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

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

	Steels	Aluminum Alloys	Magnesium Alloys	Titanium (6Al-4V)
Density (kg/m3)	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

On comparing the properties of these lightweight materials listed in Table 1, it 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 ‘β_1, β_2, β_3‘ 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.

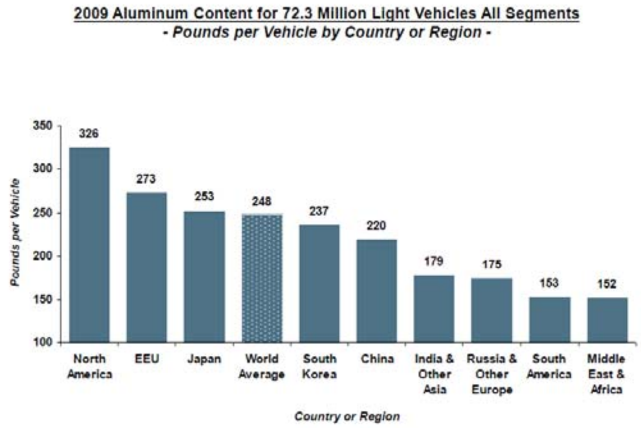

Figure 1: Aluminum content in pounds/vehicle by country for passenger vehicle segment [26]

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.

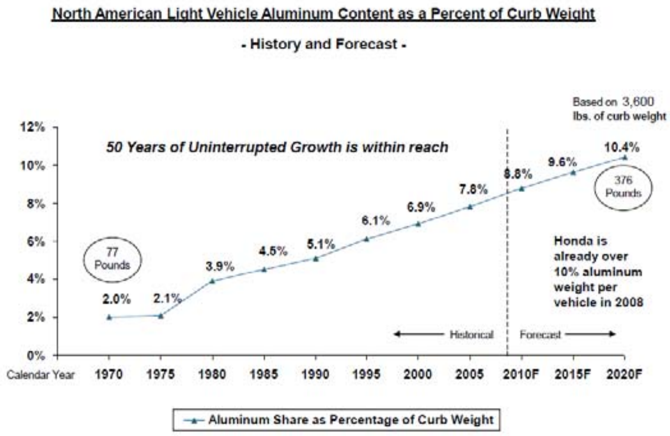

Figure 3: Growth of North American aluminum content as a percentage of vehicle curb weight [26]

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.

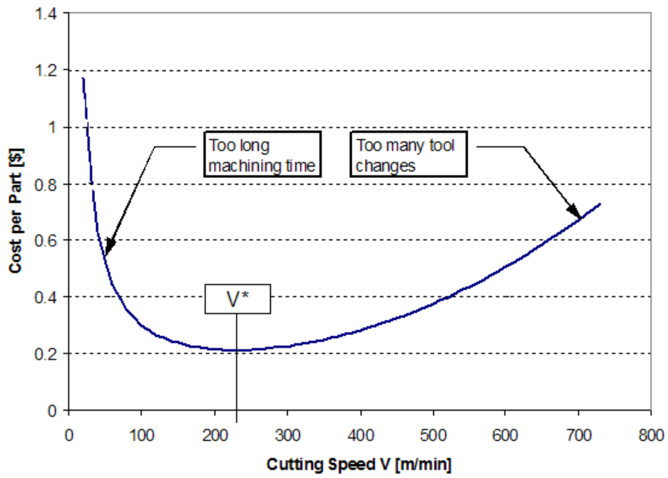

Figure 4: Machining cost/part for a typical machining scenario

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) (RMS) given by Eq. (4) and the Peak-to-valley roughness (R_t) (PV or 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 surfaces could have the same roughness value, but quite different topographies. The process finish capability of a rough machining operation is about 0.05 mm and for finishing is about 0.005 mm. Note however that these values are affected by machining parameters and other factors.

Measurement of surface roughness is usually accomplished through commercially available surface profilometers, the most common featuring a a diamond stylus traveling over a surface. Additionally, it can also be observed directly through interferometry, either optical, Scanning-electron or Atomic-force microscopy.

PREDICTION OF SURFACE ROUGHNESS: METHODS

An investigation of the various methodologies and practices employed for the prediction of surface roughness is detailed in [5]. This section serves to summarize and list these methods in terms of the approach adopted into four broad categories as given below.

MACHINING THEORY BASED APPROACH

The prediction methods in this category are based on fundamental machining theories on cutting tool characteristics and process kinematics to develop analytical models to represent the machined surface. These theoretical surface prediction models have been observed to be closely comparable to the actual experimental measurements of surface characteristics [2, 4]. One of the main drawbacks of such prediction models however, is their inability to incorporate the multiple variations and uncertainties commonly associated with the machining process.

Most typical cutting tools usually have rounded corners (as compared to ones with sharp working corners). Figure 5 shows an idealized work surface produced by such a tool.

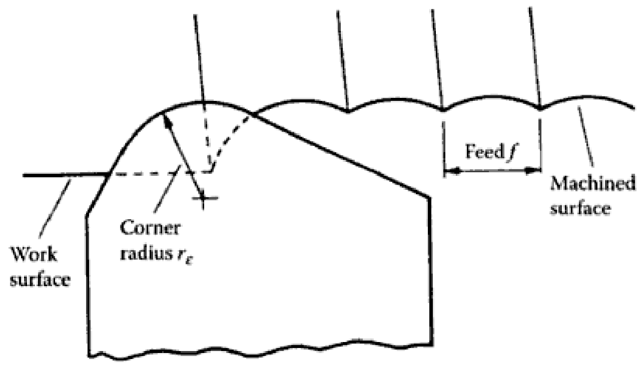

Figure 5: Idealized surface roughness model for a typical rounded corner cutting tool [25]

From such a model, the theoretical arithmetic mean value of surface roughness can be expressed as in Eq. (6).

$$R_a = \frac{0.0321 f^2}{r_c} \quad (6)$$

where, 'R_a' is the surface roughness in µm, 'f' is the feed in mm/tooth, and 'r_c' the tool nose radius in mm. It can be observed that the surface roughness is directly proportional to the square of the feed and inversely proportional to the corner radius of the tool.

EXPERIMENTAL INVESTIGATION APPROACH

The most direct method to predict surface quality is by the creation of regression models based on experimental investigation studies. The advantage of such models is that they are able to take into account multiple factors influencing surface quality that would not have been able to be accounted for in analytical models and for cases where an analytical formulation is not feasible. Though it is comparatively easier to implement, the obtained results can have little or no general applicability.

DESIGN OF EXPERIMENTS APPROACH

These approaches comprise a systematic method of scheduling experiments as well as gathering and analyzing records with a near-optimum use of resources. The most widely employed methodologies for surface roughness prediction in terms of machining parameters are the Response Surface Methodology (RSM) and the Taguchi techniques for design of experiments.

Response Surface Methodology (RSM):

RSM is a fundamental method to derive the relationship between the different parameters affecting the process. RSM works by applying different designed experiments to obtain a polynomial model of the process keeping the independent variable as the system output which is minimized. A comprehensive algorithm of the procedure/calculations involved is given in [13].

Taguchi Techniques for DoE:

Taguchi DoE is a class of factor-monitoring methods to resolve the importance of each factor contributing to the process. It identifies the most dominant parameters and the values that generate the preferred output without formulating a model. A comprehensive reference for the procedure involved is provided in [3].

RSM is more of a model formulation procedure which can be used to create contour plots to understand of parameter behavior, while Taguchi DoE is more of a factor screening procedure to determine the significance of each parameter with respect to the process behavior.

ARTIFICIAL INTELLIGENCE OR SOFT COMPUTING APPROACH

Artificial Intelligence (AI) [14, 15] is usually implemented in engineering problems through development of Artificial Neural Network (ANN) models and genetic algorithms (GAs). Thse simulate the manner in which humans process information and make decisions for predicting surface roughness.

Artificial Neural Network (ANN):

ANN is a mathematical or computational model which is comparable to biological neural networks. ANN is used to solve a variety of problems in pattern recognition, prediction, optimization, association and control. The main advantage of ANN, compared to conventional methods is the ability to manage and use noisy or incomplete data.

Genetic Algorithms (GA):

GA is a search technique used in optimization problem approximations, based on Darwin's Theory of Evolution. The algorithm is initiated with a range of solutions (represented by chromosomes) called population. Solutions from one population are taken and utilized to shape a new population. This is motivated by an expectation, that the new population will be better than the old one. Solutions which are selected to form new solutions are chosen according to their fitness - the more suitable they are the more chances they have to reproduce. The two chief advantages of GA are the simplicity of application and the efficiency with multiple criterion optimizations though it could be very demanding on computational power.

MACHINE PARAMETERS ON SURFACE ROUGHNESS [23]

The most significant machine parameters that have a direct effect on surface roughness are discussed below [10, 12-15].

FEED, SPEED AND DEPTH OF CUT

In general, it is found that surface roughness increases with an increase in the feed rate and depth of cut and a decrease in cutting speed. Roughness is found to reduce drastically up to a particular critical value of surface speed which is attributed to the reduction in size of the built up edge. At this speed, when the effect of the built up edge is considered negligible, the profile of the cutting edge of the tool (pointed or curved) gets imprinted on the work surface, and the surface roughness from this point on depends on the feed rate. A larger depth of cut, or in other words a larger chip cross-sectional area adversely affects surface finish though it is usually not significant until it is large enough to cause chatter. Note that the effect of increased feed is more pronounced on surface finish than the effect of an increased depth of cut. Thus, measures for improving machining productivity (increasing feed and depth of cut) work against achieving better surface quality.

TOOL GEOMETRY

It is obvious that a larger nose radius leads to better surface finish. Additionally, it has been observed that an increase in the rake angle improves surface finish significantly.

GEOMETRY OF CHIP FORMATION

Depending on the type of chips formed (continuous or discontinuous), the surface finish will increase directly with increasing friction between the tool surface and the chips formed.

CUTTING FLUIDS

Generally, it is observed that the use of cutting fluids improves the surface finish, which is attributed to the reduction in the coefficient of friction as well as the size of the built up edge. Further, fluid penetration into the cutting interface reduces adhesion between the tool face and the chip through a chemical reaction, which therefore depends on the surface speed. Hence, cutting fluids are more effective at lower surface speeds.

VIBRATION AND CHATTER [20]

For a machine tool, its stiffness and damping are the two important factors determining the dynamic characteristics of the machine-tool structure; for a stable system the vibrations decay with time. Stiffness depends on the dimensions and rigidity of the structure while damping depends on the type of material used as well as the number/nature of joints.

Cutting operations generate two basic types of vibrations. Forced vibrations are usually caused by a periodic force present in the machine tool, such as an imbalance in rotating masses, external excitations or due to periodic engagement/ disengagement of the workpiece. Self-excited vibration (chatter) is caused by the interaction of the chip removal process and the structure of the machine tool. Vibrations can cause loss in dimensional accuracy and performance, as well as adversely affect tool life, surface roughness and hence cost/productivity. These effects are even more pronounced if the frequency of any component within the machine-tool-workpiece system approaches their respective natural frequencies. Some of the recommended suggestions to reduce vibration and chatter are as follows: Standard requirements call for a more rigid structure and a higher damping capacity. Additional suggestions include using tools with unequal spacing of peripheral teeth, with odd number of teeth, properly orienting the workpiece, proper clamping, minimizing overhang, etc.

ADDITIONAL FACTORS

The built-up-edge (BUE) which changes the instantaneous cutting tool profile has the greatest influence on surface roughness than most other factors. Thus, ceramic and diamond tools generally produce better surface finish due to their lower tendency to form BUE [20]. Additionally, the tendency to for BUE reduces with increasing cutting speeds.

From this section, we are able to gather a general outline of the changing surface finish levels with varying machine parameters (speed, feed, depth of cut, etc.). Thus, on increasing surface speed, surface roughness is observed to reduce drastically up to a particular critical value beyond which the feed rate had a more pronounced effect on surface roughness.

DOMINANCE OF FEED ON SURFACE QUALITY

The focus of numerous and extensive studies that evaluate surface finish is usually centered on the effect that machining parameters (speed, feed, depth of cut, etc.) have on the surface quality. However, vibrations within the system can have an even more significant adverse effect on the surface finish of a machined component. These vibrations originate directly from the stiffness and damping capacity of the environment-machine-tool-workpiece-clamping system. Most of the modern CNC machine tools manufactured recently have excellent stiffness and damping capacities when installed and calibrated appropriately. However no real machine can have infinite stiffness and thus there is always a certain amount of vibration within any machine tool which cannot be eliminated.

This realization suggests the need for an alternate manner of assessing the effects of machining parameters on the surface finish. Thus, comparing the effects of a particular combination of a speed and feed on the surface quality with a different combination of speed and feed brings into play a hidden effect in terms of changed machine dynamics caused due to the difference in surface speeds. This suggests that one needs to fix the dynamic characteristic of the machine (i.e., having a fixed vibration amplitude and frequency at a particular surface speed), before analyzing the rest of the parameters' effects on surface quality. Thus, changing speeds cause a difference in the vibration dynamics of the machine which remains constant as long as the surface speed remains constant. However, at a constant fixed speed, changing feed rates create differences in surface quality, and these differences can be attributed predominantly if not completely to changing feed rates.

This reasoning is validated by the results from a number of independent studies where a variety of methods were used to predict and measure surface roughness values. In all of these studies, the dominance of feed on the surface roughness over other machining parameters is reiterated.

[7] developed a regression model for surface roughness prediction in end milling to evaluate spindle speed, depth of cut and feed rate on 6061 aluminum. It was reported that surface roughness was most influenced by the feed rate. [8] discussed the surface roughness optimization of AA6061-T6 aluminum using RSM and Radian Based Function Network (RBFN) approaches by optimizing cutting depth, feed rate and radial depth. Again, it was reported that feed rate was the most significant factor affecting surface roughness. [12] modeled the surface roughness in end milling using adaptive neuro-fuzzy inference system (ANFIS) and genetic algorithms (GA) using spindle speed, feed rate, depth of cut and the workpiece-tool vibration amplitude as inputs. The results show the dominant effect of feed rate on surface quality.

[13] explored the optimization of the roughness characteristics of milling 6061-T6 aluminum by predicting surface roughness using RSM. It was reported that feed rate was the most influential factor on surface roughness. [14] used multiple regression analysis to predict and determine surface roughness and it was reported that feed rate was the most significant machining parameter. [15] determined the effect of feed rate and cutting speed on machined surface quality both experimentally and analytically. A sensitivity study was conducted, which showed that feed rate was the most significant parameter affecting the machined surface roughness when end milling aluminum. [16] reported that an increasing feed rate amplified surface roughness.

Thus, a common consensus of these results is that, for a better surface finish, feed needs to be reduced while speed need to be increased. However, for higher productivity, a maximum material removal rate is required, suggesting increased feeds and depths of cut. Thus, the challenge is to maximize the feed rate as much as possible while maintaining surface roughness numbers within limits or within a range, whichever is applicable for automotive component manufacture.

IMPROVED SURFACE FINISH: RECOMMENDATIONS [20, 23]

This section lists, and details on some of the general recommendations given for achieving better surface finish when machining aluminum in addition to the suggestions made in a previous section.

- Aluminum has good machinability; however, softer grades tend to form BUE due to its lower elastic modulus. This requires appropriate chucking and clamping arrangements that avoid deformation and distortion.
- A helical tooth profile results in a better finish, more widely distributed load and less chatter compared to straight edged tooth profiles.
- High rake and relief angles are recommended, which results in an increased shear angle, reducing cutting forces and hence roughness.
- The spindle could be tilted slightly in the direction of feed so that, the finished surface is not re-cut by the backside of the cutter due to the minute bending of the spindle axis.
- Use climb/down milling instead of up/ conventional milling where chip thickness starts from zero to maximum causing some rubbing action before the tool edge actually gets cutting. This causes higher pressure and heat buildup which can lead to welding/scratching of the surface. Though climb milling is recommended, it has a higher chance of inducing vibrations.
- Maintain the direction of cut, depth of cut and indexed insert edges, for operations requiring multiple milling finishing passes.
- Use copious amounts of coolant.
- Clean the workpiece surface before machining.
- Maintain sharp cutting edges so that the tools will shave the material instead of rubbing it.
- Select tool geometry that will cause chips to be lifted upwards and out from the finished surface and constantly thrown clear of the cutter.
- For very fine finishes, the cutting tool should be honed to a keen edge.
- A sulphurized mineral oil or a heavy-duty soluble oil will sometimes be helpful in obtaining a satisfactory surface finish.

EXPERIMENT DETAILS: FEED - SURFACE QUALITY DEPENDENCE

SETUP AND PROCEDURE

A controlled milling experiment was conducted on a 6061 aluminum block (with average dimensions of 175 mm x 80 mm x 30 mm) to determine the relationship between feed and surface quality. The selected depth of cut was held constant at 2 mm (finishing cut) for a length of cut of 80 mm using a 25.4 mm diameter end mill holding four indexable cutting inserts. These were carbide inserts with a PVD TiCN coating having a 28o positive rake angle. Copious amount of coolant was provided at the cutting zone throughout the experiment.

The experiments were performed as conventional/ up milling slot cut runs on an OKUMA MB-46VAE 3-axis vertical milling center at four levels of feed and speed combinations as listed in Table 2. The inserts were checked for wear after each run, and since no wear was noticeable throughout the duration of the experiment, they were retained for the whole set of 16 runs. Figure 6 shows the milled 6061 aluminum block with six slot cuts visible on the top face.

Table 2: Experimental setup: Speeds and Feeds

Runs	Speed (rpm)	Feed (mm/min)

1-4	1000	152.4, 304.8, 457.2, 609.6
5-8	2000	152.4, 304.8, 457.2, 609.6
9-12	3000	152.4, 304.8, 457.2, 609.6
13-16	4000	152.4, 304.8, 457.2, 609.6

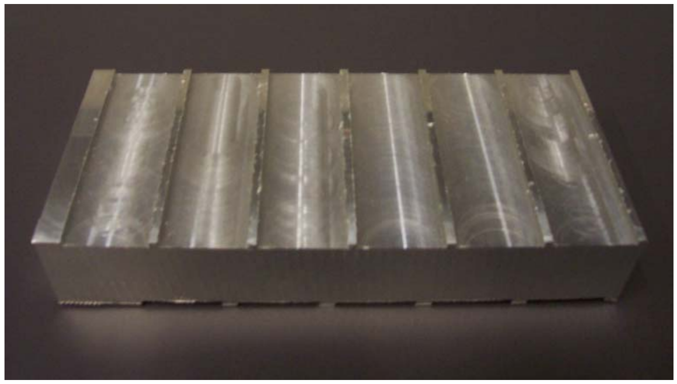

Figure 6: Milled block with 6 slot cuts visible

The surface roughness measurements of the workpiece were recorded using a Zygo NewView 7200 white light laser interferometer at 5X x 0.5X magnification using a 150 µm bipolar downward scan. No other formal cleaning process was used and care was taken not to scratch the surface of the block during handling. Surface roughness measurements were recorded along the centerline of the slot cut at three locations within each slot, at the entry, middle and exit points.

EXPERIMENTAL RESULTS

The three measured values of surface roughness along the centerline of a slot cut are averaged the results are plotted against the four surface speed increments of 1000, 2000, 3000, 4000 rpm for each of the feed increments of 6, 12, 18, 24 ipm (plots are in mm/min) as shown in Figure 7. Note that the surface roughness parameter plotted is the arithmetic mean value (R_a) which is in µm.

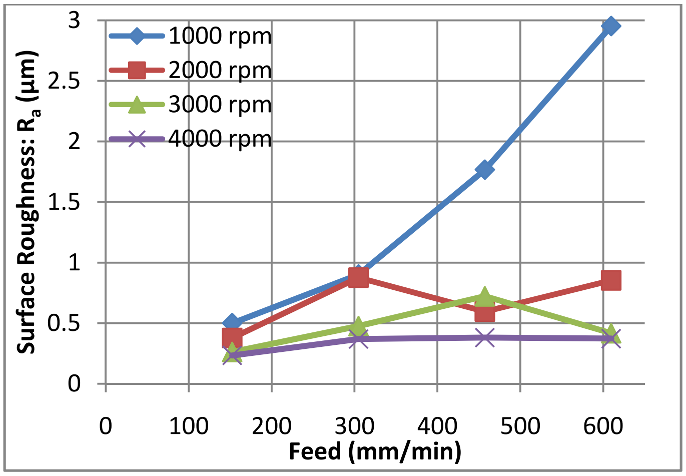

Figure 7: Plot of average surface roughness (μm) for different feeds and speeds (rpm)

Shown below is a sample set of surface roughness plots and values obtained from the 3D white light later interferometer (Figure 8). This data set is for the run with a rotational speed of 1000 rpm (79.8 m/min surface speed) and feed rate of 609.6 mm/min (24 ipm). The data point is at the center of the aluminum block along the middle line of the slot cut direction. Note that this is the data point with the worst (highest) surface roughness value out of all the runs.

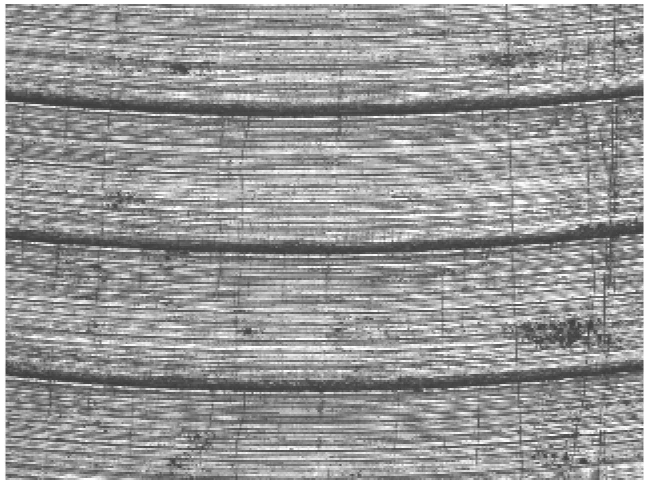

Figure 8: Intensity map of surface (picture)

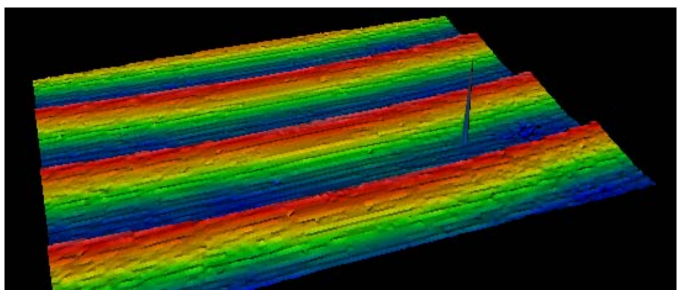

Figure 9: 3D topography model of surface

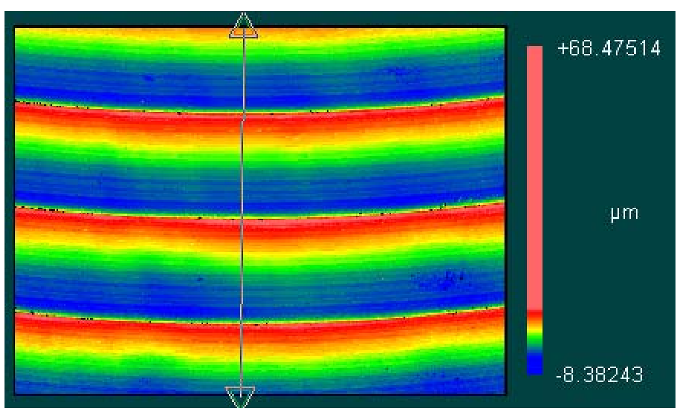

Figure 10: 2D spectrum acquired surface area

PV	76.858	µm
rms	3.261	µm
Ra	2.816	µm
Size X	2.83	mm
Size Y	2.12	mm

Figure 11: Parameters of selected area from Figure 10

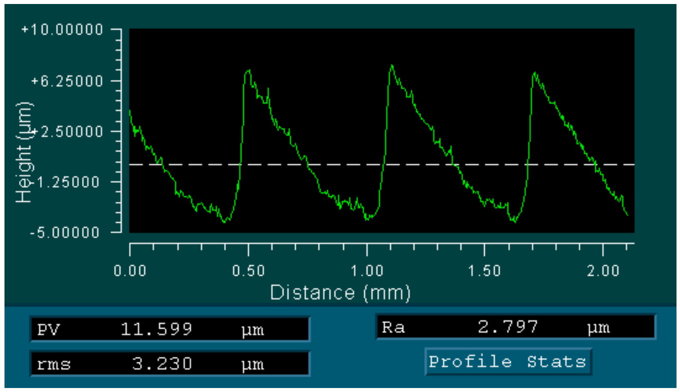

Figure 12: Surface roughness profile plot and parameters along vertical line drawn in Figure 10

ANALYSIS OF RESULTS

The captions under the above Figures (8-12) are self-descriptive. Note from Figures 11 and 12 that, two different sets of surface roughness measurements are obtained. Figure 11 shows surface roughness values (R_a, Root Mean Square, Peak-to-Valley) of the 2.83 mm x 2.12 mm area segment, while Figure 12 shows surface roughness values (R_a, RMS, PV) along the vertical line drawn in Figure 10. Since this line runs normally across the 'ridges,' it is a good estimate of surface roughness across this region, especially since it is a mill-cut surface. Note that these roughness value sets (across areas and lines) are comparable to each other, and a deviation plot (not included) indicates less than 1% deviation between the two. The range of surface roughness attained through standard machining operations is about 0.8 µm to 6.3 µm; the measured values are within these limits.

Another detail to be noted is the variation of the surface roughness between entry/exit points and the middle point along each slot. In general, the entry/exit points have a higher surface roughness compared to the middle point. This is attributed to the disturbances/vibrations induced when the cutter enters/exits the workpiece, which damps quickly with engagement providing a much smoother surface profile at the middle section when the cutting dynamics have stabilized.

As expected, the surface quality of the machined surface improved with a reduction in the feed rate (Figure 7). Increasing deterioration of surface quality can be observed at higher feed rates especially at lower surface speeds (around 80 m/min or 1000 rpm for this mill). Thus, increasing the surface speed results in increasing deterioration of the surface condition.

Additionally, the average surface roughness values are re-plotted with respect to feed distance [mm/tooth] to examine the effects of certain feed and surface speed combinations and to compare with the analytical surface roughness prediction of Eq. (6) from a machining theory based approach (see Figure 13). The experimentally measured and analytically predicted roughness values are comparable to each other with the predicted values lower as one would expect, since the analytical model considers only swept idealized geometry.

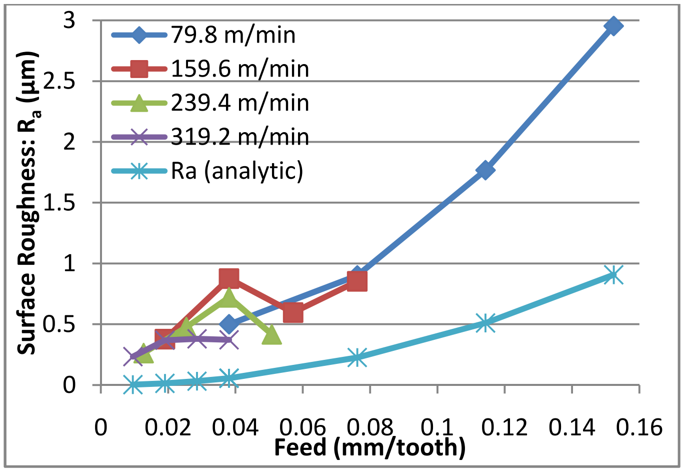

Figure 13: Plot of average surface roughness for different feeds (mm/tooth) and speeds (m/min) against an analytical surface roughness prediction

From the above plot it is noticed that though the surface roughness generally increases with an increase in feed/tooth, there is a peak in roughness around 0.04 mm/tooth feed especially between 160-240 m/min (2000-3000 rpm) surface speed for the 25.4 mm (1") mill. This suggests that there is some surface speed dependence or a surface speed-feed combination dependence as well on the roughness at certain feed rates. Though not completely investigated in this study, this dependence is expected to be hinged on a combination of cutter diameter, machine stiffness, milling type, etc. Also, the variability of roughness along a particular surface speed is noticed to be lower at higher speeds.

CONCLUSION

This paper served to introduce aluminum as a versatile and attractive lightweight automotive material with significant cost savings. Standard surface roughness prediction methodologies were explored. Parameters affecting surface roughness of machined surfaces were detailed (with an emphasis on the dominance of feed) along with practical recommendations to improve surface quality. A controlled milling experiment on 6061 aluminum depicted the relationship between feed and surface quality. These results were used to recommend machining practices for improved surface quality and hence minimizing cycle time, thus improving productivity. Thus, the contribution of each parameter was inferred, and a recipe prescribed, i.e., increase the feed up until a cutoff surface roughness limit is reached and then increase the surface speed within the roughness range, to maximize productivity.

REFERENCES

1. Kromanis, A., J. Krizbergs, “3D Surface Roughness Prediction Technique In End-Milling Using Regression Analysis,” 6th International DAAAM Baltic Conference, Industrial Engineering, 24-26 April 2008, Tallinn, Estonia.
2. Luke Huang, Joseph C. Chen, “A Multiple Regression Model to Predict In-process Surface Roughness in Turning Material Via Accelerometer,” Journal of Industrial Technology, vol. 17, no. 2, Feb. 2001.
3. Hasan Oktem, Tuncay Erzurumlu, Mustafa Col, “A Study of The Taguchi Optimization Method for Surface Roughness in Finish Milling of Mold Surfaces,” Int J Manuf Technol, vol. 28, pp. 694-700, 2006.
4. Sabahudin Ekinovic, Edin Begovic, Amira Silajdzija “Comparison of Machined Surface Quality Obtained By High-Speed Machining and Conventional Turning,” Machining Science and Technology, vol. 11, pp. 531-551, 2007.

5. Benardos, P.G., G.C. Vosniakos, "Predicting Surface Roughness in Machining: A Review," International Journal of Machine Tools & Manufacture, vol. 43, pp. 833-844, 2003.
6. Henri Paris, Gregoire Peigne, Rene Mayer "Surface Shape Prediction in High Speed Milling," International Journal of Machine Tools & Manufacture, vol. 44, pp. 1567-1576, 2004.
7. Ab. Rashid M.F.F., Muhammad N.Y., "Mathematical Modeling to Predict Surface Roughness in CNC Milling," World Academy of Science, Engineering and Technology, vol. 53, 2009.
8. Kadirgama, K., M.M. Noor, N.M. Zuki N.M., M.M. Rahman, M.R.M. Rejab, R. Daud, K.A. Abou-El-Hossein, "Optimization of Surface Roughness in End Milling on Mould Aluminum Alloys (AA6061-T6) Using Response Surface Method and Radian Basis Function Network," Jordan Journal of Mechanical and Industrial Engineering, vol. 2, no. 4, pp. 209-214, Dec. 2008.
9. Reddy, K., P. Venkateswara Rao "Selection of an Optimal Parametric Combination for Achieving a Better Surface Finish in Dry Milling Using Genetic Algorithms," Int J Manuf Technol, vol. 28, pp. 463-473, 2006.
10. Ghani, A.K., I.A. Choudhury, Husni, "Study of Tool Life, Surface Roughness and Vibration in Machining Nodular Cast Iron with Ceramic Tool," Journal of Materials Processing Technology, vol. 127, pp. 17-22, 2002.
11. Abouelatta, O.B., J. Madl "Surface Roughness Prediction Based on Cutting Parameters and Tool Vibrations in Turning Operations," Journal of Materials Processing Technology, vol. 118, pp. 269-277, 2001.
12. Samanta, B., "Surface Roughness Prediction in Machining Using Soft Computing," International Journal of Computer Integrated Manufacturing, vol. 22, no. 3, pp. 257-266, March 2009.
13. Kadirgama, K., M.M. Noor, N.M. Zuki N.M., M.M. Rahman, M.R.M. Rejab, R. Daud, K.A. Abou-El-Hossein, "Surface Roughness Prediction Model of 6061-T6 Aluminum Alloy Machining Using Statistical Method," European Journal of Scientific Research, vol. 25, no. 2, pp. 250-256, 2009.
14. Mike S. Lou, Joseph C. Chen, Caleb M. Li, "Surface Roughness Prediction Technique for CNC End-Milling," Journal of Industrial Technology, vol. 15, no. 1, Nov. 1998.
15. Abdullah, A.B., L.Y. Chia, Z. Samad, "The Effect of Feed Rate and Cutting Speed to Surface Roughness," Asian Journal of Scientific Research, vol. 1, no.1, pp. 12-21, 2008.
16. Reis, D.D., A.M. Abrao, "The Machining of Aluminum Alloy 6351," Proc. IMechE, vol. 219, Part B, 2005.
17. Vijayaraghavan, A., Aaron M. Hoover, Jeffrey Hartnett, David A. Dornfild, "Improving Endmilling surface Finish by Workpiece Rotation and Adaptive Toolpath Spacing," International Journal of Machine Tools & Manufacture, vol. 49, pp. 89-98, 2009.
18. Toh, C.K. "Surface Topography Analysis in High Speed Finish Milling Inclined Hardened Steel," Precision Engineering, vol. 28, pp. 386-398, 2004.
19. Chaoudhury, S.K., J.B. Bajpai "Investigation in Orthogonal Turn-milling Towards Better Surface Finish," Journal of Materials Processing Technology, vol. 170, pp. 487-493, 2005.
20. Kalpakjian, S. (1997) Manufacturing Process for Engineering Materials, 3rd ed., Addison-Wesley, Menlo Park, CA.
21. A. Morita, "Aluminum alloys for automobile applications," Proc. of ICAA-6, Toyohashi, vol. 1, pp. 25–32, 1998.
22. Sears, K., "Automotive Engineering: Strategic Overview 2," Vol. 1, pp. 55–68, 1997.
23. Jain, R.K., (2000) Production Technology, 15th ed., Khanna Publishers, Delhi.
24. Davis, J.R., Aluminum and Aluminum Alloys, J.R. Davis & Associates, ASM International. Handbook.
25. Boothroyd, G. (2006) Fundamentals of Machining and Machine Tools, 3rd e., Winston Anthony Knigh.
26. Ducker Worldwide LLC, "Aluminum Association Auto and Light Truck Group 2009 Update on North American Light Vehicle Aluminum Content compared to other Countries and Regions of the World Phase II," December 2, 2008.

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