Influence of cutting parameters on surface hardness in milling of AL6061T6

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Abstract. Milling is an important industrial common machining operation used to produce complex surfaces. Surface quality in milling operation is influenced by various factors such as cutting speed, cutting feed, depth of cut and chemical composition of the material. Surface quality is defined by roughness, residual stress and microhardness and is important in determining corrosion resistance and in fatigue crack initiation. The aim of the present paper is to analyse the influence of above-mentioned cutting parameters (cutting feed, cutting speed, depth of cut) on surface microhardness. Tests were conducted using a Coro mill 490 with a single insert that was indexed for every experiment, thus eliminating the influence of tool wear. Al 6061-T6, a material widely utilised in aircraft, defence, automobiles, and marine areas due to its good proprieties (good strength and lightweight) was used. Microhardness was measured on workpiece surface but also in the cross section of the workpiece, up to a depth of 1mm, in order to observe material state in subsurface layer. It was observed from the results that an increase of cutting speed have led to an increase of microhardness while a higher value for depth of cut has led to a lower value of microhardness. Feed rate has generated similar results with the depth of cut.

1. Introduction

The aerospace industry is increasingly demanding low-density alloys with greater resistance to stress and fatigue [1]. One of this extensively used materials is Aluminium alloy Al 6061T6 that is known that combines relatively high strength, good workability, high thermal conductivity (167w/m*K) and high resistance to corrosion [2]. In order to obtain different type of parts several operations are used that affect the surface quality. Turning, drilling, and milling are the most often used processes to achieve the parts at the desired form. Milling is a complex operation that consists in material removing using a multiple edge cutting tool that executes the work movements. Compared with turning process where the chip formation is continuous, milling is an intermittent process that lead to heat variation that influence the surface quality of machined part and tool life [3]. The main heat sources of the cutting process are the primary shear zone at the tool – work piece interface, the tool-chip interface and at the clearance face contact with the machined surface. Approximately 80% of the generated heat is transferred to the chip while 10-20% is transferred in the work piece or tool material [4]. The use of different cutting parameters will lead to various
difference of surface quality “factors”, such as roughness, residual stress and micro hardness [5-9]. For example, a cheap method to understand the distribution of residual stress in surface layer is the indentation method. This method is based on material surface microhardness that will influence the surface deformation under indentation. There are two methods of indentation known at this time, sharp pyramidal indentation, similar with Vickers indentation and spherical indentation (similar with Brinell indentation method) [10]. Microhardness is important in determining corrosion resistance, and also in fatigue crack initiation [11]. The aim of present paper is to investigate the influence of cutting parameters, such as depth of cut, cutting speed and cutting feed on surface integrity. To extend the study, an artificial neural network will be created to predict the results for other cutting parameters.

2. Experimental conditions

2.1 Workpiece material
An aluminium alloy (Al 6061-T6) was chosen to in this research where the variation of microhardness in the surface layer generated by milling is examined. The aluminium alloy has been used because of its good mechanical proprieties (good machinability, good resistance to corrosion, numerous applications in aerospace industry); the presence of some chemical elements in the composition of the alloy, such as Mg, Si, Cr, Mn etc., will improve the characteristics of material (increase the ductility, hardness, machinability etc.), which is also a reason to choose this material for comparison [12]. The chemical composition and the main mechanical properties of the material are presented in tables 1 and 2.

| Table 1. Chemical composition of material. |
|-------------------------------------------|
| Chemical composition                      |
| Al %  | Cr%   | Cu%   | Fe%   | Mg%   | Si%   |
| 95.8-98.6 | 0.04-0.35 | 0.15-0.4 | 0.7   | 0.8-1.2 | 0.4-0.8 |

| Table 2. Mechanical proprieties of material. |
|---------------------------------------------|
| Rp,0.2 (MPa)  | Rm (MPa)  | A (%)  | Theoretic HV | Initial HV (measured) |
| 276           | 310       | 17     | 107           | 112.6                  |

2.2 Machining conditions
In the experiment three sets of values for the cutting speed, cutting feed and depth of cut were used to assess the influence on surface micro hardness. The cutting parameters were chosen to obtain good quality of surface (surface roughness), according to previous experiences. The cutting parameters are presented in table 3.

| Table 3. Cutting parameters. |
|------------------------------|
| Cutting speed, vc (m/min)   | Cutting feed, fz (mm/tooth) | Depth of cut, ap (mm) |
| 80                          | 0.05                          | 0.2                        |
| 160                         | 0.1                           | 0.5                        |
| 240                         | 0.15                          | 0.8                        |

The milling was performed on a CNC machine with maximum spindle rotation equal to 12.000 rot/min. The tool was a cylindrical mill with 50mm diameter equipped with 5 inserts with an edge radius of 0.025 mm, 90° cutting insert orientation (figures 1 (a), (b) and (c)). Machining was
performed on prismatic parts, with 150 x 60 x 50 mm dimensions and a radial width of cut was of 50 mm. For each experiment, a new cutting edge was used, thus eliminating the influence of tool wear.

![Insert Geometry](image1)

![Insert Orientation](image2)

![Coromill 490](image3)

**Figure 1.** Mill type: (a) insert geometry; (b) insert orientation; (c) Coromill 490.

Surface hardness was measured with Ultramatic 2 CV-HV400 hardness tester (figure 2). 10 indentations were made on the surface in order to have an “average view” over the sample.

![Ultramatic 2 CV-HV400](image4)

**Figure 2.** Ultramatic 2 CV-HV400.

3. Results and discussions

In order to have a clear comparison between the measured values and the referenced values from the literature (107 HV) an initial measurement was conducted on an unprocessed sample. The average value of the measured hardness was found to be equal to 112.6 HV units. In order to observe various influences on surface micro hardness, the dependence between parameters were investigated (cutting feed \(f_z\), cutting speed \(v_c\) and depth of cut \(a_p\)).

3.1 Influence of cutting feed on surface microhardness in relation with the depth of cut

The use of different cutting parameter changed the micro hardness surface. Analysing the influence of cutting feed on micro hardness HV revealed that the use of a small cutting feed (0.05mm/tooth) generate high values of microhardness; this can be the effect of heat generated in aluminium surface layer as is shown also by Fuller and Azzer in previous studies over aluminium behaviour under temperature treatments [13, 14]. The increase of cutting feed led to an rapid decrease of surface microhardness, the lowest values being measured for 0.15mm/tooth cutting feed (figure 3).
3.2 Influence of cutting speed $v_c$ on surface microhardness in relation with cutting feed $f_z$

Figure 4 shows for the influence of the cutting speed ($v_c$) on micro hardness (HV) a similar tendency as in the case of cutting feed ($f_z$). The use of a small cutting speed (80 m/min) led to a high value of surface microhardness while a faster movement of the cutting tool on the material surface generated smaller value of microhardness.

The interdependence between cutting speed $v_c$ in relation with depth of cut (figure 5) revealed a insignificant change in surface microhardness.
Figure 5. The interdependence between the cutting speed and the depth of cut on the surface microhardness.

4. Theoretical prediction of micro hardness using artificial neural network

Artificial neural network are systems that emulate a behaviour similar to the human brain. Practically a neural network uses multiple layers consisting of inputs, hidden layers, and output. Weight and bias between each input neuron and its next hidden layer neuron is initially assigned randomly. Each hidden neuron will have a certain number of elements that will be connected in both directions (input-output). The behaviour of the output units depends on the activity of the hidden units and the weights between the hidden and output units [15]. In order to obtain a network that will predict the micro hardness, different models were created and tested. The model uses 60% of the data set for training (marked in black), 15% for cross validation (marked in red) and 25% for testing (marked in blue). Table 4 presents the input parameters (cutting speed - \( v_c \), cutting feed - \( f_z \) and depth of cut - \( a_p \)) whereas surface hardness HV was the output parameter.

Table 4. Cutting parameters.

| Cutting speed \( v_c \) (m/min) | Cutting feed \( f_z \) (mm/tooth) | Depth of cut \( a_p \) (mm) | Microhardness (HV) |
|-------------------------------|-------------------------------|-----------------|--------------|
| 240                           | 0.1                           | 0.5             | 176.2        |
| 80                            | 0.15                          | 0.2             | 177.1        |
| 80                            | 0.1                           | 0.5             | 178.9        |
| 240                           | 0.05                          | 0.5             | 184.8        |
| 80                            | 0.05                          | 0.5             | 186.8        |
| 240                           | 0.15                          | 0.5             | 177.1        |
| 240                           | 0.1                           | 0.2             | 177.1        |
| 160                           | 0.1                           | 0.5             | 176.8        |
| 160                           | 0.05                          | 0.5             | 186          |
| 240                           | 0.15                          | 0.8             | 171.5        |
| 160                           | 0.1                           | 0.2             | 176.9        |
| 160                           | 0.15                          | 0.5             | 173.8        |
| 240                           | 0.05                          | 0.8             | 180.4        |
| 80                            | 0.1                           | 0.2             | 172.5        |
| 80                            | 0.05                          | 0.8             | 183.4        |
The tendency of tested network was observed in order to have an accurate prediction. From the graph can be observed that the tendency of HV and predicted output HV are very similar (figure 6).

![Desired Output and Actual Network Output](image)

**Figure 6.** Desired output and actual network output.

The best network combinations are shown in table 5. Combination with one single layer with four elements on hidden layer (1-4-1) reveal the best correlation coefficient.

| Layer configuration | R (correlation coefficient) |
|---------------------|-----------------------------|
| 1-4-1               | 0.88                        |
| 2-4-6-1             | 0.63                        |
| 4-2-2-2-2-1         | 0.55                        |
| 4-12-6-4-2-1        | 0.55                        |
| 2-4-4-1             | 0.49                        |
| 1-6-1               | 0.46                        |
| 4-4-4-4-4-1         | 0.32                        |
| 1-8-1               | 0.26                        |

Considering the data presented above, several cutting parameters were verified in order to observe the predicted micro hardness. Parameters were inserted in the network model and production data set was applied (table 6).

From the presented result it can be observed that the network predicted an increase of surface hardness over 187 HV units when high speeds will be used, while the use of a small cutting speed will lead to a smaller value. Also, it can be observed that a small cutting feed, equal to 0.05 mm have generated the highest value (187.64 HV), while increase of cutting feed lead to a low value of HV units.
Table 6. Results of predicted production data set.

| Cutting speed ve (m/min) | Cutting feed fz (mm/tooth) | Depth of cut ap (mm) | Microhardness (HV) |
|-------------------------|---------------------------|---------------------|--------------------|
| 20                      | 0.05                      | 0.2                 | 181.559            |
| 20                      | 0.05                      | 0.5                 | 183.386            |
| 20                      | 0.05                      | 0.8                 | 183.916            |
| 40                      | 0.05                      | 0.2                 | 181.892            |
| 40                      | 0.05                      | 0.5                 | 183.687            |
| 40                      | 0.05                      | 0.8                 | 183.866            |
| 480                     | 0.05                      | 0.2                 | 185.464            |
| 480                     | 0.05                      | 0.5                 | 184.817            |
| 480                     | 0.05                      | 0.8                 | 187.418            |
| 1000                    | 0.05                      | 0.2                 | 187.63             |
| 1000                    | 0.05                      | 0.5                 | 187.64             |
| 1000                    | 0.05                      | 0.8                 | 187.644            |
| 20                      | 0.1                       | 0.2                 | 180.116            |
| 20                      | 0.1                       | 0.5                 | 178.475            |
| 20                      | 0.1                       | 0.8                 | 179.865            |
| 40                      | 0.1                       | 0.2                 | 180.088            |
| 40                      | 0.1                       | 0.5                 | 178.68             |
| 40                      | 0.1                       | 0.8                 | 180.004            |
| 480                     | 0.1                       | 0.2                 | 180.451            |
| 480                     | 0.1                       | 0.5                 | 182.505            |
| 480                     | 0.1                       | 0.8                 | 184.441            |
| 1000                    | 0.1                       | 0.2                 | 187.142            |
| 1000                    | 0.1                       | 0.5                 | 187.433            |
| 1000                    | 0.1                       | 0.8                 | 187.357            |
| 20                      | 0.15                      | 0.2                 | 176.664            |
| 20                      | 0.15                      | 0.5                 | 176.837            |
| 20                      | 0.15                      | 0.8                 | 176.562            |
| 40                      | 0.15                      | 0.2                 | 176.691            |
| 40                      | 0.15                      | 0.5                 | 176.83             |
| 40                      | 0.15                      | 0.8                 | 175.994            |
| 480                     | 0.15                      | 0.2                 | 175.554            |
| 480                     | 0.15                      | 0.5                 | 176.207            |
| 480                     | 0.15                      | 0.8                 | 177.131            |
| 1000                    | 0.15                      | 0.2                 | 181.221            |
| 1000                    | 0.15                      | 0.5                 | 183.25             |
| 1000                    | 0.15                      | 0.8                 | 185.05             |

5. Conclusions
The variation of cutting parameters generated changes in surface microhardness. From the presented results it can be concluded that the biggest influence over surface microhardness was obtained by varying the cutting feed fz. The use of a small cutting feed generated the highest value of surface microhardness while the increase at 0.15 mm/tooth lead to a decrease of surface microhardness value. The cutting speed had a small effect over microhardness.

Regarding the neural network prediction, it can be concluded that the prediction of different cutting parameter on HV can be a fast and cheap method to arrive at a good condition. From the presented results generated by artificial neural network we observe that a combination of high cutting speed and small cutting feed (0.05) leads to high outputs of microhardness. According to Jiang [16] an increase of hardness would lead to the increase of residual stress value (compressive residual stress) thus to an increase of workpiece fatigues resistance.
6. References

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