ISSN 0967-0912, Steel in Translation, 2008, Vol. 38, No. 10, pp. 876–880. © Allerton Press, Inc., 2008.
Original Russian Text © V.A. Ivoditov, M.M. Perkas, A.E. Shelest, V.S. Yusupov, 2008, published in "Stal'," 2008, No. 10, pp. 100–105.

Materials Science in Automobile Design

V. A. Ivoditov, M. M. Perkas, A. E. Shelest, and V. S. Yusupov
Baikov Institute of Metallurgy and Materials Science, Russian Academy of Sciences, Moscow

DOI: 10.3103/S0967091208100197

Any vehicle must satisfy four primary criteria, sometimes referred to the SAFE criteria: safety, affordability, fuel efficiency, and environmental friendliness. In the current state of the auto industry, the significance, relative levels, and mutual influence of these criteria depend on technical, social, economic, political, and many other factors. They are governed by specific requirements (including legal requirements), while the overall trend is stricter regulation. Safety is generally in conflict with the other three requirements. Thus, increasing safety entails capital expenditure for more effective and reliable passive safety systems and the introduction of active energy-consuming systems, which, in turn, increases the mass of the vehicle and hence the fuel consumption and the environmental impact.

Satisfaction of the SAFE criteria calls for practical experience, technical expertise, design skills, a mathematical approach, and the insights of materials science, among other factors.

It is of interest to consider means of satisfying the SAFE criteria for the auto industry, which is one of the world's largest consumers of steel. When we speak of auto-industry steel, we are referring to a product of ferrous metallurgy that is subjected, at auto plants, to pressure treatment (shaping), welding, cementing, and other methods of manufacturing components such as the body, the suspension, the wheels, and the fuel tank. Auto-industry steel is supplied in rolls or sheets, as a rule, and may be regarded as sheet steel.

Possible means of satisfying the SAFE criteria (within the proposed approach) are illustrated in the figure.

The simplest option in terms of affordability, fuel efficiency, and environmental impact is to reduce the vehicle mass. Four approaches are possible here.

The first is to reduce the size of the vehicle without changing the basic materials employed. Besides the benefits in terms of affordability, fuel efficiency, and environmental impact, this approach increases highway capacity and frees up parking spaces in metropolitan areas. In the long term, this trend will probably predominate, and most cars globally will be small or very small. Today, however, the large-scale introduction of small vehicles is hindered not only by subjective factors (notably, years of familiarity with spacious and comfortable cars in North America) but by objective considerations, primarily safety. Small cars constrain the use of passive and active safety systems. Until these considerations can be overcome (and quick progress cannot be expected), this approach is unacceptable. Note that, with slight changes in industry standards, vehicle safety has been transformed, for the consumer, from a somewhat abstract concept to a factor evaluated on the basis of objective crash-test data.

The second means of reducing vehicle mass is to employ light alloys, composites, and plastics. Thanks to their significantly lower density and higher corrosion resistance, these materials are significant competitors for steel, but a number of factors impede their widespread introduction: high cost, the need to retool auto plants, and (most importantly) safety concerns on account of their considerably lower strength. Note, however, that the use of such materials is growing. Today, steel accounts for 50% of the average automobile, while these lighter alternatives account for ~18% (mostly components of the motor, the internal trim, and wiring).

The third approach is to reduce the thickness of the steel sheet. However, if the corresponding loss of strength is not compensated in some way, the carrying capacity of the body will inevitably be reduced, with unacceptable safety consequences. To a certain extent, these losses may be compensated in practice by further optimization of the shape of the components. However, this design approach is equally effective for any approach to reducing vehicle mass and therefore contributes no relative advantage. Moreover, it is of independent value and falls outside the scope of the materials-science framework here adopted. Thus, this means of reducing the vehicle mass also fails to meet the safety criterion.

Hence, these simple means of reducing the vehicle mass cannot fully comply with safety requirements.

For the foreseeable future, the fourth approach is the only viable option: reducing vehicle mass by using thinner elements made of high- and superhigh-strength steel.

We will now briefly consider the market for auto-industry steel, the classification of such steel, and the main trends in steel development.

In response to the growing global competition among firms in the aluminum and chemical industry that supply materials used in auto production, the major national and transnational steel producers have joined forces. The integration of the largest global steel manufacturers—almost 30 companies, including JFE Steel, Kawasaki Steel, and Kobe Steel (Japan), SSAB (Sweden) POSCO (South Korea), and US Steel—has been underway under the coordination of the Automotive Committee (AUTOCO) of the International Iron and Steel Institute (IISI).

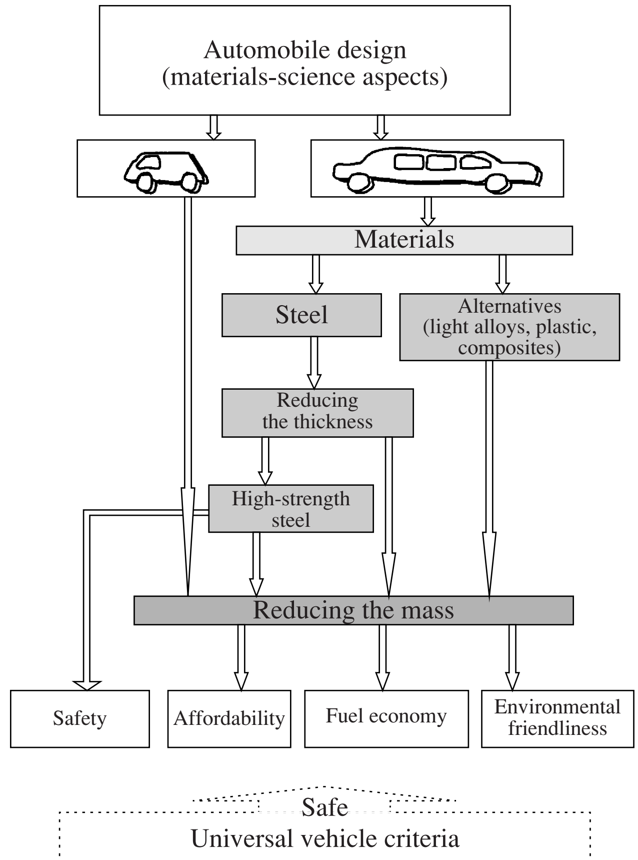
These programs are focused on the creation of superlight, economical, safe, and environmentally sound vehicles. The committee coordinates the activities of the leading producers to develop new steels. Standard documents are formulated regarding the use of high-strength steels and new processes of steel production and treatment for the auto industry. Considerable efforts have been made to systematize existing and prospective auto-industry steels.

Table 1 outlines the main features of the AUTOCO programs.

Judging from recent data, these efforts have not been in vain [1]: the consumption of auto-industry steel between 1993 and 2004 rose from 85 to 140% (relative to 1991). In the United States, the auto industry consumed all steel produced. Note that the increasing consumption of auto-industry steel in the United States is accompanied by improvement in its properties and expansion in the available range. In the last ten years, the range of steel grades employed globally in the auto industry has risen by 70% (according to the UK Steel Bulletin, August 20, 2005).

These trends call for the refinement of current concepts regarding the range, properties, application, and development of steel.

The existing classification of auto-industry steel is generally portrayed as a graph of elongation against strength (yield point or short-term strength), which is clear but lacking in sufficient information. A tabular classification including the characteristic chemical composition of each type of steel, its mechanical and operational properties, and its area of application in the auto industry was proposed in [2]. The steel is classified according to the classes and types used by the US Steel Group [3]. This classification is somewhat contradictory, since the steels are ranked in terms of opposing characteristics (plasticity and strength). However, it is historically based and reflects radical changes in steel development over time.



Automobile design

Automobile design.

Four classes of steel are identified: low-carbon steel (LC), dent-resistant steel (DR), high-strength low-alloy steel (HSLA), and advanced high-strength steel (AHSS). These classes are supplemented by types of steel recently developed or included in the range. Note that these classes, although not standardized, correspond precisely with current practices.

LOW-CARBON (LC) STEEL

The division into types within the LC class (Table 2) reflects trends that were dominant up to the beginning of the 1990s, when, in response to consumer demands, attention focused on the technological properties of steel—in particular, its shaping properties—and operational properties were a secondary concern. The types of steel in this class are ranked in order of greater susceptibility to deep drawing. This class also includes recent Japanese and South Korean developments: IF steels of Super-EDDS and Hyper-EDDS type with an anisotropy coefficient no lower than 2.5 and 2.7, respectively [4, 5]. The further development of steel in this class is inexpedient, since it already complies fully with auto-industry requirements and is close to physical limits. In addition, attention has now shifted to the

Table 1. Programs coordinated by AUTOCO

Creation of ultralight auto-body steel (ULSAB)	Creation of ultralight auto-closure steel (ULSAC)	Creation of ultralight auto-suspension steel (ULSAS)
– reduction in body mass by 25%, without increase in cost; – increase in torsional strength by 80%; – increase in flexural strength by 52%; – compliance with all crash-test standards	– reduction in mass by 42%; – reduction in door mass by 22% relative to the best reinforced doors	– reduction in mass by 34%; – approximate parity with the mass of aluminum-alloy systems, at 30% lower cost
Development of the advanced vehicle concept (ULSAB-AVC)		
AUTOBO IISI initiative for the creation of new steels and corresponding manufacturing technologies and new licensing procedures for C-class automobiles corresponding to the SAFE criteria: – safe: corresponding to high safety requirements; – affordable: the cost of the C-class automobile must be \$9200–20 300; – fuel-efficient: fuel consumption 3.2–4.5 l/100 km; – environmentally friendly: the use of steel with guaranteed recycling potential and minimization of exhaust emissions.		

Table 2. Low-Carbon (LC) Steels

Commercial steel (CS)	Drawing steel (DS)	Deep drawing steel (DDS)	Extradeep-drawing steel (EDDS)	
			–	interstitial-free (IF mild) steels*
Uncontrolled characteristic chemical composition (C < 0.15%)	Characteristic chemical composition: 0.02–0.08% C; ≤0.5% Mn; ≤0.02% P; 0.03% S	Characteristic chemical composition: 0.06% C; ≤0.55% Mn; ≤0.02% P; 0.0025% S. Impurity content strictly controlled	Characteristic chemical composition: 0.02% C; ≤0.03% Mn; ≤0.025% P; 0.025% S. Impurity content strictly controlled	Characteristic chemical composition: 0.002–0.006% C; ≤0.25% Mn; ≤0.015% P; ≤0.005% N; 0.06–0.08% T; ≤0.008% S
Characteristic properties: σ_y = 207 N/mm^2; σ_B = 204 N/mm^2; δ = 38%; no regulation of n. Inclination to aging with drop in σ_y and also to general and saline corrosion. Welds well and withstands fatigue loads	Characteristic properties: σ_y = 175 N/mm^2; σ_B = 297 N/mm^2; δ = 44%; n = 0.232. Welds well and withstands fatigue loads	Characteristic properties: σ_y = 168 N/mm^2; σ_B = 279 N/mm^2; δ = 45%; n = 0.23–0.235. Welds well and withstands fatigue loads	Characteristic properties: σ_y = 110 N/mm^2; σ_B = 270 N/mm^2; δ = 48%; n = 0.240; R > 1.6. Not susceptible to aging	Characteristic properties: σ_y = 110–190 N/mm^2; σ_B = 270 N/mm^2; δ > 43%; n > 1.6
Used for the manufacture of internal components that do not require considerable drawing, rear cabin components, truck floors	Used for the manufacture of roofs, floors, doors, and hoods	Used for the manufacture of the same parts as DS steel, but tolerates greater drawing; also used for fuel tanks	Used for the manufacture of internal components that require deep drawing (bodies, doors, etc.)	

* In Japan, Super(S)-EDDS ultrashapable IF steel has been developed ($R \geq 2.5$ when $\delta > 50\%$); in South Korea, Hyper(H)-EDDS steel has been developed ($R \geq 2.7$ when $\delta > 50\%$).

operational characteristics of the steel (such as safety, ease of repair, shock absorption, and fuel economy by mass reduction). These requirements call for higher strength of the steel.

This approach is consistent with the classification of auto-industry steels outside the LC class. The same principle is adopted in considering the relations between steels within these classes.

Obviously, the pursuit of strength will unavoidably impair (sometimes significantly) the technological properties of auto-industry steel. Nevertheless, for the foreseeable future, if auto-industry steel is to be competitive, its reserves of strength must be tapped. Minimal shaping properties must be maintained. Note that these requirements have been significantly reduced thanks to improvements in manufacturing technology (hydraulic shaping, laser welding, etc.). In turn, tapping the steel's reserves of strength with acceptable shaping properties is impossible without employing up-to-date technologies at all stages of metallurgical processing. Such technologies are essential for effective utilization of various strengthening mechanisms: solid-solution strengthening, strengthening by a second phase or by

Table 3. Dent-Resistant (DR) Steels

Interstitial-free (HS IF) steels	Phosphor-alloyed or rephosphorized (PS or RS) steels	Ultralow-carbon steels (ULCS)	Bake-hardenable (BH) steels
Characteristic chemical composition: 0.003% C; 0.01% S; 1.2% Mn; 0.05% P; 0.0025% N; 0.05% Ti; 0.01% S; 0.04% Al; 0.0015% B (IF 260)	With up to 0.1% P	Characteristic chemical composition: ≤0.003% C; ≤0.14% Mn; 0.03% Nb; 0.06–0.08% Ti; 0.001–0.03% S; alloying with boron	Precision control of the carbon content in IF steels at the level 6–20 ppm, as well as Ti and Nb; some dual-phase (DP), P-alloyed, and TRIP steels are characterized by a BH effect
Characteristic properties: steel is strengthened on stamping (increase in σ_y by 35 N/mm^2 after 2% deformation); $\sigma_y \le$ 215 N/mm^2; σ_B = 450 N/mm^2; $n \le 0.2$. Used for the manufacture of doors and floors (including external components)	Characteristic properties: 08ЮП steel (an analog of ZstE 220 P steel, DIN 1623), $\sigma_y \ge$ 220 N/mm^2; $\sigma_B \ge$ 340 N/mm^2; $\delta \ge 34\%$; $R \ge$ 1.8, $n \ge 0.232$ Used for the manufacture of roofs, hoods, and other parts	Characteristic properties: σ_y = 220 N/mm^2; σ_B = 390 N/mm^2; $\delta = 37\%$; $n = 0.21$; $R = 1.9$. Used for the manufacture of body parts	Characteristic properties: σ_y = 180–280 N/mm^2; σ_B = 310–365 N/mm^2; n = 0.2–0.15. After 2% deformation and drying at 170–200°C, the increase in σ_y may be 70 N/mm^2. Used for the manufacture of doors, floors, and hoods

disperse particles (including nanoparticles), grain-boundary hardening, etc.

DENT-RESISTANT (DR) STEEL

This class (Table 3) begins with recently developed high-strength IF steels (such as IF-260, which is alloyed with phosphorus, up to 1.2% manganese, silicon, and boron), for which σ_B = 450 N/mm^2 [6, 7]. There is also information on the manufacture of auto body parts by means of Cu IF steels, containing up to 1.35% Cu and 0.65% Ni, which offer an excellent balance of strength and plasticity [8].

In considering BH steels within the DR class, we may note other bake-hardenable steels: phosphor steels ($\Delta\sigma_B$ = 40–60 N/mm^2), DP and TRIP steels in the AHSS class ($\Delta\sigma_B$ = 70 N/mm^2), and IF steels ($\Delta\sigma_B$ = 30–40 N/mm^2). Note that the latter steels cannot strictly be regarded as interstitial-free, on account of the presence of 5–20 ppm dissolved carbon, which ensures the BH effect [9].

HIGH-STRENGTH LOW-ALLOY (HSLA) STEEL

High-strength low-alloy (HSLA) steels are stronger than DR steels. They are characterized (Table 4) by a narrow range of types (traditionally only a single type, HSLA steel) and a broad range of grades. Some specialists question whether these are low-alloy steels and prefer to characterize them as microalloyed high-quality carbon steel. Steels in this class are alloyed with copper (0.2–1.0%) to improve the corrosion resistance. They are widely used for the manufacture of structural components of the Fors F150 US Army truck. This class also expediently accommodates isotropic steels that differ from HSLA steels in that the properties are very isotropic, alloying is more economical, and the strength and plasticity are higher. This class is still of high value. (According to various estimates, it accounts for 10–15 wt % of the auto body.)

ADVANCED HIGH-STRENGTH STEEL (AHSS)

The AHSS class (Table 5) includes a dynamically developing type of dual-phase (DP) steel, permitting 25% reduction in automobile mass. Thanks to the wide range of mechanical characteristics (for example, the short-term strength varies from 500 to 1000 N/mm^2), dual-phase steel should account for 75% of the auto-body mass according to ULSAB-AVC principles.

This class also includes the new type of TWIP steels (which are highly alloyed: up to 30% Mn and 9% Al), which ensure uniform elongation by as much as 80% with a yield point of more than 600 N/mm^2, on account of twinning deformation.

Steels with a TRIP effect are promising for the auto industry, since they have good shaping properties and high strength. Steel containing up to 1.32% Cu has recently been developed [10–12]. Copper facilitates the development of fine-grain structure and strengthening of the metal, while also increasing the proportion of residual austenite, which plays the major role in the TRIP effect.

Of course, martensitic steel is of most interest in this class. Strictly speaking, this is carbon (0.22%) steel alloyed with manganese (1.2%) and microalloyed with boron (0.002%). On quenching from 900°C in water, such steel passes from a relatively soft pearlitic state to a high-strength martensitic state. Such steel is supplied in the hot-rolled state and then subjected to hot stamping and subsequent quenching at the auto plant. By this means, the yield point and short-term strength may be almost tripled. Broader introduction of such steel is hindered by the bulk effect and by the impossibility of thermal straightening of elements deformed on impact.

The AHSS class includes the latest type of high-strength steels (NHSS). So far, this only includes steel strengthened by nanoparticles, developed by JFE (Japan) in 2005 (σ_B = 780 N/mm^2; δ = 18%) [13]. This steel is already being used to manufacture components of the suspension and frame. By further improvement in the balance of alloying elements and in precision (in terms of the deformation and heating conditions) hot rolling led to the introduction of Nano-hiten steel with σ_B = 1180 N/mm^2 and 15% increase in elongation at the end of 2007 [14].

It is probable that a new class of auto-industry steel may be developed from NHSS steel with new and perhaps revolutionary advances in materials science.

AHSS steel contains many phases, which permits adjustment of the strengthening mechanisms so as to maximize the strength and plasticity. In addition, it is possible to produce steels whose properties may be adjusted by the customer in accordance with certain design specification. In particular, the customer is interested in the precision use of different high-strength steels, even within a single component. At the same time, steel producers are tending to manufacture products such as welded subassemblies and hydraulically molded components that are ready for use on auto-plant assembly lines [15].

CONCLUSIONS

1. Today, the only realistic means of satisfying the SAFE criteria is the wide use of high-strength auto steels.

2. The range of available steels must be constantly updated by: a) improving the shaping properties of the relatively soft steels in classes LC and DR; b) increasing the strength of steels in the intermediate classes (in particular, DR and HSS), without impairment of the shaping properties; c) the development or adaptation (for auto-industry purposes) of AHSS steels with even higher strength and the minimum necessary shaping properties (including control of the multiphase composition).

3. As well as the trend to precision use of high-strength steel at auto plants (even for a single component), steel producers are tending to manufacture products ready for immediate use as auto components.

4. The latest trends n the auto industry—in particular, the development of new grades of steel—require steel producers to develop and introduce new technologies, which entails retooling and corresponding capital expenditures, as well as research costs.

REFERENCES

1. Kozlov, A.V., Global Markets for Steel, *Proizv. Prokata,* 2006, no. 3, pp. 41–47.
2. Ivoditov, V.A., Auto-Industry Steel, *Proizv. Prokata*, 2005, nos. 1-3.
3. http://www.ussautomotive.com.
4. Urabe, T., Ono, Y., Matsudu, H., et al., Practical Properties of IF-HSSS for Application to Automotive Usage, *Forum Book: Intern. Forum for the Properties and Applications of IF Steels (IF Steel 2003)*, Tokyo, 2003, pp. 170–177.
5. Kwon, O., Lee, K.Y., and Hong, M.H., Interstitial-Free Steels for Automotive Applications in Korea, *Forum Book: Intern. Forum for the Properties and Applications of IF Steels (IF Steel 2003)*, Tokyo, 2003, pp. 39–46.
6. Rodionova, I. and Filippov, G., Technological Aspects of Steel Production for the Auto Industry, *Nats. Metall.*, 2004, no. 2, pp 93–97.
7. Titov, V., Rolled Steel for the Auto Industry, *Nats. Metall.*, 2004, no. 5, pp. 84–89.
8. Misawa, T. and Komazaki, S., Hydrogen Embrittlement and Electrochemical Corrosion of Cu-IF and Microalloyed HSLA Steels, *THERMEC 2003: Materials Science Forum*, 2003, vols. 426–432, pp. 1425–1432.
9. Bhattacharya, D., Metallurgical Perspectives on Interstitial-Free Steels in the New Millennium, *Forum Book: Intern. Forum for the Properties and Applications of IF Steels (IF Steel 2003)*, Tokyo, 2003, pp. 29–38.
10. Traint, S., Pehler, A., Hauzenberger, K., et al., Influence of Silicon, Aluminum, Phosphorus, and Copper on Phase Transformation of Low Alloyed TRIP-Steels, *Int. Conference on TRIP-Aided High Strength Ferrous Alloys,* Cooman, B.D., Ed., Ghent: GRIPS, 2002, pp. 121–128.
11. Lucas, A., Herman, J.-Cl., and Schmitz, A., Cu-Containing TRIP-Steels, *Int. Conference on TRIP-Aided High Strength Ferrous Alloys*, Cooman, B.D., Ed., Ghent: GRIPS, 2002, pp. 231–236.
12. Kim, S.-J., Lee, C.G., Jeong, W.-C, and Park, I., Microstructure and Mechanical Properties of 0.15% C TRIP-Aided Cold-Rolled Steels Containing Cu, Ni and Cr, *Int. Conference on TRIP-Aided High Strength Ferrous Alloys*, Cooman, B.D., Ed., Ghent: GRIPS, 2002, pp. 165–169.
13. http://www.jfe-steel.co.jp/en/products/sheets/hot/nano.html.
14. http://www.nanowek.com/news/newsid/=2595.php.
15. Kozlov, A.V., High-Technology Metallurgical Products, *Proizvodstvo Prokata*, 2006, no. 10, pp. 30–46.