

Life-Cycle Integration of Titanium Alloys into the Automotive Segment for Vehicle Light-Weighting: Part II - Component Life-Cycle Modeling and Cost Justification

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ABSTRACT

To warrant the substitution of traditionally used structural automotive materials with titanium alloys, the material substitutional and redesign advantages must be attainable at a justifiable cost. Typically, during material replacement with such 'exotic' aerospace alloys, the initial raw material cost is high; therefore, cost justification will need to be realized from a life-cycle cost standpoint. Part I of this paper highlighted the redesign, fabrication, and validation of an automotive component. Part II details the particulars of constructing the total life-cycle cost model for both prototypes (P1, P2). Considerations in the model include adaptation to a high volume production scenario, availability of near-net size plate/bar stock, etc. Further, response surfaces of fuel costs savings and consequent life-cycle costs (state-variables) are generated against life-cycle duration and unit fuel price (design-variables) to identify profitable operating conditions. In conclusion, it is evident that total life-cycle costs (primary metric) are closely comparable to that of the original component, thereby cost-justifying the redesigns as well as substantiating the practicality of replacement.

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INTRODUCTION

The primary drive for vehicle light-weighting is to reduce energy consumption through vehicle mass reduction while maintaining or improving road performance. The most common approaches in light-weight engineering involve efficient redesign of components for optimized geometry, elimination of lazy parts [1], or through the use of lighter or more advanced materials. Cost-effective vehicle light-weighting involves material replacement as well as an integrated multifunctional design. Figure 1 shows the often conflicting multifaceted requirements of effective mass reduction procedures - essentially, one of increasing performance while reducing product/production costs and impact on the environment. When considering material replacement, it has been traditionally suggested that non-ferrous lightweight materials may not be economically viable for high production volumes [2]. More recently, a low mass vehicle (LMV) prototype design was developed which achieved a total weight reduction of about 30%, while

satisfactorily maintaining performance typical for that vehicle class - this design was expected to be profitable in low volumes only [3].

Common selection criteria for lightweight materials include a right balance between weight savings, corrosion/aging resistance, availability, processability, material/tooling costs, etc. The common candidate materials for vehicle light-weighting include alloys of aluminum, magnesium and titanium. Out of these, titanium alloys, and specifically grade-5 titanium alloy or Ti-6Al-4V has one of the highest strength-to-weight ratio among them (~0.22), thus having potential for the maximum mass reduction. Thus, titanium alloys have traditionally been utilized extensively as a lightweight, strong and exceedingly corrosion resistant material in the aerospace industry, electric power plants, seawater desalination plants, and heat exchanges as well as in many industrial applications such as petroleum refining, food processing, marine applications, etc. [4].

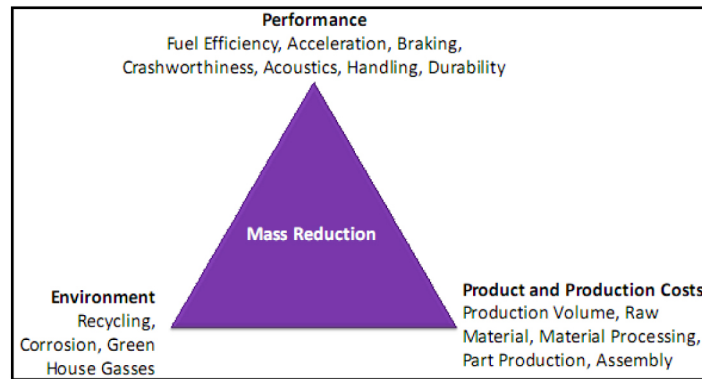


Figure 1. Mass reduction objectives with often conflicting multifaceted requirements [2]

LIGHT-WEIGHTING WITH TI-6AL-4V

When considering titanium alloys as a lightweight automotive component material alternative, its material and processing costs are still major barriers to their widespread adoption. Further, the cost of finished titanium components are currently considerably larger compared to those made of aluminum or steel. The ongoing improvement of processing methods is however slowly resulting in an increase in titanium use in the automotive market [5, 6, 7, 8, 9, 10, 11, 12]. Studies have been conducted which propose a net-shape forming of automotive components by casting followed by a machining process [13, 14]. Also, feasibility studies have been conducted for low-volume prototype manufacture of a number of titanium components [15, 16, 17, 18, 19].

Vehicle mass reduction by incorporating titanium components leads to a reduction in the energy required to propel a vehicle forward which in turn translates directly to reduction in fuel consumption. It has been reported that a 1% reduction in vehicle mass would provide an approximate fuel economy increase of 0.7% to 1.2% [3, 6]. This cost-saving is further amplified by the mass de-compounding effects (weight-cascading) and inertia multipliers for rotating/reciprocating parts. It has been reported that for typical passenger cars, the sum of relevant mass de-compounding coefficients is about 1.04, which suggests that for a 1 kg component mass reduction, about 1 kg of additional (secondary) mass can be taken out of the vehicle [20, 21]. Additionally, about \$24 billion/year is spent battling automobile corrosion damage; titanium alloys are one of the most corrosion resistant alloys among all metals, thus providing additional savings. By adapting the manufacturing process to a high-volume production scenario and adding up all of the above numbers over the lifetime of a vehicle, and applying it across the number of vehicles in operation (in the US alone), would translate into significant energy/cost savings and reduced emissions, thus substantiating the fundamental motivation for this study.

Thus, for this light-weighting procedure, the basic facts remain that the initial material cost is significantly higher and

the manufacturing cost is marginally higher than those for traditional iron and steel components. The approaches therefore to check for feasibility include adapting the component for a high-volume production scenario (typical of automotive production lines) and considering costs from a total life-cycle cost standpoint.

SUMMARY FROM PART-I

The summary of component results from Part-I of this paper is given in [Figure 2](#). Note the evident advantages in terms of significant weight savings (27% for P1 and 68% for P2) while maintaining satisfactory functional performance. The main conclusion from Part-I is that it is functionally feasible (and commercially manufacturable) to replace certain existing iron and steel components in an automobile with titanium alloys for eventual savings in energy (fuel consumption) and reduction in emissions.

TOTAL LIFE-CYCLE COST MODEL FOR THE TI-6AL-4V PROTOTYPES

The National Institute of Standards and Technology (NIST) handbook [22] defines Life-Cycle Cost (LCC) as “the total discounted dollar cost of owning, operating, maintaining, and disposing of a system over a period of time.” Thus, life cycle costs are “summations of cost estimates from inception to disposal for both equipment and projects as determined by an analytical study and estimate of total costs experienced during the project life” [23]. From the standpoint of this component, for road vehicles, the component cost (material and manufacturing costs) ties into the owning cost and the operating cost is described mainly by fuel consumption, which can be quantified by operating cycles. The maintenance cost is expected to be lower than those for traditional iron and steel components due the comparatively excellent corrosion resistance of titanium alloys (galvanic potential of Ti-6Al-4V is ~ 0.0 V).

The procedure for component identification, functional redesign, process planning, prototyping, and validation was described in Part-I of this paper. [Figure 3](#) shows the general outline of how all parts of this procedure ties back into the



Figure 2. Summary of component results from part-I

life-cycle cost analysis which is the central driver of the titanium component integration [23] process.

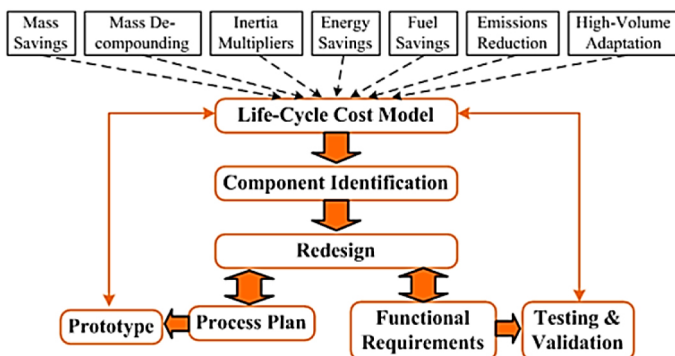


Figure 3. General outline of the titanium component integration process with LCC as the central driver [23]

The major components of the total life-cycle cost model for both prototypes are constructed as follows:

1. MANUFACTURING COST MODEL

The component manufacturing cost can be determined by adding its essential constituent elements: raw-material cost, processing cost, and other burdened costs. The basic objective of a manufacturing cost model is to estimate the total cost per part of a complex processing procedure and hence formulate a template for predicting final part cost when one or more constituents are perturbed. These manufacturing cost models can vary drastically based on the type of manufacturing processes selected for fabricating the component. Elaborate cost models in varying detail have been formulated for many of the common manufacturing processes like casting, forging, machining, welding, powder metallurgy, etc. [24]

For an economic evaluation of the manufacturing process, both direct and indirect (burden) costs need to be included.

For this, a general manufacturing cost model can be adopted [25] as given by Eq. (1), where ' C_p ' is the total cost per part, ' C_m ' is the material cost, ' C_l ' is direct labor cost, ' C_t ' is the tooling cost, ' C_e ' is the capital equipment cost, and ' C_e ' is the cost of energy used.

$$C_p = C_m + C_l + C_t + C_e + C_e \quad (1)$$

Considering direct costs

(1) The total material cost ' C_m ' is a function of the mass-based (or volume-based) specific material cost ($c_{m,m}$) at the market rate and the mass (m_{part}) (and geometry) of the part. Further, almost all manufacturing processes generate some scrap; hence, the mass of reclaimed scrap (m_{scrap}) and its specific salvage value (c_s) need to be accounted for as well. The salvage amount and value of scrap depends on the manufacturing process; for instance, the salvage value of machining chips is generally about 5 to 10%, however, for titanium machining chips, it can be as high as 25%; (2) Considering the direct labor cost ' C_l ', it is a function of the cycle time (t_{cyc}) and the unit cost of labor (L) (per hour), which can have different rates for operating labor cost (L_{oper}) and setup labor cost (L_{setup}). Also, depending on the product line and fixturing setup, typical batch sizes (n) and associated setup time (t_{setup}) can be incorporated into the model. For a typical high-volume automotive production line this can be about 250-500 parts; (3) For the tooling cost ' C_t ', it is a function of the cost per tool (c_t) and the number of tool changes per part (n_t), which can be difficult to predict for a complex set of successive processes; (4) For the capital cost of equipment ' C_e ', it is a function of the specific capital cost (c_c) and the cycle time (t_{cyc}). The specific capital cost is constituted of the original investment cost (C_{inv}), annual