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Determination of the Quality of the Machined Surface Using Fuzzy Logic

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Abstract**—**This paper deals with measuring and modelling of the quality of the machined surface of the metal machining process. The average surface roughness (R_a) which represents the quality of the machined part was measured during the dry turning of the AISI 4140 steel. A large number of factors with the unknown relations among them influences this parameter, and that is why mathematical modelling is extremely complicated. Different values of cutting speed, feed rate, depth of cut (cutting regime) and workpiece hardness causes different surface roughness values. Modelling with soft computing techniques may be very useful in such cases. This paper presents the usage of the fuzzy logic-based system for determining metal machining process parameter in order to find the proper values of cutting regimes.

Keywords**—**Metal machining, surface roughness, fuzzy logic, process modelling.

I. Introduction

METAL cutting process is a complex physical process with many influencing factors, such as: the cutting speed, the feed rate, the depth of the cut, the physical and chemical characteristics of the workpiece etc... [1]. The output parameters of the metal cutting process are cutting temperature, quality of the machined surface, cutting force, so on. It is necessary sometimes to estimate some of these parameters. But, it is almost impossible to take into account all relevant input factors and their influence on the output parameters.

In most situations, calculating the exact values of the output parameters is not of primary interest. Instead of this, quickly and easily estimation of the range of some process' parameters is necessary. Mathematical modeling is often used in such situations. Soft computing-based models, which represent essential techniques of artificial intelligence, can be very helpful in cases like this. These models use basic mathematical apparatus, with the large number of simple, simultaneously executed mathematical operations. The simulations of soft computing systems can be performed on the classic computer platforms and extra investments are not necessary. Development of such systems, with the usage in various engineering problems is permanently in progress and the list of their applications is practically endless [2], [3]. For example, it is possible to create a model which can serve as an adviser, analyser, predictor or optimizer in the process of determining the optimum cutting regime.

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II. The Quality of the Machined Surface

The surfaces of the machined parts are never ideally smooth. Less or more irregularities are always present on the machined surface. A collection of irregularities which forms the surface of the workpiece, on the exactly defined surface sector, is called surface roughness.

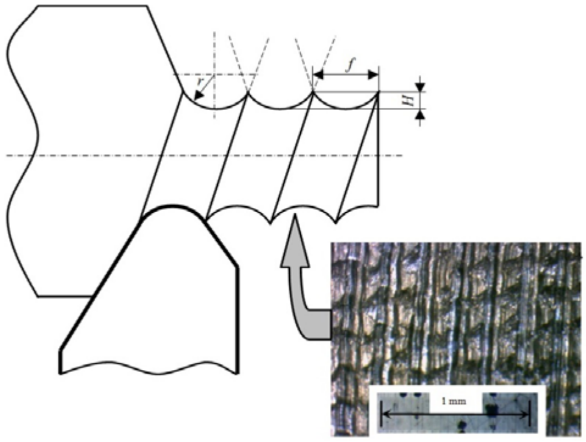

Fig. 1 Metal cutting mechanism and the quality of the machined surface

The distance between two adjacent irregularities is in the range 2÷800 μm, while the irregularities' height is in the range 0.03÷400 μm [4]. During the metal cutting process, the tool nose forms the curved line in the space, see Fig. 1.

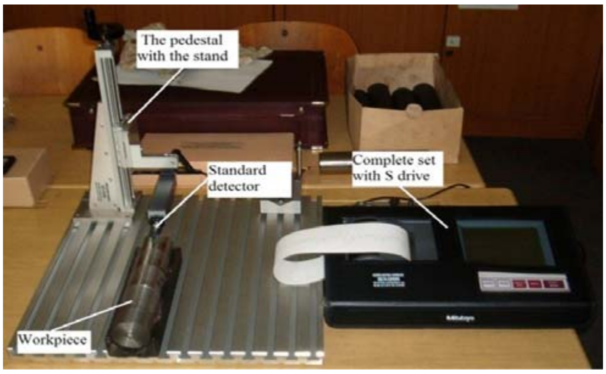

Fig. 2 The measuring system

The system used for measuring of the quality of the machined surface is shown in Fig. 2.

The roughness is defined as a collection of the irregularities which form the surface of the workpiece, on the exactly defined surface sector, excluding the faults caused by the waviness of the surface. Geometric characteristics of the cutting tool and the feed rate theoretically define the height of the irregularities in the metal cutting process [4]:

$$H = 125\frac{f^2}{r} \tag{1}$$

where H [µm] is the height of the irregularities, r [mm] is the tool nose radius, and f [mm/rev] is the feed rate.

It is noticed that the increase of the average surface roughness is pronounced at the higher cutting speed, especially while machining with the small depths of cut. Increasing the depth of cut causes the increase of the average surface roughness, too. A constant presence of the friction forces causes the interruptible character of the cutting process which affects the surface roughness. With the increase of the cutting speed, this effect is almost totally eliminated, so the real value of the surface roughness reaches the theoretical value. The conclusion is that the real surface roughness depends on the geometric factors on one side, as well as on the other factors which directly influence the chip forming process, and they are as follows: the cutting speed, the characteristics of the workpiece material, the cutting tool angles, the cutting tool condition (sharp or worn) etc.

The surface quality of the machined parts is very important quality characteristic of the product, as well as one of the most common customer demands. There exists a large number of various parameters which represent surface roughness. In the present research, the Average Surface Roughness (R_a), as one of the most widely used surface parameters in industry, has been selected for the characterisation of the surface finish.

III. Fuzzy Logic Modelling

TABLE I
THE MINIMUM, AVERAGE AND MAXIMUM VALUES OF THE PROCESS PARAMETERS

	Minimum value	Average value	Maximum value
Workpiece hardness [HRC]	20	37.5	55
Cutting speed, V [m/min]	80	110	140
Feed rate, f [mm/rev]	0.071	0.196	0.321
Depth of cut DOC, a [mm]	0.5	1.25	2
Average surface roughness, R_a [µm]	0.47	3.535	6.6

The interdependence between the cutting regimes and surface roughness was modelled with a fuzzy logic (FL) based system. The experimentally obtained data have been used for creating such system. The used fuzzy rules are extracted from the various metal cutting handbooks and could be combined with the knowledge of the skilled and experienced machinist. FL system has four input values: workpiece hardness, cutting speed, feed rate, and depth of cut (DOC). The output from the FL system is the value of the average surface roughness. Firstly, the ranges of the input and output values should be defined. Minimum, maximum, and average values of the process parameters used for modelling of the average surface roughness are shown in Table I.

Each input parameter (workpiece hardness, cutting speed, feed rate and depth of cut – DOC) is defined with three membership functions: small (S), medium (M) and big (B). Output parameter (average surface roughness) has five fuzzy membership functions: extremely small (ES), small (S), medium (M), big (B) and extremely big (EB), see Fig. 3.

TABLE II
FUZZY RULES USED FOR THE AVERAGE SURFACE ROUGHNESS MODELLING

Average surface roughness									
	Workpiece hardness, S								
	Cutting speed S			Cutting speed M			Cutting speed B		
Feed rate / DOC	S	M	B	S	M	B	S	M	B
S	M	M	B	S	S	M	ES	S	M
M	M	B	B	M	M	M	M	M	M
B	M	EB	EB	M	M	B	M	M	M
	Workpiece hardness, M								
	Cutting speed S			Cutting speed M			Cutting speed B		
Feed rate / DOC	S	M	B	S	M	B	S	M	B
S	ES	M	M	ES	S	M	ES	S	M
M	S	M	B	ES	M	M	ES	S	M
B	S	M	M	S	S	M	ES	S	M
	Workpiece hardness, B								
	Cutting speed S			Cutting speed M			Cutting speed B		
Feed rate / DOC	S	M	B	S	M	B	S	M	B
S	ES	S	M	EM	S	M	ES	S	M
M	ES	S	M	EM	S	M	ES	S	M
B	ES	S	M	EM	S	M	ES	S	M

Operation of the FL model assumes standard steps, i.e. fuzzification, fuzzy inference, and defuzzification. The first step is converting the input value into degree of membership – μ, using the fuzzy membership functions (fuzzification). *Trapezoidal curve* membership function [5] was used for FL modelling of the surface roughness. This function is given by:

$$f(x;a,b,c,d) = \max\left(\min\left(\frac{x-a}{b-a},1,\frac{d-x}{d-c}\right),0\right) \tag{2}$$

Each fuzzy rule in proposed Mamdani FL system consists of the premise (the part of the fuzzy rule after the **IF** phrase) and consequent (the part of the fuzzy rule after the **THEN** phrase), such as:

IF Workpiece hardness is Medium **AND** Cutting speed is Small **AND** Feed rate is Big **AND** Depth of cut is Medium **THEN** Average surface roughness is Big

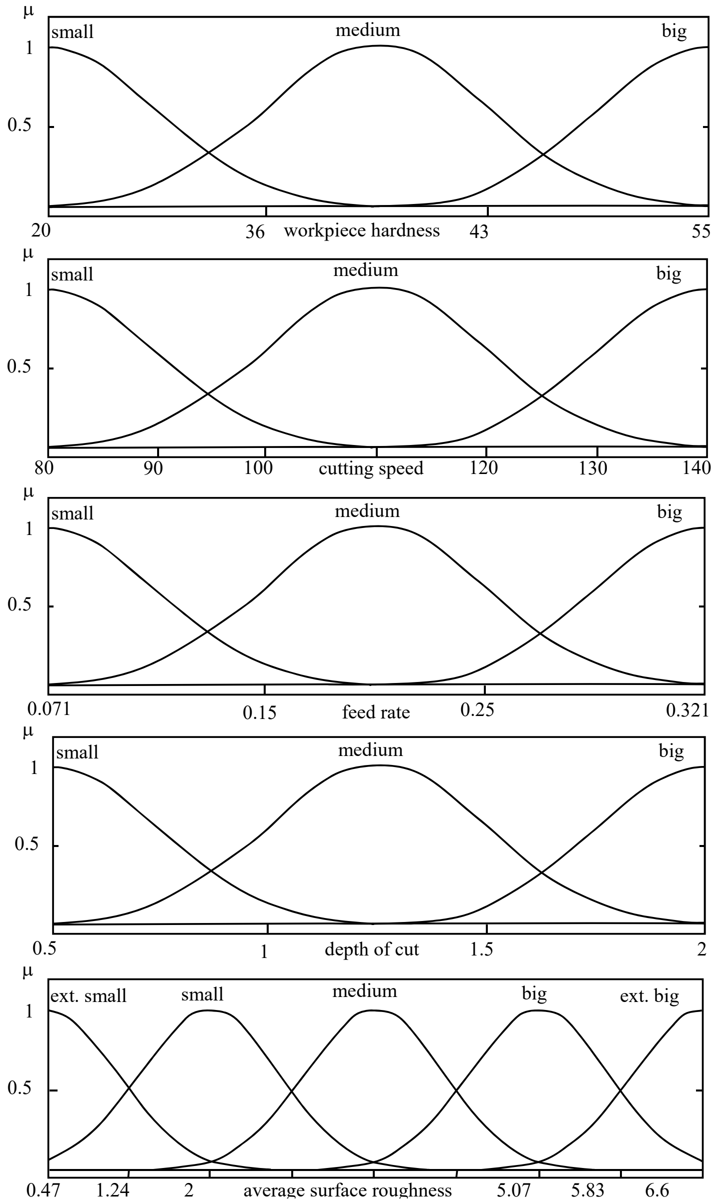

Fig. 3 Fuzzy membership functions of the input and output parameters

In this case, there are four input variables, and each one of them is defined with three fuzzy sets, so the overall number of rules of the FL system is 3^4=81. The rule base consists of 81 rules, which are used for the average surface roughness modelling, as shown in Table II.

The consequent is transformed according to the value defined by the premise. The input value in the implication process is a number, while the output value is a fuzzy set. The implication is performed on each rule and in that way, the output fuzzy set is "truncated" with the minimum obtained value of the degree of membership (min method).

In the aggregation process, the unique output fuzzy set is formed by combination of the truncated fuzzy sets.

The last step is defuzzification, a method which is based on finding the centroid of the obtained fuzzy set. So, the fuzzy logic is very helpful during the evaluation in the interphases, but the final output from the fuzzy system is a number.

After the modelling phase, the FL system is able to determine the surface roughness parameter for the unknown input parameters, i.e. FL system can perform the prediction of the surface roughness parameter. Fig. 4 shows the measured and modelled values of the surface roughness parameter. It is obvious that surfaces that represent the measured and modelled values coincide very well, which is the proof that obtained model is reliable.

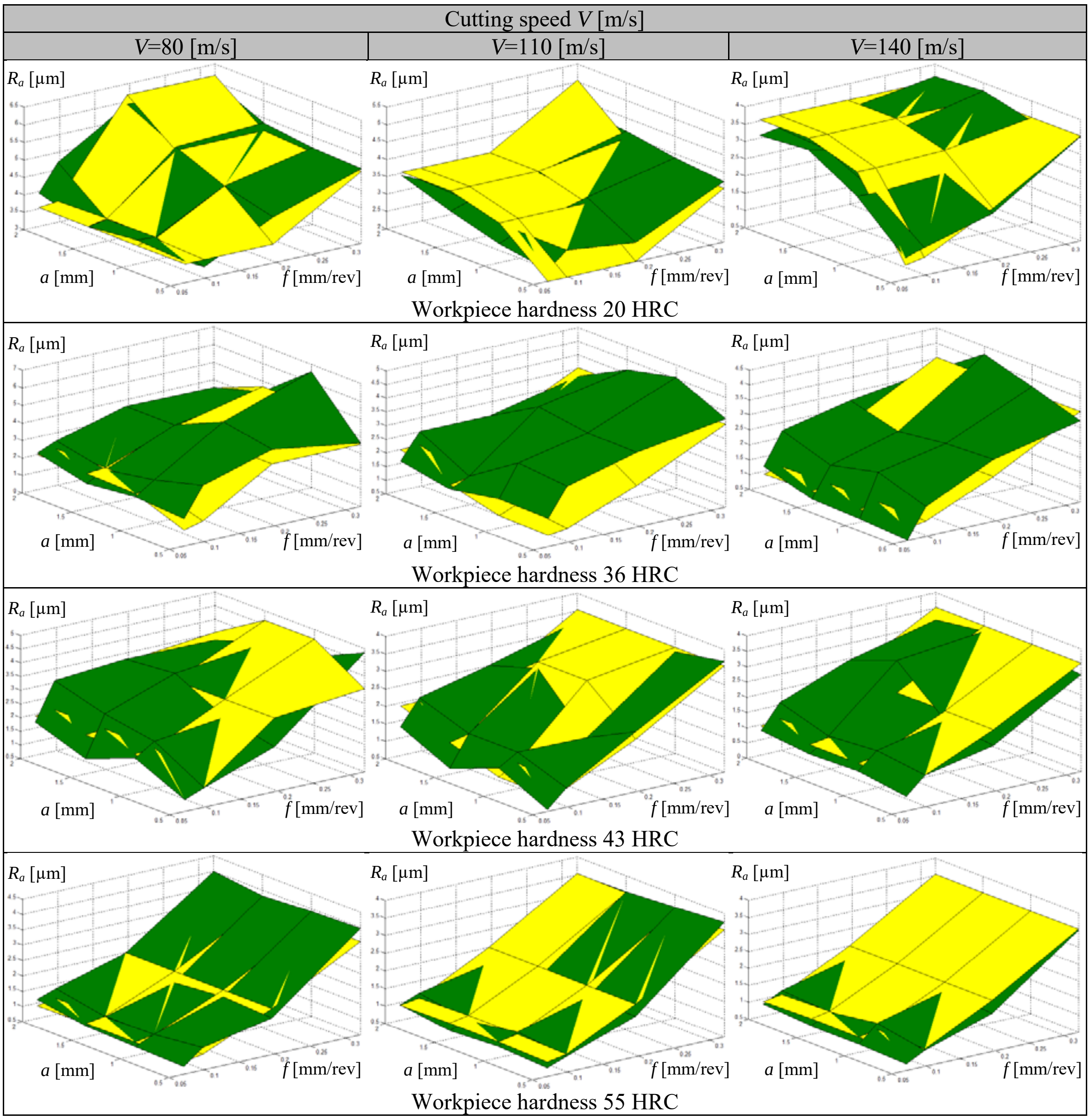

Fig. 4 Average surface roughness surfaces: measured (dark surfaces) and defined by the FL system (light surfaces)

IV. Conclusion

The number of theoretical models of the metal machining process is practically endless but reliable, comprehensive theoretical model of this process, which could encompass all the principles and mechanisms of the chip forming is still not established. Most of the theoretical models of the metal machining process cannot fully take into account all the imperfections and other unpredicted effects of the environment. Moreover, such models can be used only in a limited process domain. In this paper, fuzzy logic model for determining surface roughness was created, using the measured data and process knowledge. The obtained results are compared with the measured data, validating in that way their accuracy. Results are in good accordance, confirming the effectiveness of the fuzzy logic approach in modelling surface roughness in the metal machining process. This approach has the potential to lead to the reduction of production time and cost, as well as improvement of the product quality.

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