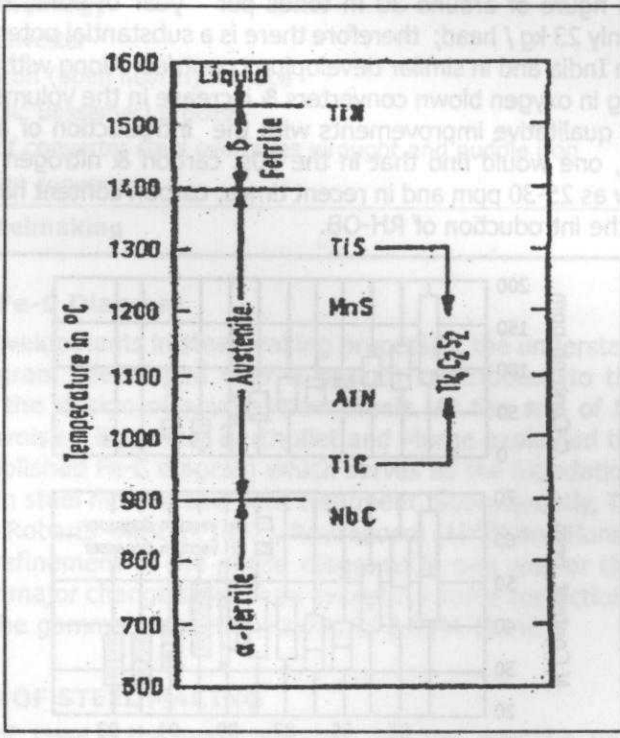

Fig. 3 : Precipitation start of several compounds observed in IF steel (<30 ppm C, <40 ppm N, > 0.02% Al, <0.10% Ti, <0.03% Nb)

The presence of the ordered TiS phase, leading to the precipitation of $Ti_4C_2S_2$ and finally the appearance of TiC / NbC induces the right crystallographic texture & hence high formability. The need to add carbide forming elements such as Ti / Nb is clear from Fig. 4. It may be observed from this figure that at very low-C (~ 30-40 ppm) the amount of carbon in solution inside ferrite increases because of very few carbide precipitates aiding heterogeneous nucleation of further carbides of Fe & consequently the YS rises & the % elongation drop. With the addition of the requisite amount of Ti & Nb (that are strong carbide formers) the residual carbon in ferrite is lowered leading to excellent drawability/strain hardening.

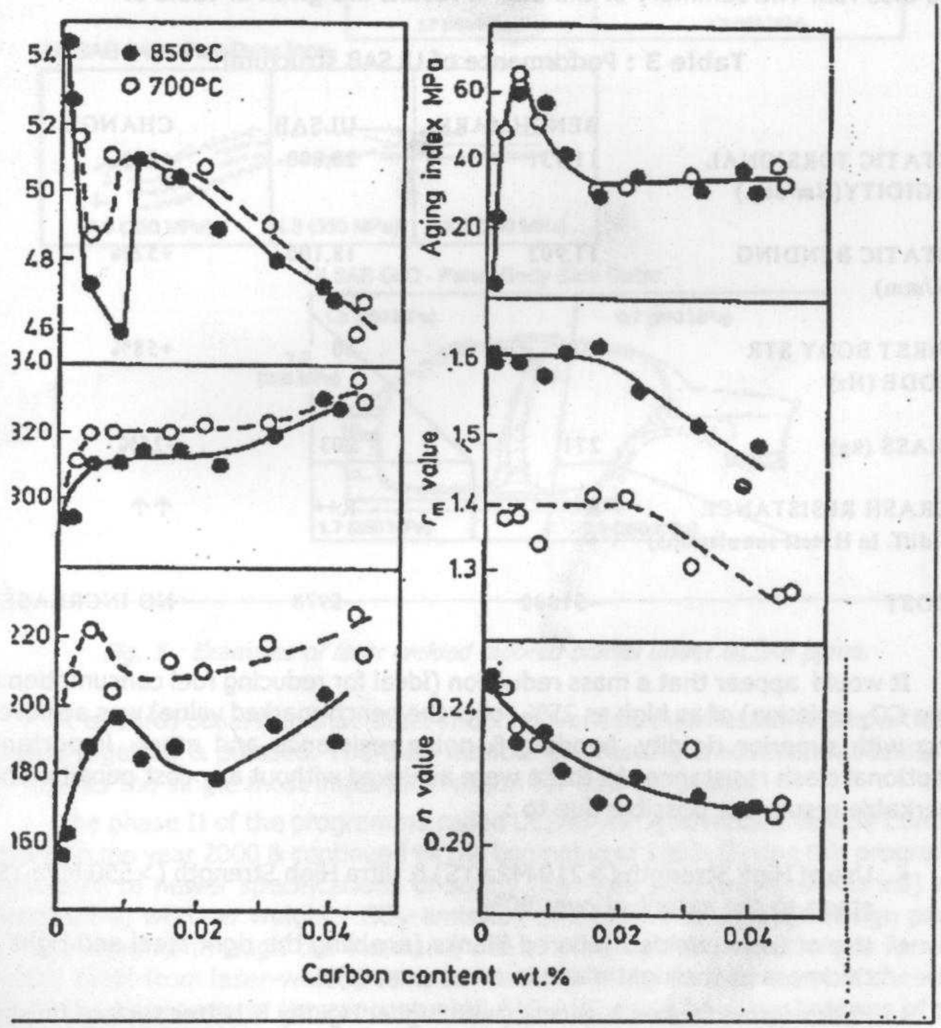

Fig.4 : Characteristics of low carbon unstabilised steels

Ultra Light Steel Auto Programmes : Development of Advanced High Strength Steel Grades

The automotive body represents a complex combination of mechanical properties (strength, rigidity, collapse strength, dentability, formability including drawability, stretchability, bendability, flangability & their combinations) & weldability etc. In addition, safety aspects such as crash resistance of the structure and environmental acceptance (CO_2-emission per unit distance of travel) along with cost factors bring in additional considerations. Keeping all these parameters in view an international consortium called ULSAB (Ultra Light Steel Auto Body) of 33 steel companies) was undertaken around 1995 and ended in the beginning of 2000 with M/s. Porsche Engg. as consultants. Simultaneously, parallel programmes such as Ultra Light Steel Auto Closures (ULSAC) & Ultra Light Steel Auto Suspension (ULSAS) were also run. The summary of the ULSAB results are given in Table 3.

Table 3 : Performance of ULSAB structural

	BENCHMARK	ULSAB	CHANGE
- STATIC TORSIONAL RIGIDITY(Nm/deg.)	11,531	20,800	+80%
- STATIC BENDING (N/mm)	11,902	18,100	+52%
- FIRST BODY STR MODE (Hz)	38	60	+58%
- MASS (kg)	271	203	-25%
- CRASH RESISTANCE (5 diff. In H. test simulations)	R	R++	↑↑
- COST	~$1000	~$978	NO INCREASE

It would appear that a mass reduction (ideal for reducing fuel consumption & hence CO_2 emission) of as high as 25% (over the bench-marked value) was achieved along with superior rigidity, bending & noise resistance and most important, exceptional crash resistance. All these were achieved without any cost penalty. This remarkable result was possible due to :

- Use of High Strength (>210 MPa YS) & Ultra High Strength (>550 MPa YS) steels to the extent of over 90%.
- Use of Laser-Welded Tailored Blanks (enabling the right steel and right thickness at the right place in a component).
- Hydro-formed tubes & sheets (with higher rigidity & better surface finish).

It may be noted that tailored blanks are in production since 1985. Some examples of the car components using laser-welded tailored blanks are shown in Fig. 5.

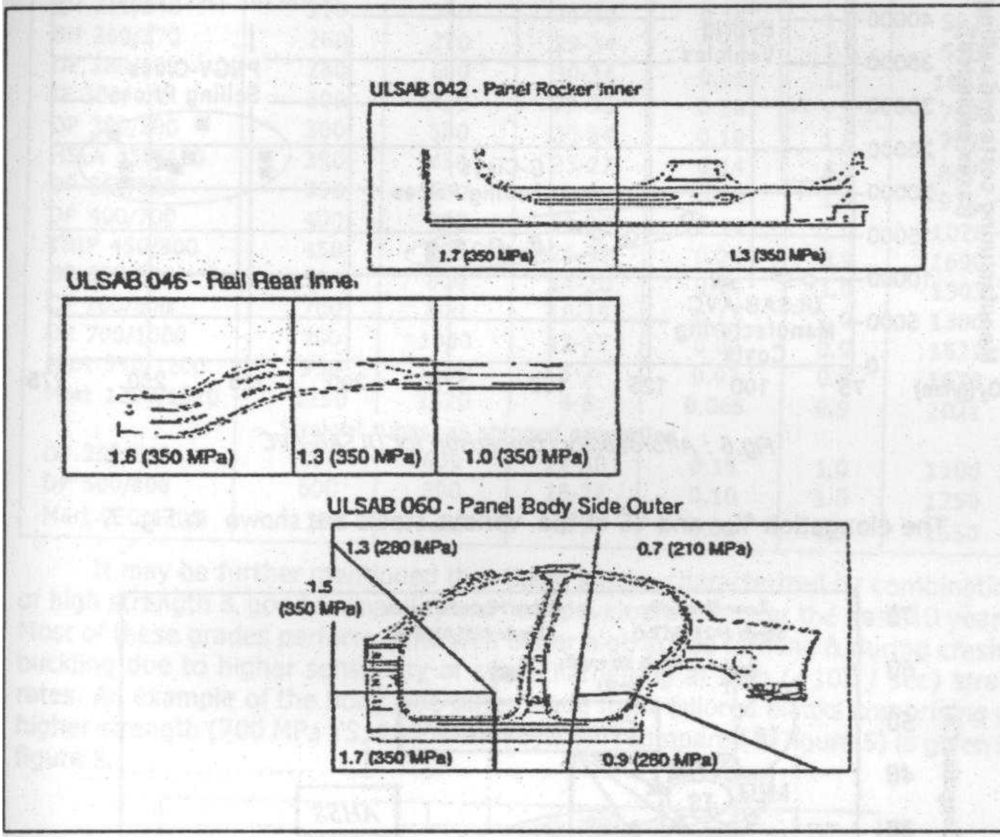

Fig. 5 : Examples of laser welded tailored blanks under ULSAB pgme.

It is worth observing that steel sheets of various thicknesses & properties are welded together & pressed. The total number of pressings reduced drastically that represents the single most important reason for cost reduction.

The phase II of the programme called ULSAB-AVC (advanced Vehicle Concept) started in the year 2000 & continued till the beginning of 2003. During this programme adherence to newer specifications of safety (i.e. side pole-crash resistance) were tested along with car weight / CO_2-emission and cost. The concept design passed all requirements through the extensive use of advanced high – strength formable grades apart from laser-welded tailored blanks & hydro-formed tubes & sheets. In Fig. 6, the superiority of the conceptual ULSAB-AVC could be seen, in terms of cost-effectiveness & CO_2-emission.

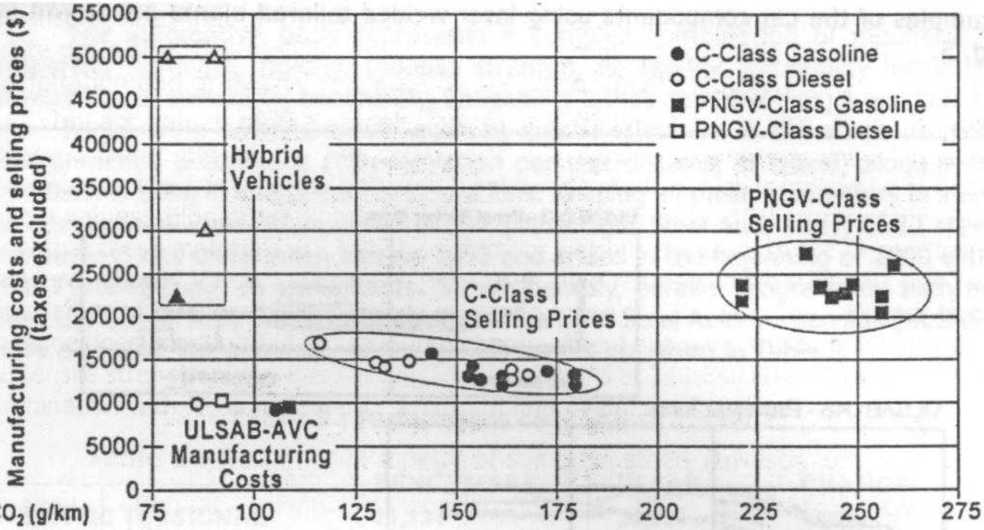

Fig.6 : Affordability comparison for ULSAB-AVC

The elongation %, and YS of the various steels are shown in Fig. 7.

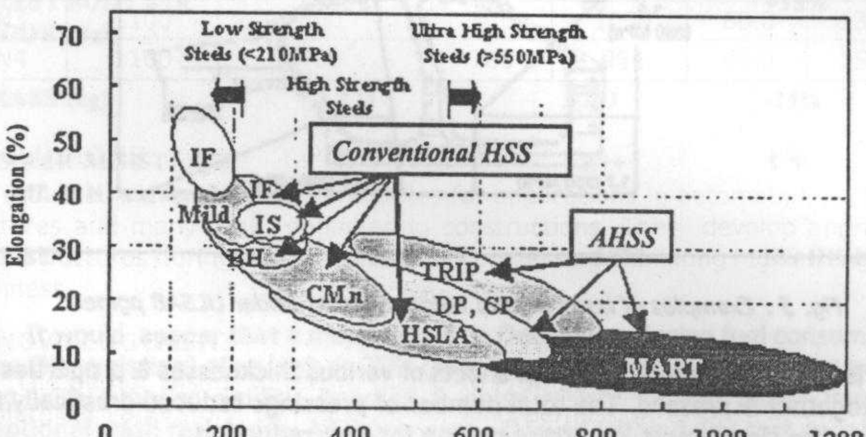

Fig. 7 : Mech. properties of HSS/AHSS

The use of Advanced High Strength Steels such as TRIP (Transformation Induced Plasticity), DP (Dual Phase), CP (Complex Phase), MART (martensitic) have been extensive in this (ULSAB-AVC) conceptual design programme. A list of various current steels & their properties are given in Table 4.

Table 4 : List of steels used in ULSAB-AVC & their properties

Steel Grade	YS (MPa)	UTS (MPa)	Total FL (%)	n-value (5-15%)	r-bar	K-value (MPa)
		First sheet, as shipped properties				
BH 210/340	210	340	34-39	0.18	1.8	582
BH 260/370	260	370	29-34	0.13	1.6	550
DP 280/600	280	600	30-34	0.21	1.0	1082
IF 300/420	300	420	29-36	0.20	1.6	759
DP 300/500	300	500	30-34	0.16	1.0	762
HSLA 350/450	350	450	23-27	0.14	1.1	807
DP 350/600	350	600	24-30	0.14	1.0	976
DP 400/700	400	700	19-25	0.14	1.0	1028
TRIP 450/800	450	800	26-32	0.24	0.9	1690
DP 500/800	500	800	14-20	0.14	1.0	1303
CP 700/800	700	800	10-15	0.13	1.0	1380
DP 700/1000	700	1000	12-17	0.09	0.9	1521
Mart 950/1200	950	1200	5-7	0.07	0.9	1678
Mart 1250/1520	1250	1520	4-6	0.065	0.9	2021
		Straight tubes, as shipped properties				
DP 280/600	450	600	27-30	0.15	1.0	1100
DP 500/800	600	800	16-22	0.10	1.0	1250
Mart 950/1200	1150	1200	5-7	0.02	0.9	1550

It may be further mentioned that these steels, characterized by combination of high strength & good formability are new developments over the past 10 years. Most of these grades perform quite well under high speed forming & during crash / buckling due to higher sensitivity of strain hardening at high (~102 / sec) strain rates. An example of the body side outer made from tailored blanks comprising of higher strength (700 MPa YS, 1000 MPa TS) steel (compared to figure 5) is given in figure 8.

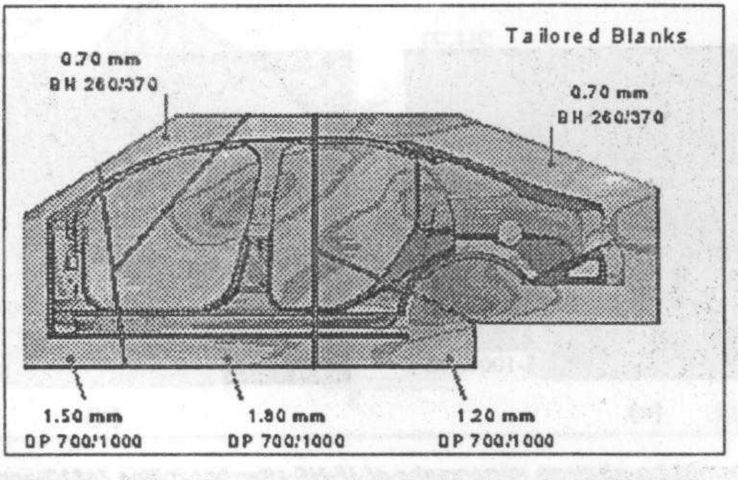

Fig. 8 : Body side outer as tailored – blank under ULSAB-AVC

New Auto Grades at Tata Steel

Some of the newer grades developed at Tata Steel for auto body application include the following :

- IF-grades (both Ti-and Nb bearing)
- IF-HS dent resistance
- Bake – Hardenable (BH)
- Dual – Phase (DP) in high-rolled

Some details of the IF-high strength dent resistant grade would be given now. Typical mechanical (strength & formability) properties are given in Table 3.

The micro- structural features in the hot-rolled (HR) and cold rolled + annealed (CR+A) condition are shown in a TEM (Fig. 9).

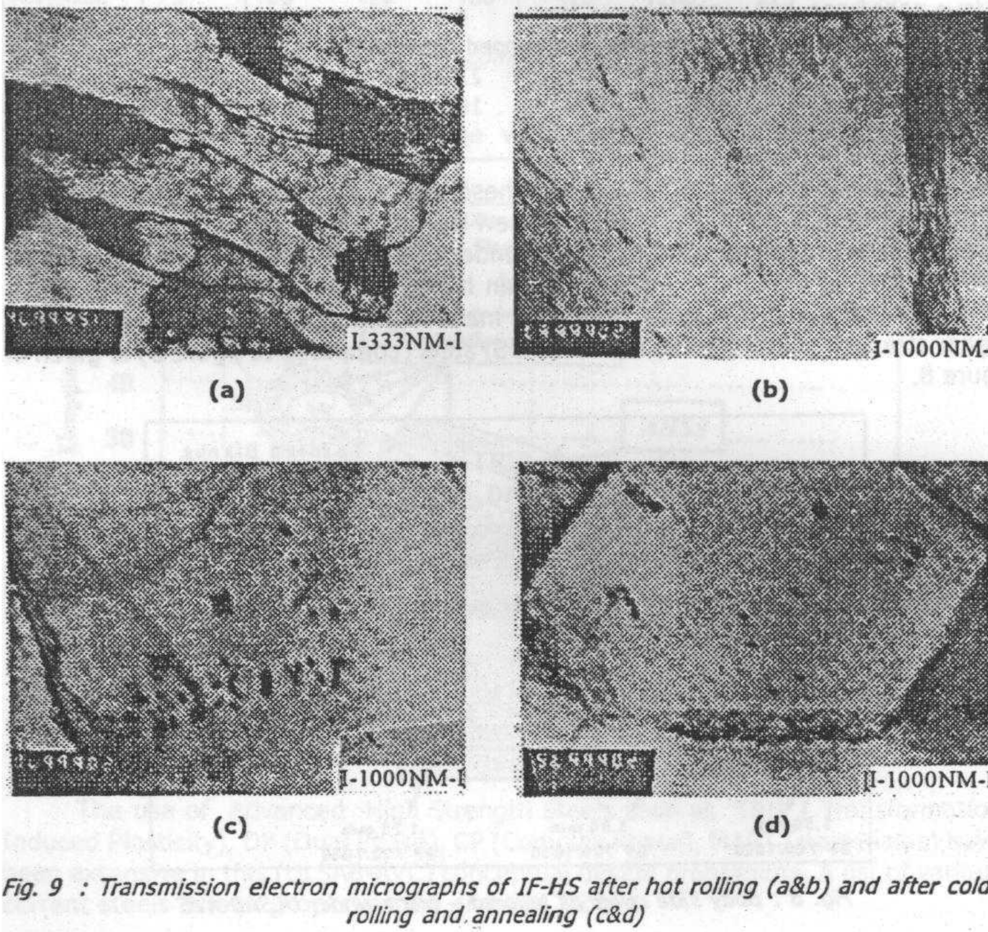

Fig. 9 : Transmission electron micrographs of IF-HS after hot rolling (a&b) and after cold rolling and annealing (c&d)

The equi-axed grains along with precipitates are to be noted in the CR+A condition. This steel, in the CR+A condition was press-formed into the outer of a car-door. For this, the computer-aided tool configuration (Fig.10) and the subsequent FLD- predictions (for a conventional EDD and for IF-HS) are given (Fig. 11).

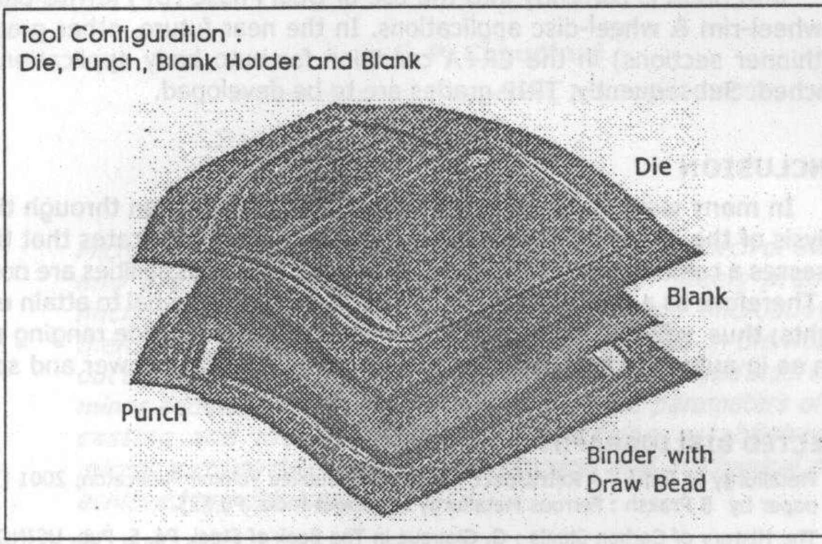

Fig. 10 : Tool configuration for door outer

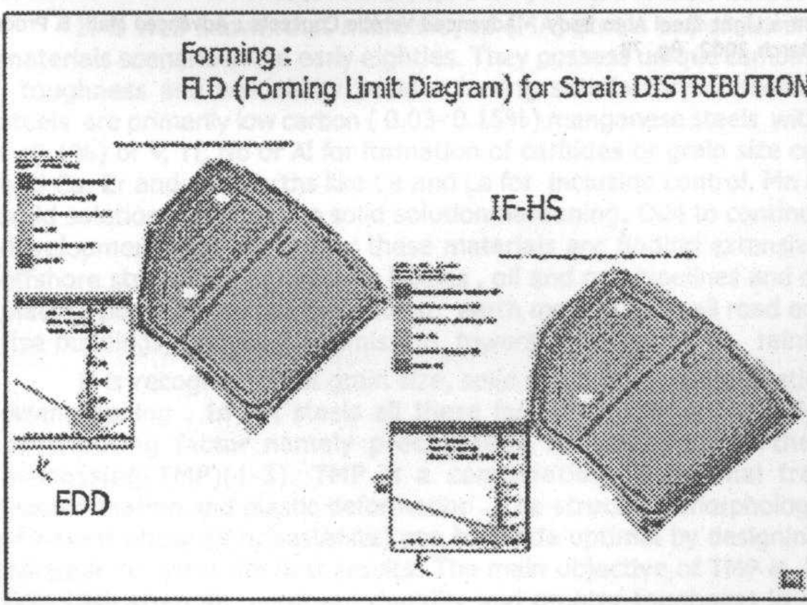

Fig. 11 : FLD & Strain distribution for EDD & IF-HS steels

It would appear that the strain distribution for IF-HS material is all within the safe limit of the forming limit diagram (FLD) and there is no cracking in the active areas. Following the positive observations in the simulation, the IF-HS sheet material was used extensively for press-forming the door outer of cars.

Tata Steel is currently into the use of Dual Phase (DP) ferrite-bainite grades for wheel-rim & wheel-disc applications. In the near future, other grades, viz. DP (in thinner sections) in the CR+A condition for auto body applications would be launched. Subsequently, TRIP grades are to be developed.

CONCLUSION

In many ways, steel has shaped the human civilization through the ages. An analysis of the use of steel over the past decade clearly indicates that this material possesses a remarkably wide range of properties & the possibilities are not exhausted yet. Therefore as a special material, steel has a great potential to attain even greater heights; thus will remain the most dominant material in wide ranging applications such as in auto, machine building, construction, electrical power and so on.

SELECTED BIBLIOGRAPHY

1. Metallurgy in India – A Retrospect, NML Golden Jubilee Volume Publicaton, 2001 [In particular, paper by B Praksh : Ferrous Metallurgy in Ancient India, Pg.52].
2. The History of Carbon Steels : G. Giauque in The Book of Steel, Pg. 5, Pub. USINOR SACILOR Group & Intercept Ltd., 1996.
3. World Steel Dynamics, Eds. : Peter Marcus, Karlis, M. Kirsis Core Report, Feb. 2002
4. Technical Transfer Dispatch (Nos. 1-6); ULSAB-AVC, 2000-01.
5. Ultra Light Steel Auto Body - Advanced Vehicle Concepts : Advanced Matl. & Processes, March 2002, Pg. 78.