Research of fuzzy logic application on surfaces roughness prediction under finishing milling process

D.P. Ghencea¹, F.D. Anania² and M. Zapciu³

¹University Politehnica of Bucharest, Doctoral School of Industrial Engineering and Robotics, Splaiul Independenței 313, Bucharest, Romania
²,³University Politehnica of Bucharest, Department of Robots and Manufacturing Systems, Splaiul Independenței 313, Bucharest, Romania

¹daniel.ghencea@blackseasuppliers.ro, ²dorel.anania@upb.ro, ³miron.zapciu@upb.ro

Abstract. Artificial intelligence systems are usefully tools for estimation of different parameters for industrial and non-industrial applications. In this paper is presented a fuzzy logic application for surface roughness prediction for two material type for a CAM milling process. A minimum number of measurements have been made on a specific material (Al 6061) and were used for prediction of a roughness of another material (Al 7075). The link parameters between these materials, used in Fuzzy logic system, is the Rockwell hardness. In this way many correction parameters of cutting regime can be calculated in a short time with minimum resource (less experiments and tests needed).

1. Introduction

Today the requirements of product quality are getting bigger. High quality products depend of many aspects related with functionality, aspects, strength etc. Some of these aspects are directly related to manufacturing processes and many of these processes are from metal cutting field [1].

In metal cutting process the milling is one of the most used in industry for many fields like aerospace, automotive etc. The milling NC machines, tools and software are developing continuously bringing new flexibility in the cutting process such as possibility of tool orientation (4x, 5x continuous milling), different toolpath over surfaces (like spiral, parallel cut, ISO cutting etc.). Due to these possibilities in machining process the quality of the part obtained can be various through the surface quality (which is influenced by many factors like constant cutting speed, cutting direction, depth of cut, radial step etc.) [2-3].

This research is focus on achieving a constant roughness on different type of material by using similar cutting condition with minimum modification. In order to establish an algorithm and some correction necessary to be made, by the classic way, many experimental tests must be made. This means a lot of time and money for materials, cutting tools, and work hour [4].

By using Artificial Intelligence algorithm, we are trying to make roughness prediction for a variety of material starting from minimum experimental tests for milling processes parameter variation.

The use of artificial intelligence in research on milling free-form surfaces using ball mills is a sensitive topic but one that is on the rise due to IT, both hardware and software [5].

Fuzzy logic prediction of surface quality provides a powerful tool for reducing the number of tests and thus the number of measurements for each test. The use of prediction is a consequence of the
growing demand for productivity and product quality. The prediction unifies by the construction
model of the membership functions and the inference rules the geometric properties of the surface that
depend on the diameter of the cutter, the number of cutting teeth, the cutting speed, the passage and
the feed rate [6].

Establishing the fuzzy inference rules (FIS) for the roughness parameter is the most important
aspect of the construction of the model under analysis with fuzzy logic because it depends most on the
accuracy of the prediction given that the prediction is made for the same material but with different
hardness (measured roughness surface Al 7075 and predicted surface roughness Al 6061).

2. Methodology for simulation, prediction and interpretation of results

2.1 Simulation methodology and objectives

The aim of the study is to identify a method to predict as accurately as possible with fuzzy logic the
roughness of an aluminum surface finish by milling for different tool trajectories type on a aluminum
type (6061) starting from experimental results measured on 7075 aluminum.

The characteristics for Al 6061 and Al 7075 are shown in Table 1 [7], [8].

| Physical Properties | Al 6061 | Al 7075 |
|---------------------|---------|---------|
| Density             | 2.7 [g/cm³] | 2.81 [g/cm³] |

| Mechanical Properties |                      |
|-----------------------|----------------------|
| Hardness, Brinell     | 95                   |
| Hardness, Rockwell A  | 40                   |
| Hardness, Rockwell B  | 60                   |
| Tensile Yield Strength| 276 [MPa]            |
| Modulus of Elasticity | 68.9 [GPa]           |
| Poisson's Ratio       | 0.33                 |

For prediction, the average Rockwell A and B harnesses are used, respectively 1.39375.

Milling tests were performed on a First MCV300 3-axis machining center, which has a maximum
shaft speed of 8000 [rpm], a shaft power of 7.5 [kW] and a maximum milling feedrate of 10000
[mm/min]. The mass of the First MCV 300 machining center has movements on the X and Y axes, and
the axis on the Z axis. The part under test is fixed directly on the table of the First MCV 300 machine
using two supports to ensure maximum rigidity. The acquisition of the data set is performed with the
Mitutoyo Surftest SJ210 instrument which has a measuring range (on the X axis) of 17.5 [mm] and a
measuring speed of 0.25 [mm/s] for measuring roughness [9].

2.2 Prediction method

The research focuses on identifying how to construct membership functions for inputs for Al 7075 and
outputs (P_6061 and P_7075) to make an accurate prediction.

The application settings in, valid for the four ways to build membership functions, are: and method
- min, or method - max, implication - min, aggregation - max, defuzzification - centroid (mamdani).

The fuzzy logic architecture used (2 inputs and 2 outputs) is shown in Figure 1.
Figure 2 Models of membership functions tested: a) the peak of the triangle is in the middle of the field, b) the peak of the triangle is off-center, c) the peak of the triangle is off-center and the partial overlap, d) the peak top of the triangle is off-center and total overlap

Four ways of constructing triangular membership functions were researched, namely:

- the peak of the triangle is in the middle of the field - C (Figure 2 a));
- the peak of the triangle is off-center - D (depending on the concentration of the data set values in that field) (Figure 2 b));
- the peak of the triangle is off-center and the partial overlap (SP) of the membership functions (20%, respectively: 10% left, 10% right) over the neighboring ones (Figure 1 c));
- the peak top of the triangle is off-center and total overlap (ST) of the membership functions over the neighboring ones (Figure 2 d));

Step 1. Determine the input variables (x and y) and the output variables (average roughness Al 7075 and correction coefficient for average roughness Al 6061) (Figure 1).

Step 2. From the initial data set (35 measurements) for Al 7075 the gross errors represented by the interval ends (min / max for x / y - 4 values) are eliminated. From the initial data set (14 measurements) for Al 6061, chosen to validate the prediction, the gross errors represented by the max interval head for x / y - 3 values are eliminated.

Step 3. The set of 31 values was divided into 7 unequal intervals (as domain and number of values) to which linguistic values were assigned, respectively: VL, L, ML, M, MH, H, VH.

Step 4. Establishing the rules of roughness inference Al 7075 (27 rules - valid for the four ways of building the membership functions).

Step 5. Run the application.

2.3 Interpretation of results and discussions

Following the establishment of the rules of inference of the roughness and running of the application, the 3D surfaces (the four analyzed cases) are obtained, shown in Figure 3. It is observed that the shape of the 3D surface, construction of triangular membership functions, a) and b) for both types of aluminum.
Figure 3 The 3D surface in the four cases analyzed for Al 6061 and Al 7075: a) the peak of the triangle is in the middle of the field, b) the peak of the triangle is off-center, c) the peak of the triangle is off-center and the partial overlap, d) the peak top of the triangle is off-center and total overlap.
Supplementing the conditions by partially overlapping the triangular membership functions leads to small surface changes between case b) and c) (Figure 3 b) and c)). Total overlap of membership functions leads to a major change in surface geometry between case c) and d) (Figure 3 c) and d)).

**Figure 4** The mode of action of the quiver in the four cases analyzed for Al 6061 and Al 7075: a) the peak of the triangle is in the middle of the field, b) the peak of the triangle is off-center, c) the peak of the triangle is off-center and the partial overlap, d) the peak top of the triangle is off-center and total overlap.
From the quiver point of view, the four ways of constructing the membership functions, it is observed that the dynamics of variation has an evolution from the uniform distribution of majority action-reaction type with 2 areas of local solutions, (Figure 4 a) 6061 and 7075) to a concentrated action-reaction distribution with 4 zones of local solutions (Figure 4 c) 6061 and 7075) which is followed by a relaxation distribution of the action-reaction concentration of the 4 zones of local solutions (Figure 4 d) 6061 and 7075).

**Results for prediction at the theoretical level**

| 6061 | C     | D     | SP    | ST    |
|------|-------|-------|-------|-------|
| c_{min} | -14.77% | -5.81% | -6.39% | -7.11% |
| c_{max} | 29.42%  | 29.42% | 8.16%  | 4.80%  |
| 7075 | C     | D     | SP    | ST    |
| c_{min} | -12.44% | -4.42% | -5.02% | -6.43% |
| c_{max} | 28.73%  | 28.73% | 8.24%  | 9.40%  |

For the case of the prediction based on the hardness coefficient at theoretical level in the analysis of Table 2 it is observed that the best accuracy is obtained for the triangle with off-center peak and partial overlap (SP - variant c)) of the membership functions (20%, respectively: 10 % left, 10% right) over the neighboring ones.

**Table 3 Prediction results for Al 6061 based on measurements for Al 7075**

| 6061 | C     | D     | SP    | ST    |
|------|-------|-------|-------|-------|
| > 15% | 18.58 / 5 | -13.47 / 2 | 29.42 / 1 |
| < 15% | 11.71 / 1 | 6.78 / 3 | -5.81 / 2 | 6.62 / 4 | -6.10 / 2 | -6.73 / 2 |
| < 10% | 7.77 / 4 | -8.80 / 1 | 1.53 / 12 | -2.14 / 13 | 1.54 / 12 | -2.08 / 13 | 2.53 / 18 | -2.40 / 11 |
| < 5%  | 1.66 / 11 | -1.41 / 7 | 2.00 / 10 | 2.00 / 14 | -2.35 / 14 | 1.97 / 14 | -1.82 / 12 | 1.70 / 14 | -2.68 / 14 |

As the conditions become stricter in the construction of triangular membership functions, errors of medium and large values disappear, with the majority of small errors centered around ± 6.5% (Table 3). The SP model has the best distribution of error accuracy from the total of the 4 analyzed models.

**Table 4 Results obtained by prediction compared to those measured for Al 7075**

| 6061 | C     | D     | SP    | ST    |
|------|-------|-------|-------|-------|
| > 15% | 20.28 / 5 | 28.73 / 1 |
| < 15% | 12.84 / 2 | 12.34 / 2 |
| < 10% | 7.36 / 2 | -8.89 / 1 | 6.53 / 2 | 6.60 / 4 | -5.02 / 1 | 9.40 / 1 | -6.10 / 2 |
| < 5%  | 2.29 / 9 | -2.01 / 10 | 2.00 / 14 | -2.35 / 14 | 1.97 / 14 | -1.82 / 12 | 1.70 / 14 | -2.68 / 14 |

Table 4 shows that the accuracy of the SP model prediction improves (in total by 1%) compared to those presented in Table 3, in 3 of the 4 cases.

At a theoretical level the most accurate prediction is obtained for the case where the top of the triangle is off-center and we have partial overlap (SP) of the membership functions over the neighboring ones.

**Results for validation of the prediction at a experimental level**

For the case of the prediction based on the 11 measurements performed for 6061 (validation by experimental measurements of the prediction) the results presented in Table 5 were obtained.
Table 5 Validation of the results obtained by prediction compared to those measured for Al 6061

|       | C      | D      | SP     | ST     |
|-------|--------|--------|--------|--------|
|       | (+)    | (-)    | (+)    | (-)    | (+)    | (-)    |
| e > 15% | 19.99 / 3 | 31.52 / 1 | 30.91 / 1 | 31.82 / 2 |
| e: 7 - 15% | 9.56 / 2 | -12.80 / 3 | 12.38 / 2 | -12.80 / 3 | 11.22 / 1 | -12.80 / 3 |
| e: 0 - 7%  | 3.69 / 2 | -1.71 / 1 | 0.93 / 2 | -3.48 / 3 | 0.93 / 2 | -3.48 / 3 |
| General average | 4.21 % | 0.85 % | 0.79 % | 2.54 % |

It is observed that for the case of the triangle with off-center peak and partial overlap (SP - variant c)) of the membership functions over the neighboring ones, the best results are obtained. Variant c) is extremely close to variant b), the difference being made by:

- error size greater than 15% (31.52% vs 30.91%);
- the difference of the general average of 0.06%.

At the level of validation of the prediction by measurement, the most accurate prediction is obtained also in case the peak of the triangle is off-center and we have partial overlap (SP) of the membership functions over the neighboring ones.

3. Conclusions

The objective of the study to make a prediction of the roughness of a surface of the same material but with a different hardness than the one on which the measurements were performed was achieved.

We have shown that the restrictions that can be imposed in the performance of membership functions and inference rules do not have to be extremely precise because we go over the areas of local solutions tending to a general solution that no longer has the same accuracy. Applying the same set of fuzzy inference rules to the four cases analyzed showed that they are constant regardless of how the membership functions are constructed.

The prediction method based on fuzzy logic AI algorithm has been developed by using a set of experimental test for a milling process with a ball cutting tool for machining a 3D surface on an Al 7075 material [3], [9]. For validation of fuzzy logic algorithm developed, a new set of machining test on a different material AL6061 was made in similar cutting condition. The machining parameter were adjusted according with the material characteristics.

The experimental results were compared with the fuzzy AI logical prediction and an overall accuracy of 99.21% was found for the experimental prediction and 99.12% for the theoretical prediction.

In order to use the prediction fuzzy logic AI algorithm like alternative to experimental cutting measurement more tests are needed to be done on different type of material.

4. References

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