Fuzzy inference system for modelling cutting temperature of AISI 1060 Steel in turning operations

A Belloufi, M Abdelkrim, I Rezgui, M E Arbaoui and A Tebib
Université Kasdi Merbah Ouargla, Faculté des Sciences Appliqués, Département de Génie Mécanique, Ouargla 30000, Algeria

E-mail: belloufi.ab@univ-ouargla.dz

Abstract. During the cutting, knowledge of thermal phenomena induced is essential for the understanding of the cut and to improve the machinability of certain materials. Moreover, these temperature influence the final product (residual stresses, surface states, geometrical tolerances, etc.) Experimental techniques were used to measure the cutting temperature during machining: indirect measurements, direct measurements, optical temperature measurement, and analytical and numerical methods. Experimental techniques are enormously difficult and require a lot of time and material. They allowed choosing in a way not precise the parameters of cut. Thus some works have used soft computing techniques to find solutions for the selection of cutting conditions problems, because of their efficiency in modelling the different thermo-mechanical phenomena of cutting. However, the results obtained from these techniques are sometimes uncertain, imprecise and approximate. To avoid these disadvantages, and in order to improve the selection procedure of cutting parameters and to study their effects on the cutting temperature of the AISI 1060 steel, we propose to solve this problem with fuzzy logic.

1. Introduction
Several experimental methods were used to measure the cutting temperature during the turning operations: indirect measurements, direct measurements. Some work has been done with indirect measurement methods [1-3], with these techniques the cutting temperature is measured using a thermosensitive varnish. The latter is deposited on the tool and changes colour from a well-defined temperature value. The boundary between two colours shows the isotherm. Other work consists in using direct measurement methods [4-9], based on the following principle: if two metals are welded at their ends and if one of these welds is brought to a good temperature the other being maintained at a different temperature, an electromotive force will then be observed between the two junctions. The evaluation of this force, which depends on the materials used, symbolizes the measured temperature. Techniques based on the use of thermocouples remain costly techniques and do not allow exact measurements to be obtained. Therefore, it is necessary to use other techniques for measuring the temperature, which allow an instantaneous acquisition of the cutting temperature. See also at the tool / workpiece contact. The methods for measuring the temperature in this level are: the optical pyrometer, the infrared camera and the near infrared camera.

Experimental techniques are enormously difficult and require a lot of time and material. They allowed choosing in a way not precise the parameters of cut. Thus numerical techniques [10-14] were used to solve the problem of selection of cutting conditions because of their efficiency in modelling the different thermo-mechanical phenomena of the cut. However, these techniques are sometimes
uncertain, imprecise and approximate. In order to avoid the disadvantages of these methods, we propose to analyze the effect of the cutting conditions on the cutting temperature during the turning operations of AISI 1060 steel using fuzzy logic. This technique is easy to use and does not require important equipment [19]. With the fuzzy logic technique the cutting temperatures during the turning can be obtained by carrying out only a few experimental tests.

In this work the fuzzy logic technique is applied in order to study the influence of the cutting conditions on the cutting temperature during the turning of AISI 1060 steels.

2. Experimental procedure

For the realization of the tests, a cylindrical parts of length 500 and diameter 40 mm are used and held on the lathe in mixed assembly (by a mandrel with three jaws concentric on one side, and on the other side by a counter-tip). The lathe used to perform our tests is a parallel model EMCO, power: 6.6 kW. The rotational speeds available on the machine range from 30 (rpm) to 2500 (rpm) and feed rates range from 0.045 (mm/rev) to 0.225 (mm/rev). The steel used in all tests is AISI 1060 according to the AISI standard. It is intended for the manufacture of mechanical parts, die soles and rolling paths ... etc. The following table gives the chemical composition of the steel used.

Table 1. AISI 1060 chemical composition.

|     |     |     |     |     |     |
|-----|-----|-----|-----|-----|-----|
| C%  | Si% | Mn %| P%  | S%  | Cr% |
| 0.440 | 0.250 | 0.610 | 0.0162 | 0.024 | 0.160 |
|     |     |     |     |     |     |

The tool used in our work is PCLNR/L2020K09 with 80° rhombic plates (CNMG120404-M34)

3. Fuzzy modeling

We chose a fuzzy inference system with three variables at the input (depth of feed, feed per revolution, and rotation speed) and a variable at the output (cutting temperature).

3.1. Fuzzy variables

Table 2 presents the universe of discourse variables used in this study.

Table 2. Limits on fuzzy variables.

| Variable                        | Valeur MIN | Valeur MAX |
|---------------------------------|------------|------------|
| Depth of cut a (mm)             | 0.25       | 1.5        |
| Feed rate f (mm/rev)            | 0.045      | 0.225      |
| Rotation speed N (rev/min)      | 440        | 2500       |
| Temperature T (°C)              | 34         | 157        |
3.2. Linguistic variables
The linguistic variables used in this study are chosen as shown in figure 2. All these variables correspond to experimental values.

![Linguistic variables](image)

**Figure 2.** Linguistic variables for: (a) Depth of cut, (b) Feed rate, (c) Rotation speed.

3.3. Membership functions
We associate to each of the variables a set of terms characterized by membership functions defined on the same discourse universe. The membership functions are used to determine the percentage of veracity for the affirmation of each variable. The forms of the most used membership functions are: triangular form, trapezoidal form, Gaussian and sigmoidal form. In this study, trapezoidal membership functions have been proposed. These functions are defined in a discourse universe limited by the limits of each variable. This function is defined by four parameters that take their values in the universe of discourse. Based on the choice of linguistic variables for the cutting conditions in figure 3, the membership functions are given as follows:

![Membership functions](image)

**Figure 3.** Membership functions: (a) Depth of cut, (b) Feed rate, (c) Rotation speed, (d) Temperature.

3.4. Fuzzy rules
Based on the results of the experimental tests, 150 fuzzy rules have been elaborated in table 3. These rules allow the production of a fuzzy output. Each rule is presented on the form below:

If is (linguistic variable) and Vc is (linguistic variable) and a is (linguistic variable) Then T is (linguistic variable).
The fuzzy rules developed are presented in table 3.

| a(mm) | TP | P | M | G | TF | TG |
|-------|----|----|----|----|-----|-----|
| F(mm/tr) N(tr/min) | P | M | G | TG | F(mm/tr) N(tr/min) |
| TP | TF | TF | TF | F | P | M | M+ | F | TP | P | M | ME |
| TP | TF | TF | TP | TP | M | M | G | F | TP | P | M | ME |
| TP | TF | TF | TP | TP | M | M | TG | TP | P | M | ME | ME |
| TP | TF | TF | TP | P | P | G | TP | F | TP | P | P | M |
| TP | TF | F | TP | P | M+ | G | P | F | P | M | M+ | M |
| TP | TF | TF | TP | P | P | M | M | G | F | P | M | M+ | ME |
| TP | TF | F | TP | P | M | G | G | F | M | M+ | ME | G |
| TP | TF | F | P | P | M | G | TG | TP | P | M | M+ | G |
| TP | TF | F | TP | P | M+ | TG | TP | P | ME | M | G |
| P | TP | TF | TF | TP | TP | P | G | M+ | F | P | M | M+ | ME |
| P | TF | F | TP | P | M | G | G | F | M | M+ | ME | G |
| P | TF | F | P | P | M | G | TG | TP | M | M+ | G | G |
| P | TF | F | TP | P | M | TG | TP | P | ME | M | M+ | TG |
| M | TP | TF | TF | TP | P | P | TG | M+ | P | M | ME | ME | TG |
| M | F | TP | P | M | M | TG | G | P | M+ | ME | G | TTG |
| M | F | TP | P | M | M | TG | TG | M | M+ | ME | TG | TTG |

4. Results and discussion
The results are obtained during defuzzification which is the last step in fuzzy logic. This step consists in transforming the linguistic value resulting from the fuzzy regulator into a numerical value. The functions obtained using the fuzzy logic are represented in figure 4 and figure 5.

4.1. Discussion of results
Analysis of these surfaces shows that the cutting temperature increases with increasing cutting conditions (feed depth, feed per revolution and rotational speed). The surfaces of figure 5 clearly show that the maximum values of the cutting temperature are obtained for maximum values of the advance per revolution, which reflects the great influence of this condition on the cutting temperature.

The analysis of the three surfaces leads to the conclusion that the maximum values of the cutting temperature are obtained in the case of a combination of the maximum values of the other cutting conditions, it is therefore recommended to avoid this combination when setting the machine. The highest value of the cutting temperature is obtained with a combination of a maximum value of the feed per revolution and a maximum value of the feed depth. The above surfaces clearly show that the most influential condition on the cutting temperature is the advance per revolution, followed by the depth of pass and then the speed of rotation of the spindle.

4.2. Study of the error and the accuracy of the fuzzy inference system
The errors represent the difference between the experimental value and the predicted value. The errors are calculated using equation 1. The percentage of individual errors was calculated as the absolute difference of the value of the predicted temperature over the value of the experimental temperature.

The accuracy has been defined as the approximate value of the predicted temperature relative to the experimental value. In equation 2, A represents precision and N represents the total number of tests. The precision of the model represents the average of the individual accuracies.
Figure 4. Variation of the predicted temperature as a function of:
(a) feed rate and Depth of cut, (b) rotation speed and Depth of cut, (c) rotation speed and Feed rate.

\[ e_i = \left( \frac{T_{\exp} - T_{Pr}}{T_{exp}} \right) \times 100 \]  
(1)

\[ e_i = \frac{1}{N} \sum_{i=1}^{N} \left( 1 - \frac{T_{exp} - T_{Pr}}{T_{exp}} \right) \times 100 \]  
(2)

4.3. Validation of results
Figure 5 shows a superimposition of the two curves of variation of the cutting temperature of the AISI1060 steel: experimental and predicted respectively.

Figure 5. Variation of the predicted temperature as a function of Feed rate and rotation speed.

In order to validate the results, the percentage of error and the accuracy of the fuzzy model were determined. The average prediction error percentage of the model was 4.65%. This error clearly shows that the temperature results obtained by fuzzy inference system were very close to the actual experimental temperatures. Most prediction errors have become experimental conditions.
Therefore, the accuracy of the fuzzy inference system is of the order of 95.35%. This value indicates that the proposed model can be used successfully to determine the cutting temperature of AISI 1060 steel during turning operations. The low level of error indicates the effectiveness of the proposed approach for determining the cutting temperature.

5. Conclusions
In this paper, a fuzzy inference system has been proposed for predicting the cutting temperature during AISI 1060 steel turning. An experimental database was used to develop the fuzzy model. The fuzzy model has been verified and validated, which proves that the adequacy of the model is sufficient with an accuracy of 95.35%. The model developed in this study can be used to predict other parameters of the thermomechanical phenomenon of cutting during the turning of AISI 1060 steel. The increase of the cutting temperature of AISI 1060 steel is essentially conditioned by increase of feed rate. The other cutting conditions have less influence on the evolution of the cutting temperature.

The high precision of the model is proved by a comparison of the fuzzy results with the results of the experimental tests. The fuzzy modelling technique could be an efficient and economical method for predicting the cutting temperature when machining AISI 1060 steel.

6. References
[1] Habak M 2006 Etude de l’influence de la Microstructure Et des Paramètres de Coupe Sur le Comportement en Tournage Dur de l’Acier a Roulement 100Cr, Ph.D. thesis, Laboratoire Procédés-Matériaux-Instrumentations ENSAM, CER d’Angers
[2] Rossetto S 1971 An Investigation of Temperature Distribution on Tool Flank Surface Annals of the C.I.R.P XVII 291-293
[3] Casto SL et al 1989 Measurement of Temperature Distribution within Tool in Metal Cutting Experimental Tests and Numerical Analysis J. Mach. Work. Technol. 20 35-46
[4] Trigger K J 1998 Progress Report no: 1 on Chip-Tool Interface Temperatures Trans ASME 70 91-8
[5] Groover M P and Kane G E 1971 A Continuing Study in the Determination of Temperatures in Metal Cutting Using Remote Thermocouple Journal of Engineering for Industry 603-608
[6] Matsumoto Y, Barash M M and Liu C R 1987 Cutting Mechanism during Machining of Hardened Steed Materials Science and Technology 13 229-305
[7] Bouzid W 1993 Etude Expérimentale et Numérique de la Coupe Orthogonale Thèse de Mécanique et Matériaux. ENSAM 1993-20
[8] El-Wardany T I, Mohammed E and Elbestawi M A 1996 Cutting Temperature of Ceramic Tools in High Speed Machining of Difficult-to-Cut Materials International Journal of Machine Tools and Manufacture 36(5) 611-634
[9] Lazard M, Corvisier P 2004 Modelling of a Tool during Turning Analytical Prediction of the Temperature and of the Heat Flux at the Tool’s Tip Applied Thermal Eng. 24 839-849
[10] Grzesik W 2005 Analytical Models Based on Composite Layer for Computation of Tool-Chip Interface Temperatures in Machining Steels with Multilayer Coated Cutting Tools Dept of Manufacturing Engineering and Production Automation, Faculty of Mechanical Engineering, Technical University of Opole, Poland, 54 91-94
[11] Abdelkrim M, et al. 2016 Numerical study of cutting temperature during drilling process of the C45 steel. International Journal of Modern Manufacturing Technologies VIII(2) 42-47
[12] Turgay K 2014 Optimization of surface roughness and flank wear using the Taguchi method in milling of Hadfield steel with PVD and CVD coated inserts Measurement 50 19–28
[13] Patricia M, et al 2015 A geometrical model for surface roughness prediction when face milling Al 7075-T7351 with square inserts tools, Journal of Manufacturing Systems 216–223
[14] Hamed H, et al 2016 Investigation of surface roughness, microhardness and white layer thickness in hard milling of AISI 4340 using minimum quantity lubrication Journal of Cleaner Production 124-134