

Effect of Machining Feed on Surface Roughness in Cutting 6061 Aluminum

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ABSTRACT

The general manufacturing objective during the fabrication of automotive components, particularly through machining, can be stated as the striving to achieve predefined product quality characteristics within equipment, cost and time constraints. The current state of the economy and the consequent market pressure has forced vehicle manufacturers to simultaneously reduce operating expenses along with further improving product quality. This paper examines the achievability of surface roughness specifications within efforts to reduce automotive component manufacture cycle time, particularly by changing cutting feeds. First, the background and attractiveness of aluminum as a lightweight automotive material is discussed. Following this, the methodologies employed for the prediction of surface roughness in machining are presented. The factors affecting surface roughness as well as practical techniques for its improvement through optimizing machining parameters are discussed next. Emphasis is placed on portraying the dominance of feed on surface quality over other controllable machining parameters, thus substantiating the motivation for this study. Controlled milling experiments show the relationship between feed and surface quality for 6061 aluminum, and the results are used to recommend machining practices for cycle time reduction while maintaining quality requirements.

INTRODUCTION

Aluminum is the second most abundant metallic element and the most abundant structural metal in the earth's crust. It is mostly extracted by the chemical refinement of bauxite using the Bayer process to form aluminum oxide (alumina) from which (99.9% pure) aluminum extracted by the Hall-Heroult method. It is commercially available as wrought or cast in the form of ingots, bars, sheets, etc.

Aluminum is a silvery white metal especially noted for its density: about a third that of steel. The oxide layer formed on freshly machined aluminum insulates it against further attack thus providing good corrosion resistance. It has good electrical and thermal conductivities as well as good ductility and malleability. Also, it can be surface finished within a wide range of values. Some of the limitations of aluminum are lower strength at elevated temperatures, limited formability and relatively higher cost compared to steel. Aluminum is widely used in the food and chemical industry, in metallurgical applications, the electrical industry, for structural applications, cryogenic applications, etc., and of course extensively in the transportation industry.

The growing requirement to improve fuel economy due to the the demand for reduction in energy consumption and pollution has strongly influenced the exploration of lightweight materials within the automotive industry. The desirable properties of aluminum favor it as a replacement material for heavier automotive steel components. Weight reduction enables vehicle manufacturers to achieve the same vehicle performance utilizing a smaller engine, transmission and associated components. This in turn leads to reduced operating expenses for automotive OEMs and significant cost benefits in terms of higher fuel economy and thus reduced energy consumption and emissions.

ALUMINUM AS A LIGHTWEIGHT AUTOMOTIVE MATERIAL

When targeting the reduction of the mass of automotive components by replacing heavier steel components with lightweight materials, there are a number of candidate materials that fit the requirements. Three of these common lightweight engineering materials include: aluminum, magnesium and titanium. Some of the most relevant material properties of these three materials are compared in [Table 1](#)

Table 1. Relevant material properties of lightweight automotive metals compared to steel

	Steels	Aluminum Alloys	Magnesium Alloys	Titanium (6Al-4V)
Density (kg/m ³)	7850	2700	1810	4500
Yield Strength (MPa)	230	350	140	900
Tensile Strength (MPa)	430	400	200	970
Strength to Weight Ratio	0.05	0.15	0.11	0.22
Specific Cutting Energy (W-s/mm ³)	2.7-9.3	0.4-1.1	0.4-0.6	3.0-4.1

along with the properties of steel that is used in automotive components.

<table 1 here>

On comparing the properties of these lightweight materials listed in [Table 1](#), it can be observed that aluminum having a density of a third of that of steel possesses twice its strength-to-weight ratio. Though the comparative properties of magnesium and titanium seem attractive, their alloys are plagued by severe machinability limitations. Thus, aluminum with its numerous attractive physical and mechanical properties, especially its lightweight characteristic, is favored as the best candidate material for automotive component manufacture.

TOTAL LIFE COST MODEL

The tractive force supplied to propel the vehicle works to overcome three main resistive forces, namely: the rolling resistance of the tires due to material hysteretic loss, the aerodynamic force, and the inertial force due to the vehicle acceleration. A mass-energy relationship can be written over standard driving cycles as in [Eq. \(1\)](#).

$$E = m.\beta_1 + \frac{1}{2}.C_d.\rho.A_f.\beta_2 + m.g.C_r.\beta_3 \quad (1)$$

where, 'E' is the energy required at the tires for propelling the vehicle over a standard driving cycle, 'm' is the mass of the vehicle, 'C_d' is the drag coefficient, 'ρ' is the density of air, 'A_f' is the vehicle frontal area, 'g' is the acceleration due to gravity, 'C_r' is the rolling resistance coefficient of the tires

and 'β₁, β₂, β₃' are vehicle independent, but cycle dependent driving cycle constants for driving/braking, aerodynamic, and rolling resistance effects respectively.

On examining the above relationship, it is observed that the mass of a vehicle and its fuel consumption are directly proportional to each other such that as the mass is increased, the inertial and rolling resistance effects become increasingly arduous to overcome and hence they increase the amount of energy required to propel the vehicle and thus fuel consumption and vehicle emissions.

It has been estimated that a 10% reduction in vehicle mass results in a fuel economy improvement of 8-10% [21]. Use of aluminum in a standard road vehicle can reduce the original vehicle mass by up to 40%. On adding up such numbers over the overall lifetime of a vehicle and multiplying it with the number of vehicles out on the road today, it would translate into significant energy savings and reduced emissions. Thus even with its higher relative cost to steel, aluminum can compete successfully with other engineering materials owing to the advantages it brings in primary and secondary weight savings as well as structural performance, safety and design flexibility.

ALUMINUM IN THE AUTOMOTIVE INDUSTRY

Vehicle manufacturers have increasingly turned to aluminum to improve fuel economy, safety and performance. As a result, aluminum has surpassed iron as the second most used automotive material worldwide (behind steel). In North America, the current average aluminum content in passenger



cars and trucks is 324 lbs and a comparison with other major countries is show in [Figure 1](#). Currently, over forty 2009 North American vehicles contain over 400 pounds of finished aluminum: a list is show in [Figure 2](#).

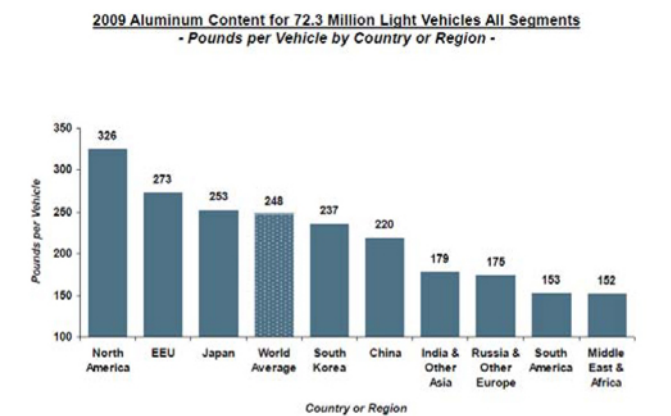


Figure 1. Aluminum content in pounds/vehicle by country for passenger vehicle segment [26]

North American 2009 Light Vehicles with Over 400 Pounds Aluminum Content* Based on Curb Weight		
Acura MDX	Chevrolet Impala	Honda Pilot
Acura TL	Chevrolet Suburban	Honda Odyssey
BMW X5	Chevrolet Tahoe**	Hummer H3
BMW X6	Chevrolet Traverse	Jeep Grand Cherokee
Buick Enclave	Chrysler Town & Country	Lincoln MKS
Cadillac CTC	Daimler MB GL-Class	Lincoln MKT
Cadillac CTS	Daimler MB ML-Class	Lincoln Town Car
Cadillac CTW	Daimler MB RL-Class	Nissan Altima**
Cadillac DTS	Dodge Caravan	Nissan Maxima
Cadillac Escalade**	Dodge Challenger	Nissan Quest
Cadillac SRX	Dodge Charger	Subaru Tribeca
Cadillac STS	Dodge Viper	Toyota Sienna
Cadillac XLR	Ford Explorer	Volkswagen Routan (Made by Chrysler)
Chevrolet Avalanche	GMC Acadia	** Hybrid and Non Hybrid
Chevrolet Corvette	GMC Yukon**	

Figure 2. North American 2009 Vehicles with over 400 lbs of finished aluminum content [26]

Both wrought and cast aluminum parts have been extensively incorporated into the automobile in the form of multiple engine and powertrain components, brake systems components, body panels, structural parts, suspension system components, etc. Additionally, cast and forged aluminum alloy wheels have been a popular buy among car enthusiasts. Aluminum components have been used extensively in trucks, both in the cab and trailer sections to maximize payload capacity while remaining within legal weight limitations. Additionally, mobile homes, travel trailers and mass transportation vehicle bodies are being constructed almost exclusively from aluminum.

North America has the highest aluminum penetration at 8.6% of the average curb weight in the form of aluminum wheels,

hoods, knuckles, heat exchangers and automatic transmissions; the second highest aluminum block penetration and the third highest penetration of aluminum heads. The growth of the North American aluminum content in vehicles as a percentage of curb weight is shown in [Figure 3](#).

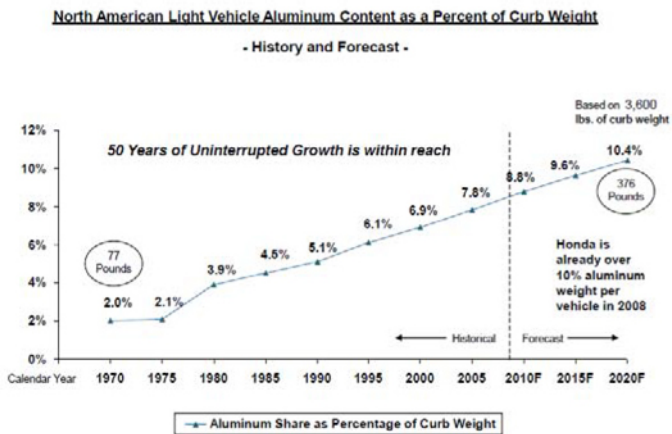


Figure 3. Growth of North American aluminum content as a percentage of vehicle curb weight [26]

The automotive industry being the fastest growing consumer of aluminum, the usage is expected to increase significantly due to the ongoing need for better fuel economy. The long term worldwide light vehicle aluminum content growth is expected to be in the order of 4 to 5 lbs/vehicle per year range and approach 300 lbs/vehicle worldwide by 2020.

PROCESSING OF ALUMINUM MACHINABILITY

Machinability is considered as the ease with which a material can be machined and it is customary to speak of it as a material property. Although there is no physical quantity to rate machinability, it can be quantified as a combination of the machinability index, chip formation characteristics, tool wear, cutting forces acting on the tool, material removal rates, achievable surface finish, etc. Usually good machinability translates to a combination of cutting with minimum energy, minimum tool wear and good surface finish.

The machinability of aluminum is considered to be very good and by some definitions, excellent. In the automotive industry, it is a direct measure of the quality of a product which affects manufacturing cost. Additionally, it influences surface friction, the ability of holding lubricant, light reflection, electrical and thermal contact resistances, etc. The desired roughness value and the relevant process to achieve it are usually specified for each individual part in the automotive industry [7].

MACHINING ECONOMICS

The fundamental idea of machining economics is simply to obtain the lowest possible cost per part that is manufactured while maintaining the quality standards of the product. A fundamental cost model [20] for machining a part is given by Eq. (2).

$$C_p = C_m + C_s + C_l + C_t + C_{rm} \quad (2)$$

where, ' C_p ' is the total cost per part, ' C_m ' the machining cost, ' C_s ' the setup cost, ' C_l ' the material handling cost ' C_t ' is tooling cost and ' C_{rm} ' the raw material cost. A plot of the machining cost/part for a typical machining scenario is depicted in Figure 4.

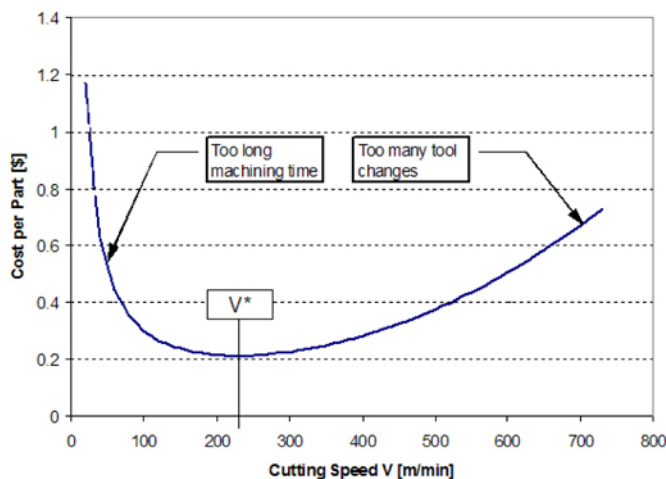


Figure 4. Machining cost/part for a typical machining scenario

Note that, the process of reducing the total cost per part by varying the cutting parameters (speed, feed, depth of cut, etc.) consists mainly of two conflicting factors: reduced cycle time and too many tool changes. An optimal cutting speed (V^*) can be solved for analytically, however it is difficult to accurately include all the factors contributing to it. Usually, the machining process can be run at these optimal cutting speeds without adverse effects; it is usually limited only by specific requirements such as a predefined surface roughness.

Surface roughness is of considerable significance as it influences both the functional behavior and manufacturing cost of a component. Attempts to decrease surface roughness below certain limits generally elevates manufacturing expenses exponentially, however surface quality of machined products is a requirement in today's market [8, 11].

SURFACE ROUGHNESS FROM AN AUTOMOTIVE STANDPOINT

Surface roughness and integrity are of prime importance for machined automotive components in terms of aesthetics, tribological considerations, corrosion resistance, subsequent processing advantages, fatigue life improvement as well as precision fit of critical mating surfaces. Hence, the achievement of a predefined surface finish for automotive components directly translates to product quality and hence the motivation for this study.

The natural metallic surface finish of aluminum is usually aesthetically satisfactory without further polishing. The natural protective oxide layer that is formed is transparent and does not affect the appearance of the material surface. A wide variety of surface textures can be created from rough to mirror smooth. The hue and color can be affected chemically, and paints, enamel and other surface coating can be applied with ease without adverse effects or deterioration [24].

SURFACE ROUGHNESS AND ITS MEASUREMENT [20]

Surface Roughness is a measurable surface characteristic quantifying high frequency deviations from an ideal surface. Usually measured in micrometers (μm), it is a subjective property incorporating appearance, smoothness, etc. It is usually described by the arithmetic mean value (R_a) (formerly AA or CLA), based on the mean of the normal deviations from a nominal surface over a specified 'cutoff' length and is given in Eq. (3).

$$R_a = \frac{1}{n} \sum_{i=1}^n y_i \quad (3)$$

where, ' R_a ' is the surface roughness, ' n ' is the number of measurement points and ' y_i ' is the surface deviation at measurement point 'i.'

Other common measures of surface roughness are the root mean square average (R_q) given by Eq. (4) and the Peak-to-valley roughness (R_t) (the height from the deepest trough to the highest peak) given by Eq. (5).

$$R_q = \sqrt{\frac{1}{n} \sum_{i=1}^n y_i^2} \quad (4)$$

$$R_t = y_{\max} - y_{\min} \quad (5)$$

In general, a surface cannot be adequately described by its ' R_a ' or ' R_q ' values alone, since these are averages. Two