

Life-Cycle Integration of Titanium Alloys into the Automotive Segment for Vehicle Light-Weighting: Part I - Component Redesign, Prototyping, and Validation

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ABSTRACT

Current vehicle manufacturers must meet economic demands and design/manufacture more fuel efficient vehicles with increasingly better performance. As a result, they are turning to the use of more non-traditional lightweight materials in their products. One favorable material due to its excellent strength-to-weight ratio and high corrosion resistance is titanium. However, to warrant the replacement of traditional materials with titanium alloys there must be the benefit of reduced vehicle mass as well as performance enhancement gains from the substitution at a justifiable cost. In this work, an unsprung suspension component is selected and redesigned from the standpoint of (i) a direct material substitution and (ii) a material and requirements consideration based substitution. In addition, for the redesign of the component in titanium, the manufacturing procedure and process plan is integrated into the design phase for the component. Following the design and analysis, the components are prototyped and tested both dimensionally and for functionality. Specifically for functionality, both static testing on a test bench and in-vehicle dynamic testing are performed. The outcome of this work is not only a feasible example of a titanium component being produced for a current production vehicle, but also a cost justified fabrication and implementation process plan from a life-cycle cost analysis standpoint, which will be discussed in Part II of this paper.

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INTRODUCTION

Today, automotive manufacturers must meet the economic demands of consumers while also producing vehicles with greater fuel efficiency and higher performance. Additionally, pressure from government agencies such as the National Highway Traffic Safety Administration (NHTSA) requires vehicle manufacturers to produce vehicle fleets which satisfy a Corporate Average Fuel Economy (CAFE) standard [1]. As a result of these conflicting targets (fuel efficiency and performance), automotive OEMs are faced with certain trade-offs or design limitations when producing vehicles to meet the demands of the consumer. Hence, vehicle lightweight engineering which is a drive for mass reduction while also attempting to increase vehicle performance has been growing in this industry. The frequent method used in vehicle lightweight engineering is to adopt

and implement lightweight materials such as aluminum, magnesium, titanium, high-strength steels, composites, etc. Considering these materials, titanium which is highly used in the aerospace industry still lags in usage for the automotive market. Although titanium has a superior strength-to-weight ratio as compared to existing automotive metals and a great corrosion resistance, material and processing cost are still the major barriers to the widespread adoption in this industry. As a consequence of these barriers, research and processing technology of titanium which is aimed to enable and increase the usage in the automotive industry can be found in works by [2, 3, 4, 5, 6, 7, 8, 9]. Additionally, the present barriers to adoption have stemmed works which still examine the feasibility for titanium implementation at low production volumes [10, 11, 12].

This work examines the implementation of titanium into the automotive sector by considering the design and

manufacturing of an existing vehicle component. For this process, the manufacturing or production aspects are incorporated into the design phase of the component unlike the traditional view of “over-the-wall” flow from design to production. Overall, the justification of titanium implementation and process plan decisions from this paper are warranted through a life-cycle cost analysis.

VEHICLE LIGHTWEIGHT ENGINEERING

In the last few decades there have only been a few major stable trends in the automotive industry. Major ones are the increased demand for drive performance, safety and comfort features. These have lead to a substantial increase in the weight of vehicles. Only in more recent years these trends were accompanied by the strong demand for fuel efficiency and emission reduction as far as zero emission requirements. This induced a merely irresolvable conflict of objectives. Besides expensive engine and drive train technology (including hybrid technology), which all will further increase the vehicle weight, lightweight engineering is one of the very few measures that can be taken to support more than one trend. And also here, cost is the most critical opponent. Noteworthy in this context of course is the shift in customer expectation towards more efficiency and reduced emissions which will ultimately shift the equilibrium for lightweight opportunities towards more expensive measures.

The direct effect of lightweight engineering on fuel efficiency caused by reduced acceleration and roll resistance effort is rather small. The major benefit lies in improved drive performance. Nevertheless there is a tangible effect on fuel efficiency, if the improved drive performance enables a smaller engine (downsizing). Also there are secondary weight savings through reduced brake energy (smaller breaks, reduced crash loads, smaller engine, etc.).

The measures in lightweight engineering are manifold. Conceptual measures can be taken such as the integration of different functions into one part, paying a price for the increased design and validation complexity for this part. Another possibility is the structural optimization through rearranging or sometimes reducing requirements on a part or system. These normally are the cheapest opportunities, though they are often difficult to find, if not connected to a customer relevant functional degradation. Further there is the opportunity of material replacement. Very common in the automotive industry is replacing steel with (reinforced) plastic or other metals. State of the art is replacing complete or partial bodies with aluminum. Magnesia is used for instance in engine components. Often the increase in material price or the higher cost through increased product or manufacturing complexity can only be compensated through combining the material replacement with function integration or conceptual changes. This gets most obvious when using high-tensile steels in certain areas of the body to improve crashworthiness. Only through structural optimization high-

tensile steel becomes a lightweight material. Therefore, for vehicle lightweighting to be successfully implemented it must incorporate an integrated design and material substitution. For material replacement, common metrics that should be evaluated may include: mass savings, mass decompounding effects, material cost, operations cost, availability, production costs, processability, recyclability, production volume, and material design criteria. Last, one more important aspect when looking at different lightweight measures is customer perception. Whereas high-tensile steels aren't normally perceived as lightweight material, they in general are much more efficient than for instance carbon fiber composites.

This work examines the usage of titanium which is traditionally used in the aerospace industry, heat exchangers, electric power plants, nuclear waste storage, and marine applications as a result of its retained strength at elevated temperatures and its high corrosion resistance [13]. Along with these properties, titanium possesses one of the best strength-to-weight ratios for engineering metals and has very good high temperature stability (*i.e.* low thermal expansion). The most common and commercially available titanium alloy used is Ti-6Al-4V, which dominates the defense and aerospace sectors. As a result, this alloy is used in the design stage for the selected vehicle component.

ISSUES FOR INTEGRATING TITANIUM ALLOYS INTO AUTOMOBILES

The main inhibitor for titanium to be utilized in the automotive industry on a larger scale is the material cost. This is a result of a limited development of lower class grades outside the aerospace industry which could potentially drive down the costs and the issues with the extraction processing of titanium. The extraction process is currently not highly automated and is only performed using low volume batch production [14]. Aside from the material cost itself, the processing costs of titanium may be larger as a result of its unique intrinsic material properties. For example, its high strength requires high amounts of energy to form and its low ductility typically requires forming to be done at elevated temperatures. Also, issues are present while casting titanium as it has a high chemical reactivity with oxygen at elevated temperatures which limits the casting to be performed in a vacuum environment with specialized mold materials. Also, as most engineering components require machined surfaces, titanium suffers in this area as it has a high work hardening rate, typically reacts with tool materials, has a low thermal conductivity which retains heat in the cutting zone, and a low elastic modulus which can cause high workpiece deflection during machining. As a result of these attributes, there are typically issues with accelerated tool wear and failure during machining. A detailed review of present research aimed to mitigate processing issues is given in [15]. Last, when considering the incorporation of any new material, there is a concern associated with the joining and galvanic corrosion of

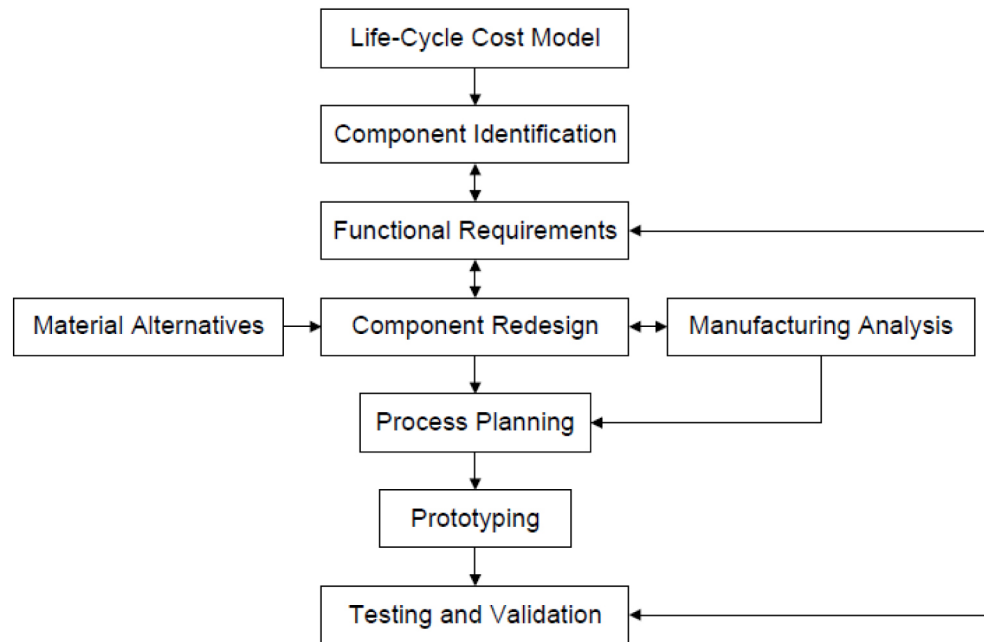


Figure 1. Integration Outline of Titanium Components to the Automotive Segment

these new materials with common automotive materials such as steel and aluminum. Therefore, this could be a barrier when incorporating titanium into certain components of the vehicle.

INTEGRATION OF A TI-6AL-4V AUTOMOTIVE COMPONENT

For consideration of Ti-6Al-4V or any other material in the automotive segment, it is necessary to examine the life-cycle cost rather than the material or processing cost only. This methodology was principally described in [16], however, this work considers a more detailed methodical procedure for successful integration. The procedure is outlined in [Figure 1](#) where the life-cycle cost model is the foundation or driver for component identification. The life-cycle cost modeling is discussed in part II of this paper and the remainder of the integration process is covered herein.

From the life-cycle cost analysis, this leads to the identification of a feasible component to be redesigned using lightweight engineering techniques. The identified component must first have a detailed set of functional requirements or engineering specifications that must be fulfilled and satisfied. These are then used in the redesign phase along with a material or several material alternatives. For the given procedure, the redesign and manufacturing analysis occur simultaneously so that the flow of design information to production or manufacturing is not in series. This methodology helps to mitigate design iterations and it also reduces the issues during production. Then, the design and manufacturing analysis directly flow into the final process planning which leads to prototyping. Following the prototyping, this leads to the testing and validation to ensure

that the physical parts meet all of the set functional requirements of the part. Upon refinement, the production of the component can be extrapolated to higher production sequences.

1. IDENTIFICATION OF COMPONENT AND FUNCTIONAL REQUIREMENTS

For component identification, the integration of titanium needs to be fully exploited to take advantage of the mass savings as well as the other beneficial material properties. These beneficial properties may include the higher yield strength, higher retained strength at elevated temperatures, higher fatigue strength, and high corrosion resistance as compared to conventional automotive materials.

A similar selection criteria as applied in [16] was utilized where there are four main groupings. These are highlighted in [Table 1](#).

Table 1. Selection Criteria Groupings

Criteria	Considerations
Cost	Total Life-Cycle Cost
Function and Safety	Design Specifications, Design Requirements, Failure Modes
Manufacturability	Sequence, Process Plan, Production Volume, Processes
Sustainability	Fuel Consumption, Recyclability, Emissions

Using these criteria for analysis of the main vehicle subsystems (chassis/suspension, body-in-white, engine/powertrain, and interior) by a decision matrix led to the determination of two main vehicle areas which were highly favorable for replacement with titanium. These areas were the components which could be grouped into the unsprung mass of the vehicle and engine/highly cyclic components. The unsprung mass components were highly beneficial as they have a great potential for large dead weight savings and the cyclic components were favorable as a result of the potential for inertial mass benefits. Also, a reduction in the unsprung mass of the vehicle typically improves the responsiveness of the vehicle's suspension and also leads to an improved ride quality. The high cycled components are beneficial as they would have large inertial savings and a higher impact on weight cascading (mass decompounding) savings.

Using this analysis and then a more detailed total life-cycle cost analysis for a few select components, the final component for this case study is a front suspension fork on a sport activity vehicle (SAV) currently in production. A CAD and in vehicle image are shown in [Figure 2](#).

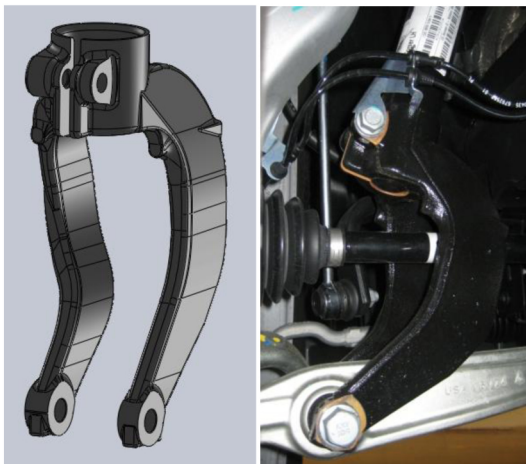


Figure 2. Front Fork (CAD and In Vehicle)

The front suspension fork is responsible for carrying loadings from the wheel carrier/suspension linkages into the spring/damper assembly which then transmits forces to the vehicle body. The current component is manufactured from cast iron using a sand casting process. Following the casting, the component is machined to provide the correct geometric mating conditions. The mass (one on each vehicle side) is approximately 2.57kg. Considering a direct material replacement with titanium, the component would now have a mass of 1.56kg. However, when considering a material replacement with titanium, an exact geometric match would obviously not be the optimal design choice. From the quality specification and functional requirements of the component, the design targets which were required to be met were established and used in the redesign phase. The functional requirements included specific material characteristics, strength, dimensionality, quality features and there testing

conditions, and reliability features and there testing conditions.

2. COMPONENT REDESIGN AND MANUFACTURING ANALYSIS

For the redesign process of the selected component, an original solid model of the current production component was analyzed using the appropriate loading characteristics from the engineering specifications and the associated boundary conditions as the component would be subject to in the vehicle. Using this analysis along with the material properties of the current production component, FEA simulation gave the resultant stress and deflection profiles of the component. These results were used to verify that the loading and boundary conditions were appropriate by comparing the obtained stress and deflection results with the corresponding material limits. The overall result from the analysis showed that the applied loading and boundary conditions were accurate and could be utilized for the analysis of redesign variants manufactured from titanium.

In the following two sections, the design process is discussed for two prototypes. The components were designed based on the notion that the parts would be manufactured using standard wrought Ti-6Al-4V products. The first prototype (P1) is a geometric recreation of the current production component manufactured using rod and plate stock. The second prototype (P2) is a titanium leveraged design which exploits the high strength properties of titanium and also uses standard wrought products. Additionally for the redesign process, another aspect that needed to be carefully accounted for is the allowable clearance envelope of the component as the other linkages and suspension components can travel significantly as the suspension system is actuated over varying road conditions.

2.1. Prototype 1 (P1): Material Substitution (Recreation)

For P1 which was a recreation of the current production component in titanium using standard wrought titanium products, several design variants were first developed. [Figure 3](#) shows the three best variants that were considered for full analysis in FEA and for manufacturing analysis.

Upon examining the FEA analysis results each variant was then discussed on the relative ease and method of manufacture. Specifically, a generalized process plan was created which determined the required component bill of materials, the manufacturing process to create each part of the component, the process sequence for production of each part, and the assembly procedure. This analysis was fed back to the design of the component to be modified to reduce and make the manufacture of the component more efficient by eliminating any detected issues or possible difficulties perceived that would occur during manufacturing.