Design, Evaluation Methods and Parameters of Automotive Lightweight

Mingtu Ma and Hongzhou Lu

Abstract Automotive lightweight is quite important and active demand, due to the requirements of automotive industry development, energy saving and emission reduction. This chapter illuminates the signification, the conception and comprehension, characterization parameters and execution methods about automotive lightweight and lightweight design. The physical and technical signification of parameters in the lightweight coefficient equation is explained also. A more direct parameter, lightweight exponent L^i is suggested, and the physical and technique significations of those parameters in lightweight exponent L^i equation are clarified for various conditions of lightweight. The execution approaches of automotive lightweight and the relationship of the performance of typical parts with the performance of materials are discussed. A life cycle analysis method is presented to evaluate the economy, selection and application of the lightweight materials and technologies.

Keywords Automotive lightweight · Lightweight coefficient · Lightweight exponent · Execution approach · Life cycle analysis

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1 Introduction

The automotive industry in the world is developing fast, and the annual output of automobiles in the world is 73 million and the retaining number is more than 500 million in 2007. The automotive industry is a principal industry in developed countries. Automotive industry impulses the progress of human civilization, and, however, also results in the problems including safety, fuel consumption and emissions [1]. Due to increasing the retaining number and annual output of automobiles, emissions of CO_2 and other environment pollutants become worse. Energy consumption and environment pollutants by automobiles have been a serious problem. At the same time, because the price of international oil climbs fast and the requirements of the whole performance by customer are much higher, automotive lightweight becomes more and more significant. This chapter illuminates the signification, conception and comprehension of automotive lightweight. Characterization parameters, and execution methods of automotive lightweight are also clarified.[1]

2 China Automotive Industry Development and Automotive Lightweight

China's automobile industry develops fast in these years. Figure 1 shows an obviously increasing trend in the annual output of automobiles in China [2]. In 1996, the output and sale number per year is about 1.0 million, but in 2007, the annual output will be near 9.0 million, a fast increase trend comes up. Since 2000, the purchasing power of personal cars and development of China automotive industry have been accelerated, and the annual output and sale number increase significantly. The output of automobiles in China in 2007 is about 8.88 million, and the output of automobiles in China for the 2008 will add up to more than 10.0 million. So it is quite important and active demand to save energy and reduce emissions.

In order to solve the problems of energy consumption and environment pollution produced by automobiles, the automotive lightweight has been attained much more attentions in China. To impulse the steps of automotive lightweight, an automotive lightweight creating alliance was established on 27 Dec 2007 in China. The automotive lightweight alliance leaguers include main carmakers of China and relational research institutes, and universities etc. The main aim to establish this alliance is to reduce the automotive weight for increasing fuel efficiency and decreasing CO_2 emissions by usage of optimization design, and advanced forming technologies, and high strength lightweight materials such as HSS (high strength steel) and aluminum alloy and magnesium alloy, plastic composites.

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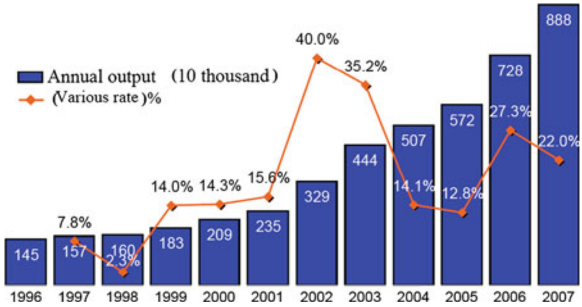

Fig. 1 Development of China automotive industry and annual output

3 Requirement for Design of Body-In-White

Several requirements should be put forward, including requirements of Body-In-White (BIW) for smooth going and stable property, requirements of body structure and sealing for acoustic and NVH (Noise, Vibration and Harshness), materials requirements of safety for crash performance (front crash, rear crash, side crash and roll, others), performance and technical requirements of body covers for geometry and dent resistance, performance and technical requirements of fatigue and antirust for some typical parts, protection requirements of BIW for roll, relational requirements of body for satisfy difference of profile, torsion stiffness and bending stiffness requirements of BIW for improving performance etc. These requirements are shown in Fig. 1. Besides those requirements, the engineering feasibility and cost must be considered. Under the condition of satisfying functions, the cost should be the lowest i.e. a high ratio of performance to cost (Fig. 2).

4 Conception of Automotive Lightweight and Automotive Lightweight Design

Lightweight design and weight reduction of the body-in-white (BIW) can not always be measured in kilograms, but they are related to the achieved vehicle dimension and functional requirements. Three aspects are used to expatiate on the conception of automotive lightweight and automotive lightweight design. Firstly, for a vehicle with fine functions, a automotive lightweight design is performed to reduce the mass but keep the whole performance, and this can be called direct lightweight. Secondly, for a vehicle without fine functions, a automotive lightweight design is performed to improve the whole performance but keep the mass, such as smooth going and stable property, acoustic and NVH safety, torsion stiffness and bending stiffness [3, 4]. Thirdly, an automotive lightweight design is performed not only to reduce the mass but also to improve the whole performance. From above discussion, the conception of automotive lightweight design should be a combination of mass, function, structure and cost. In the project of ULSAB

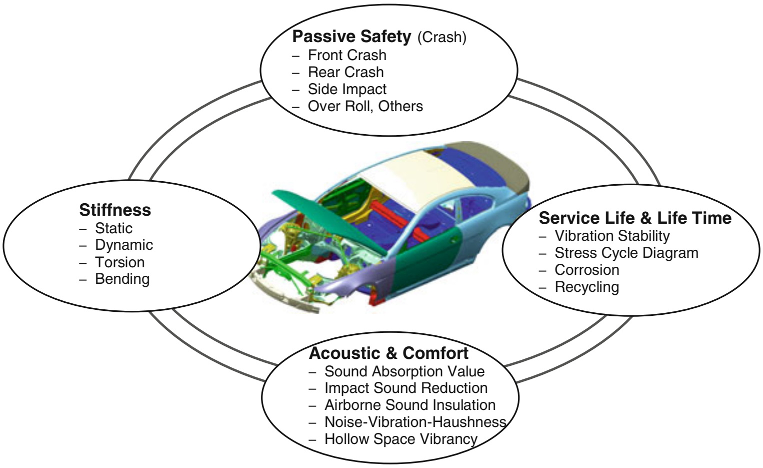

Fig. 2 Functional requirements for the body-in-white design

(Ultra Light Steel Auto Body) organized by internal steel association [5], the automotive lightweight is divided into ULSAB, ULSAC (Ultra Light Steel Auto Covers) and ULSAS (Ultra Light Steel Auto Suspension). The objects, materials and methods for the three kinds of lightweight are different, but the conception of automotive lightweight design is the same.

5 Characteristic Parameters of Automotive Lightweight

Lightweight design should include weight reduction of the body-in-white (BIW) and performance improvements. The functional requirements for stiffness, crash and car lifetime have to be considered in selection of the materials for a body in white. The stiffness of a structure can be influenced by the E-modulus and panel thickness and construction. Crash and vehicle lifetime are controlled by the strength of the material and thus affected by high strength steel grades. A specific lightweight coefficient L is suggested in literature [4]. The specific lightweight coefficient L is developed by Bruno Lüdke from BMW and is expressed by the formula (1). L is the ratio of structure weight mGer (excluding glass) to static torsion stiffness Ct (with glass) and the associated area A (footprint track × wheelbase), it can be also as a customer benefits evaluating parameter. Increased customer benefits are reflected in a decreased lightweight coefficient.

$$L = \frac{m_{Ger}}{C_t \times A} [\frac{Kg}{Nm/^{\circ} \times m^2} \times 10^3] \quad (1)$$

Figure 3.

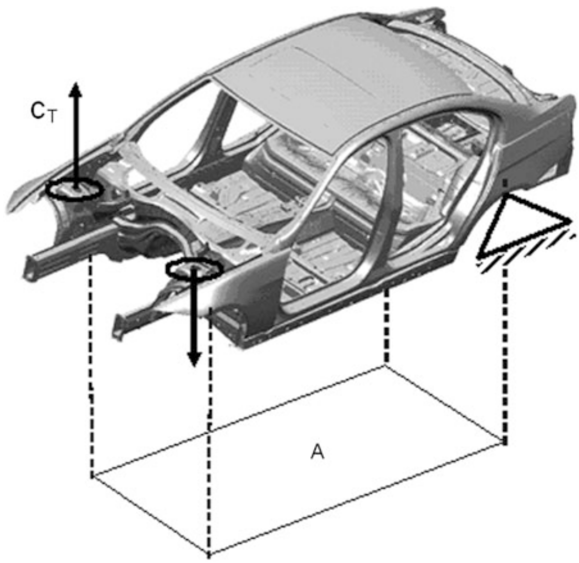

Fig. 3 The specific lightweight coefficient

In order to reflect directly the lightweight effect, a lightweight exponent Li is presented and suggested based on formula (1). Lightweight exponent Li is expressed in formula (2),

$$L^i = \frac{L_1 - L_2}{L_1} = 1 - \frac{m_{Ger2}}{m_{Ger1}} \cdot \frac{C_{t1} \times A_1}{C_{t2} \times A_2} \tag{2}$$

where L_1 represents the lightweight coefficient of the original vehicle, and L_2 represents the lightweight coefficient of the lightweight vehicle. When the properties of BIW are invariable, the formula (2) can be simplified as formula (3),

$$L^i = 1 - \frac{m_{Ger2}}{m_{Ger1}} \tag{3}$$

Similarly, when the weight of the vehicle is invariable, but the properties of BIW are enhanced, a vehicle is also lightweight, and then formula (2) can be expressed as formula (4),

$$L^i = 1 - \frac{C_{t1} \times A_1}{C_{t2} \times A_2} \tag{4}$$

In order to reflect comprehensively the influence of lightweight on the whole performance, the radio of loads for front axes to loads of rear axes must be kept to be 1:1, and the functions, cost and weight reduction all should be considered. Take an instance for ULSAB-AVC, three factors have been required, i.e. (1) lightweight of BIW must satisfy crash requirements, (2) mass relative to conventional vehicles should reduce 20 %, (3) no additional cost (Table 1).

Table 1 The targets of ULSUB and ULSUB-AVC

	2000 BIW	ULSAB	ULSAB-AVC
Crash requirements	2000 Year's law	2000 Year's law	2004 Year's law
BIW mass	270 kg	203 kg	218 kg
BIW costs	US$979	US$947	US$972

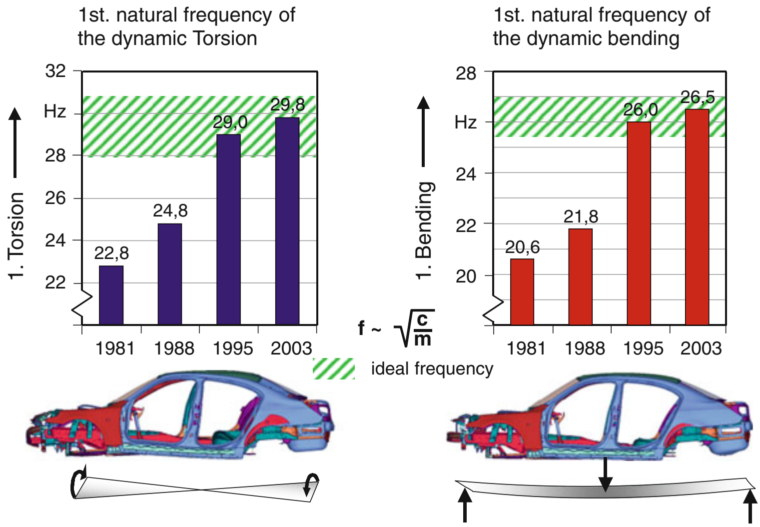

Fig. 4 The evaluation for NVH performance

However, not only the BIW, but also the auto-body covers and chassis should be lightweight. When the level of lightweight is increased due to other performance variation, the Ct in formulas should be replaced by other performance parameters.

When the NVH performance is used to evaluate the effect of lightweight, the Ct in formula (1) should be replaced by f, i.e. the 1st nature frequency of dynamic torsion or 1st nature frequency of dynamic bending. The evaluation instance can be seen in Fig. 4, and it is expressed in formula (5).

$$L^i = \frac{L_1 - L_2}{L_1} = 1 - \frac{m_{Ger2}}{m_{Ger1}} \cdot \frac{f_1 \times A_1}{f_2 \times A_2} \tag{5}$$

When auto-body covers are lightweight, the Ct in formulas (2) should be replaced by the dent resistance value (DR), and it is expressed in formula (6).

$$L^i = \frac{L_1 - L_2}{L_1} = 1 - \frac{m_{Ger2}}{m_{Ger1}} \cdot \frac{DR_1 \times A_1}{DR_2 \times A_2} \tag{6}$$

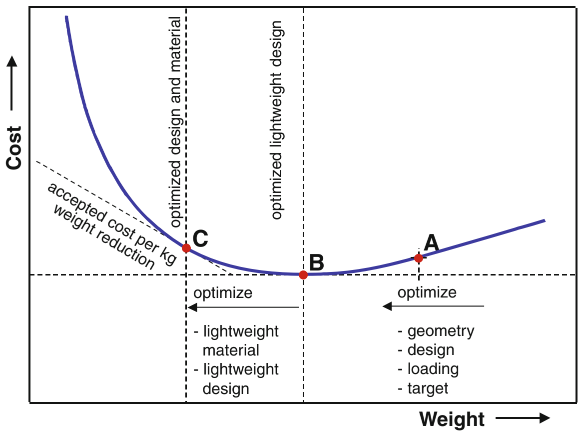

Fig. 5 Relationship of the cost (R&D, material, process, and repair) and weight

In the same way, when suspending system of chassis is lightweight, the Ct in formulas (2) should be replaced by the stiffness and fatigue performance of spring.

Another important factor for automotive lightweight engineering is cost. Particular care should be exercised when lightweight construction materials are used, because they not only increase the materials costs of the half finished products, but also the costs of manufacturing and repair. Relationship of the cost (R&D, material, process, and repair) with weight is shown in Fig. 5 [6]. Every effort should be made to get from status A to an optimal status B through "shape- and condition-related" lightweight structural design. Only then should status C be tried through material substitution. Cost should be controlled better.

6 Execution Approaches of Automotive Lightweight

From Fig. 6, a lightweight design should be a superior integration of different materials, a superiority integration of different specialties, a superiority integration of design, materials and advanced manufacture technologies. A lightweight design can be performed by optimized geometry to attain the effect of lightweight. But the better effect of lightweight can be able to perfect by the dominant integration of design, materials and manufacture.

From the formula (1), area A is an important parameter for the design of automobiles. The class of vehicles and the performance Ct of BIW are determined by this parameter. The parameter mass is related to the strength of materials, specific strength, ductility, modulus, geometry and forming technologies of materials. The choice of advanced forming technology is important, for the application of SHSS (super high strength steel) to improve the safety performance. Due to the poor formability of SHSS, the hot forming must be used in order to attain the strength more than 1,500 MPa. The high strength floor panels of vehicle body can be manufactured by roll forming. TWB (tailored welding blanks)

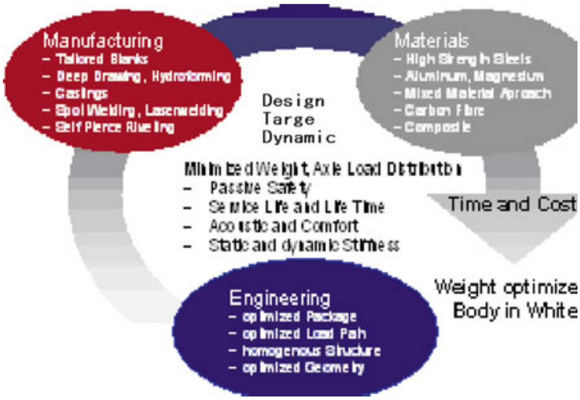

Fig. 6 Lightweight design approaches

technology can reduce the numbers of parts and weld points, resulting in improvement of the fatigue performance and sealing performance as well as reduction of weight. Hydroforming can reduce the numbers of parts and improve the performance of parts (for example, sub-frame of engine). These are the foundation of the design.

The computer simulation is an effective method in execution approaches of automotive lightweight. The load paths for crash and formability for a part can be simulated, and thus reasonable technological parameters can be attained for lightweight design and selection of materials and advanced forming technologies.

7 The Relationship of Performances of Typical Part with Properties of Materials

The relationship of performance of typical part with properties of materials is listed in Table 2, which shows how to choose a material according to the performance of various parts.

Application of lightweight materials is an important aspect of automotive lightweight, The aspect of material selection based on functionality of a body in white must be considered. The following six given characteristics have to be paid attention to for the purpose of lightweight design and selection in Fig. 6 [6]. A lightweight design is not only to choose some lighter materials to satisfy some performance of the part, but also to analyze the stress, optimize the design of structure, to select advanced manufacture technologies (Fig. 7).

A life cycle analysis method should be used to evaluate the feasibility of the lightweight [7]. The life cycle analysis equivalent especially for energy consume equivalent and CO_2 emissions equivalent should be used as an evaluation parameter to evaluate the application of the lightweight materials and technologies. Of course such an evaluation method has to face much of complicated

Table 2 The relationship of performances of typical part with properties of materials [8]

Deformation	Typical part	Required performance of the parts	Relationship of thickness, strength and performance
Big plastic deformation	Bumper, reinforcement panel; Anti-collision pillar of door; Reinforcement rib of side beam	High collapse strength High absorb energy	$Ps \propto t(\sigma_b)^n$ $n \sim \frac{1}{2}$ $A_E \propto t^2(\sigma_b)^{2n}$ $n : \frac{1}{2} - \frac{2}{7}$
Small plastic deformation	Outer panel of roof and engine hood; Outer panel of door; Outer panel of luggage lid	High dent resistance	$Pt \propto t(\sigma_p)^n$ $n \approx \frac{1}{2.5}$
Smaller elastic and plastic deformation	Side beam of body; Cross beam	High modulus	$P \propto t \cdot E_D^n$ $(\frac{1}{E_D} = \frac{1}{E} + \frac{1}{E_s})$
Smaller deformation	Side beam Wheel	Fatigue strength	$\sigma_w \propto \sigma_b$

Note P_S collapse strength
A_E collapse absorb energy
P_t dent force
P resistant force of smaller deformation
σ_W fatigue strength
σ_b tension strength
t thickness
σ_p the flow stress under the strain of some forming parts
e dynamic modulus, $e$eis constant

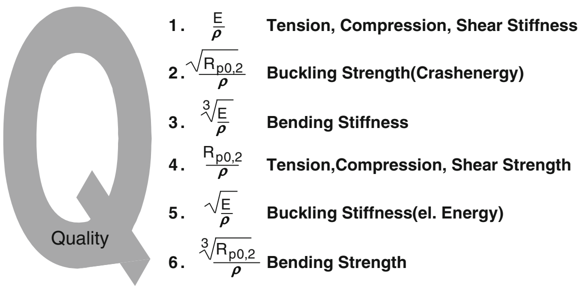

Fig. 7 Ranking of characteristic quotients for the purpose of lightweight design E elastic modulus P density $R_{P0.2}$ yield stress

factors, and a number of data are needed for this evaluation, but the life cycle analysis method will provide a crucial foundation for lightweight design.

8 Conclusion

1. Automotive lightweight is quite important and active demand due to the requirements of automotive industry development, energy-saving and CO_2 emission reduction;
2. Lightweight design should include weight reduction of the body-in-white (BIW) and performance improvements.
3. Based on the lightweight coefficient equation, a more direct parameter: lightweight exponent Li is suggested. The physical and technical significations of the parameters in lightweight exponent Li equation are clarified for various conditions of lightweight.
4. The execution approaches of automotive lightweight include geometry structure optimization, seasonable application of advanced forming technologies and lightweight materials, or a superior integration of design, materials and advanced manufacture technologies. The relationship of performances of typical parts with properties of materials is important for the selection of lightweight materials and should be considered.
5. The life cycle equivalent analysis especially for energy consuming equivalent and CO_2 emission equivalent should be used as an evaluation parameter to evaluate the application of lightweight materials and advanced forming technologies, and it will provide a crucial foundation for lightweight design.

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