Engineering Transactions, **70**(2): 141–156, 2022, doi: 10.24423/EngTrans.1822.20220530
Institute of Fundamental Technological Research Polish Academy of Sciences (IPPT PAN)
Université de Lorraine • Poznan University of Technology

Research Paper

A Simplistic Regression-Based Genetic Algorithm Optimization of Tool-Work Interface Temperature

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This work aims to investigate the average tool-work interface temperature for the HSS tool and AISI 1040 steel pair. A tool-work thermocouple is proposed for the measurement of temperature because of its simple construction in addition to the low cost. The machining process of AISI 1040 steel is considered due to its extensive application, including industry usage. The changes in cutting temperature are studied for combinations of cutting speed, feed and the depth of cut during turning operation. The orthogonal array L_9 by Taguchi is adopted for designing the experiments within a restricted set of runs. The average cutting temperature shows an increasing curve with functions of speed versus depth of cut and speed versus feed. But no clear trend is observed for a combination of feed versus depth of cut. A second-order regression equation with reasonable accuracy ($R^2 = 0.99$) is fitted using the data. Analysis of variance (ANOVA) reveals the highest contribution from cutting speed, which influences average temperature at the interface of tool and work. Further, the genetic algorithm predicts an optimal combination of parameters, which is 82.542 m/min cutting speed, 0.276 mm/rev feed rate and 0.2 mm depth.

Key words: turning; tool-work thermocouple; cutting temperature; ANOVA.

1. Introduction

It is a well-known fact that a significant amount of heat is released during machining. The energy is transformed between the chip and tool during a chip formation. The produced heat significantly affects the workpiece and chip formation mechanism. It further influences the various cutting tool wear mechanisms (abrasive, adhesive, diffusive), tool life and cutting forces. This further causes residual stresses in several parts of the workpiece. Hence, it becomes necessary to quantify the heat generated at the tool-chip interface.

The temperature of the cutting tools and cutting forces were found to vary with various machining factors [1–3]. The cutting temperatures and tool wear were observed to be highly influenced by the cutting speed while machining carbon steel (SAE 1030) using a coated carbide tool [4]. The KC810 tool showed better machining performance and tool life [4]. During machining of materials such as quenched carbon steel, Cr-Mo steel, and chromium-bearing steel with a high carbon content using a polycrystalline cubic boron nitride (PCBN) cutting tool [5], the cutting temperature was notably affected by speed. The cutting temperature beneath the tool flank was observed to increase with cutting speed [3, 5, 6]. Research works also unveil the better performance of coated carbide tools than PCBN for certain workpiece materials and within a specific cutting parameter range [7].

The cutting temperature was found to vary with the substrate material hardness [8]. The temperature of cutting was maximum for the hardest material (AISI 52100 steel with 700 HV), which indicates the dependency of cutting temperature on workpiece material hardness [5]. It was observed by Liu *et al.* [6] that the cutting temperature of GCr15 bearing steel increased with a hardness to a particular limit, and then showed a decline upon a further increment in hardness while using a PCBN as a cutting tool [6]. PCBN as a cutting tool has high hot strength, which makes it suitable to work at a high cutting temperature range. Moreover, tribo-film formation at the tooltip leads to an improvement in tool life [7]. The temperature at the cutting zone because of tool coating was investigated for machining hardened AISI4340 steel. The study suggested that a single-layered TiAlN was better than a CVD coating or multi-layer TiCN/Al_2O_3/TiN [3].

The cutting efficiency of a cutting tool and its life depends on generating heat at the cutting zone, which can be controlled by applying a water jet [9]. But the conventional way of applying coolants was observed to be ineffective at high feed rate and cutting speed [10]. The cutting temperature while machining plain carbon steel may be controlled effectively by using a liquid nitrogen jet [10]. The effective use of cryogenic cooling not only improves machinability but also reduces cutting forces during machining, further improving tool life [10]. Gupta *et al.* [11] also observed that the average cutting temperature of AISI 1040 decreased significantly with the application of cryogenic cooling. Another investigation by Dhar *et al.* [12] recommended minimum quantity lubrication (MQL) for machining AISI 1040 steel using carbide tool, which led to a reduction in heat generated at the cutting zone. The dimensional accuracy compared to dry machining conditions also increased. MQL was also employed while turning AISI 9310 steel with a carbide tool to investigate the effect of vegetable oil for cooling purposes compared to dry machining conditions [13]. Cutting temperature measurement was carried out with the aid of a tool-work thermocouple. A significant decline in temperature and improvement in the integrity of surface could be obtained by applying MQL. Apart from cutting parameters, substrate hardness and MQL, the tool-work interface temperature was also observed to be affected by the tip radius of the tool [2].

From the ongoing discussion, it is quite natural to conclude that the investigation of average cutting temperature has gained significant importance. This is necessary to improve the machinability of material, surface integrity of work piece, dimensional accuracy, tool life and increase productivity and reduce cost in manufacturing. Cutting temperature during machining has been measured using various methods such as infrared measurements, tool-work thermocouples, two-colored pyrometers, remote thermocouple method, etc., in analyzing the cutting temperature and its effects [14–24]. Amongst several methods, the tool-work thermocouple technique is a relatively simple, reliable and low-cost method. Moreover, studies have been conducted to investigate the average cutting temperature for a broad range of materials and modeled using various mathematical and artificial intelligence tools [8, 18, 20, 25–27]. The various machining parameters have also been optimized for minimizing cutting temperature [8, 21, 28, 29]. But the investigation of tool-work interface temperature, its modeling and optimization for AISI 1040 steel is insufficient. Hence, a simple tool-work thermocouple technique is employed in the present work to investigate the same.

AISI 1040 steel is extensively used in industries owing to the vast extent of its utility and its ease of machining. The use of the high-speed steel (HSS) tool to machine AISI 1040 steel can be made more suitable for industry, and the product quality can be maintained only if the cutting parameters are properly controlled during machining. Thus, the investigation of cutting temperature, its simplistic modeling as well as optimization are reported in this study. An effort is made to minimize cutting temperature since a higher temperature may reduce tool life and dimensional accuracy and results in deterioration of surface finish. The significance of machining parameters on cutting temperature is studied. Taguchi's design principle is employed to reduce the number of experimental runs. A simple quadratic mathematical model is fitted to the obtained data. Finally, optimization of the process parameters is conducted using a genetic algorithm (GA). Optimization of complex manufacturing processes is quite effectively carried out using GA. In a recent work [30], artificial neural network-based GA was employed for optimization, which is a more complex process. Hence, a simplistic second-order regression-based GA is proposed in the present work. The cost-effectivity of the process is further improved by using a low-cost tool-work thermocouple to measure the average cutting temperature.

2. Materials and methods

2.1. Turning of the workpiece

AISI 1040 steel was turned on a lathe machine that has the ability to self-center. The parameters of the machine were altered at three equally spaced stages, as shown in Table 1. Composition analysis using EDS is depicted in Fig. 1. Elemental presence of 0.35–0.45% C, 0.15–0.4% of Si, 0.6–0.9% of Mn, 0.04% of S and 0.05% of P was observed [30]. The EDS showed minor traces of Cr, Ni or Mo because of peak overlapping and its semi-quantitative nature. The operation of turning was carried out on a lathe machine using the conventional HSS tool [31]. No special inserts or coating was used on the tool. Hence, the aforesaid combination has been chosen. Furthermore, the parameters in Table 1 are derived from a literature review [4, 8, 29, 32], limitations of the lathe as well as the combination of tool and workpiece. The workpiece was supported by the tailstock, and machining was conducted without any coolant. The workpiece with an initial roughness of almost 0.4 μm was procured from a local vendor. The orthogonal array (OA) L_9 by Taguchi was the experimental design, and experiments were carried out in accordance with its laid down parametric combination. The L_9 array was adopted to reduce the number of trials.

Table 1. Variations in turning parameters considered.

Factors	Cutting speed	Feed rate	Depth of cut
Code	A	B	C
Units	m/min	mm/rev	mm
Level 1	70	0.1	0.2
Level 2	100	0.3	0.4
Level 3	130	0.5	0.6

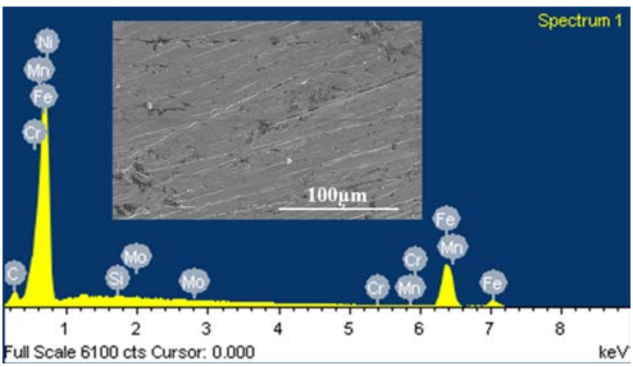

Fig. 1. Composition analysis of AISI 1040 steel.

2.2. Cutting temperature measurement

Tool-work thermocouple was employed to measure the mean temperature of cutting. The thermocouple was calibrated based on a setup as depicted in Fig. 2. The HSS tool and AISI 1040 steel formed the hot junction, which showed a temperature spike during the application of oxyacetylene flame. The digital multimeter and hot junction were connected through a chromel wire. On the other hand, the cold junction was formed at the far end of AISI 1040 steel. This end was connected to the multimeter by an alumel wire. The temperature rise at the hot junction was also monitored by a K-type reference thermocouple that has a range from −50 to 1300°C. A calibration chart was formed based on the multimeter reading of electromotoric force (EMF) in mV and the reading of the reference thermocouple, as shown in Fig. 3. The calibration is found to be satisfactory with a high R^2 value of 0.98 and, therefore, could potentially be employed to measure the cutting temperature.

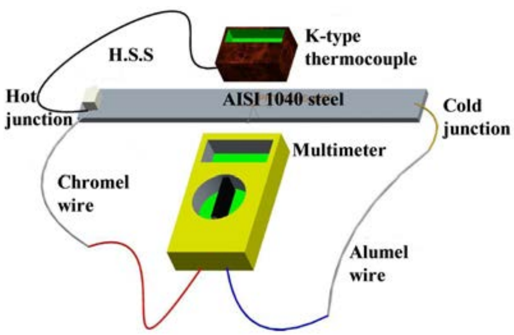

FIG. 2. A schematic diagram of the calibration setup.

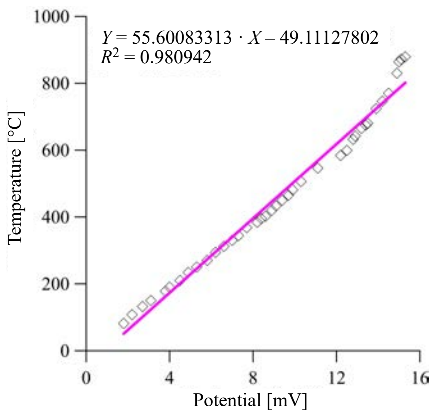

FIG. 3. Calibration plot of potential versus temperature (reproduced from [30] with permission from IOPscience).

The thermocouple and setup for turning are illustrated schematically in Fig. 4. At the far end, near the self-centering chuck, the cold junction was formed via a slip ring and a copper brush. The tool was insulated from its environment. The calibration aspect is one of the most cumbersome aspects encountered while working with a tool-work thermocouple. This is because the conditions of calibration vary from the conditions of actual machining. Therefore, during actual machining, a significant effort is given to isolate the thermocouple circuit and reduce the noise. The steel bar made out of AISI 1040 steel was also insulated from the chuck by an insulating sheet. The machining process was undertaken for some time so that the EMF could be stabilized. An average of five temperature readings at the interface of tool-work is reported.

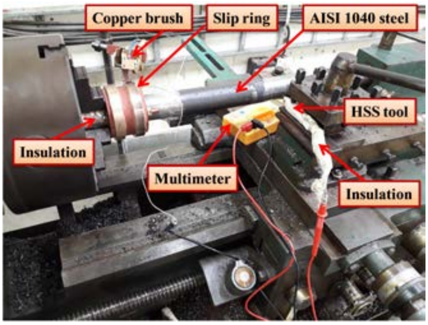

Fig. 4. Actual machining setup with temperature measuring unit (reproduced from [30] with permission from IOPscience).

2.3. Development of a regression model and optimization

After carrying out experimentation based on L_9 OA, a relationship between the average cutting temperature and the process parameters was obtained by fitting a quadratic equation. Its prediction capabilities were determined from R^2 and mean absolute percentage error (MAPE). Such models are appreciated because of their versatility, simplicity, satisfactory modeling capabilities, and their ease of optimization. ANOVA of the model was also used to ascertain each parameter's significance and involvement percentage and their interactions.

Finally, the quadratic model was optimized using GA. By employing GA, the optimal combination of the parameters was predicted to reduce the mean temperature of cutting at the interface of the tool and work. The basis of GA is Darwin's principle [33]. It is a stochastic evolutionary algorithm based on the natural genetics of reproduction. GA begins with the creation of an arbitrary initial population of solutions or chromosomes. The chromosomes contain information about a set of process parameters. Their fitness is evaluated using a target function (the quadratic equation of average interface temperature in this case). This randomly generated population of the solution is then modified by reproduction, crossover, mutation, etc. Crossover involves the exchange of genetic materials between two chromosomes, while mutation involves making changes in a single chromosome. Based on these operators, a new pool of solutions is generated and their fitness is evaluated again. This goes on for as long as the maximum number of iterations/generations is achieved or some stopping criteria are met. Thus, in every generation or iteration, biologically inspired evolution takes place. One of the advantages of using GA is the ability to obtain an optimal solution at intermediate points of experimental space. GA has also been applied successfully to the optimization of processes involving manufacturing. The schematic of the whole investigation is displayed in Fig. 5.

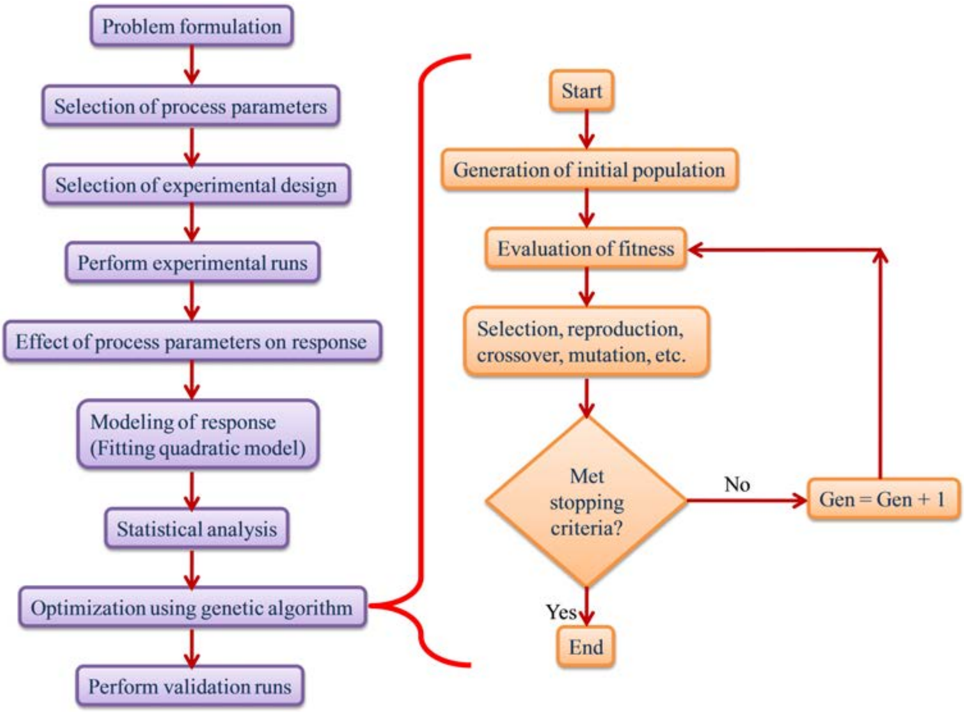

Fig. 5. Flowchart of the experimental investigation and optimization.

3. Results and discussions

3.1. Effect of the process parameters on average temperature

The mean of cutting temperature T was obtained with the help of a tool-work thermocouple and the values are presented in Table 2. The values are as per the design matrix of L_9 OA. The significance of machining parameters on temperature generated at the cutting interface is determined through surface and contour plots, as displayed in Fig. 6. In Fig. 6, "A" denotes cutting speed,

Table 2. Experimental results observed from Taguchi's orthogonal design.

Test number	A [m/min]	B [mm/rev]	C [mm]	T [°C]
1	70	0.1	0.2	141
2	70	0.3	0.4	122
3	70	0.5	0.6	159
4	100	0.1	0.4	168
5	100	0.3	0.6	148
6	100	0.5	0.2	155
7	130	0.1	0.6	369
8	130	0.3	0.2	348
9	130	0.5	0.4	400

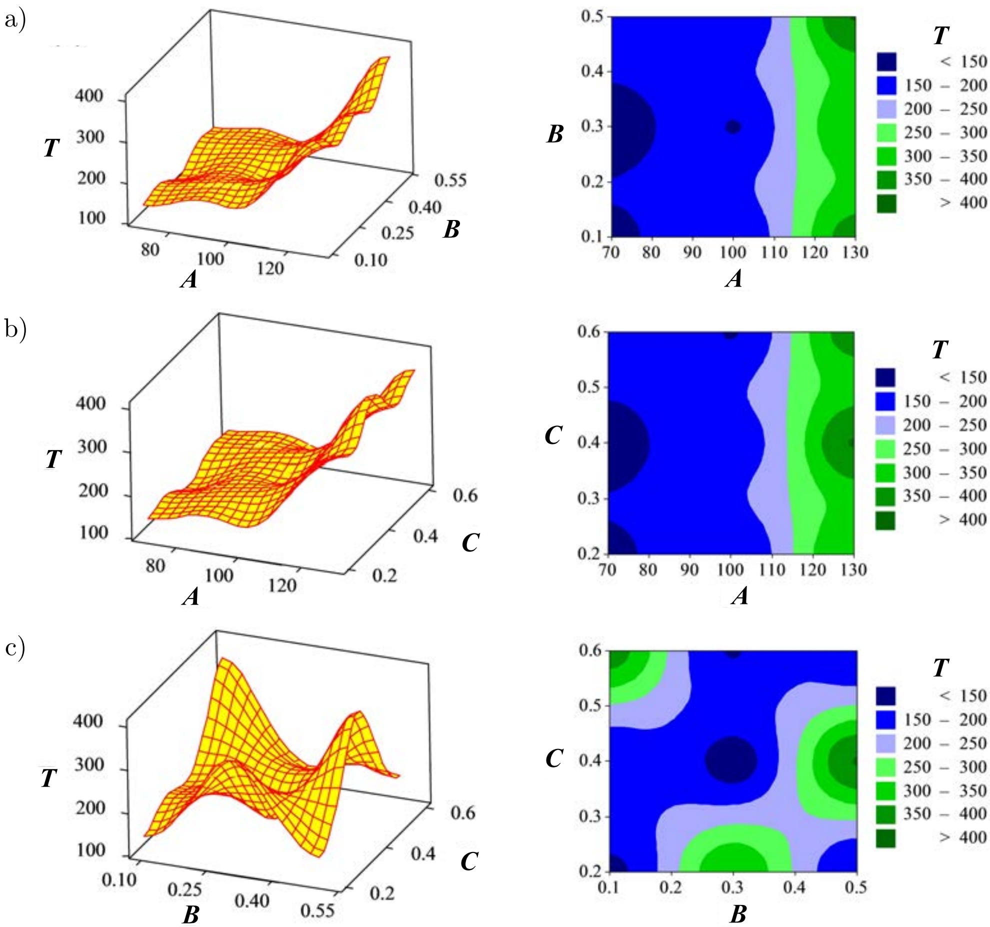

FIG. 6. Variation of average cutting temperature with a combination of: a) speed and feed, b) speed and depth of cut, c) feed and depth of cut.

"B" denotes input feed rate, "C" denotes the cutting depth and "T" denotes average cutting temperature in °C.

Within 70–100 m/min cutting speed, the average temperature generated remains almost steady for all values of feed rate (Fig. 6a). But above 100 m/min, the temperature increases with speed versus feed. Thus, up to 100 m/min, the heat is dissipated away, resulting in the average cutting temperature remaining steady. But as the speed and feed increase, a higher temperature develops. In Fig. 6b, a similar trend may also be observed for the interface temperature plotted for speed versus depth of cut. The cutting temperature for SAE 1030 carbon steel also increased harmonically as the speed and feed increased when turning with KC 810 and KC 910 coated tool inserts [4]. The cutting temperature was also observed to be related to the chip thickness and tool and chip contact length, which increased as feed increased and speed decreased.

Tool-work thermocouple was employed to find the cutting temperature during machining of AISI 52100 with an insert having a carbide coating [28]. A rise in temperature was observed as speed against the depth of cut and speed against the feed increased. Hard turning of AISI 1060 steel with a coated carbide insert resulted in the interface temperature increasing with the feed and speed [8]. In [8], it was also concluded that the work-piece hardness also affected the interface temperature, which showed a rising trend with speed and hardness. Similar results were also obtained while machining AISI 316L steel with cemented carbide inserts, where the temperature was observed to rise with feed and speed [26]. A sharp rise in cutting temperature was observed when cutting speed increased while machining hardened AISI 4340 steel using a tool with TiAIN coating and a multi-layered coated carbide tool [3]. But with the depth of cut and feed, the temperature was observed to rise slowly with a lower slope. Leshock and Shin [14] also observed a rise in interface temperature with speed during the turning of 4140 steel alloy and Inconel 718 using the WC tool. A tool-work thermocouple was also used in the same study. Thus, the present work is in accordance with the literature, except that the temperature remained steady to the mid-level of speed, feed, and cutting depth.

No clear trend was observed for the variation of temperature with feed versus depth of cut in Fig. 6c. In a recent study, the cutting temperature was investigated for machining AISI 52100 steel with a CBN-based tool & TiN ceramic phase under dry and micro-lubrication conditions [32]. A K-type thermocouple was used to measure the cutting temperature. The temperature at the interface was observed to increase with speed versus depth of cut, speed versus feed as well as feed versus cutting depth in dry conditions. This trend was maintained, but it was lower under micro-lubrication. The significance of feed rate on the temperature during machining of AISI1040 steel for dry and cryogenic cooling conditions was studied by Gupta *et al.* [11]. Under dry conditions, the temperature increased with feed but under the cryogenic cooling condition, it was significantly lower and remained steady. Apart from the cutting speed and feed, the cutting environment, along with substrate hardness, was also observed to be dominant in affecting temperature rise in hardened steel turned by coated carbide insert [29]. In fact, it was observed to make the tool softer at a higher temperature, which led to the built-up edge and degraded surface integrity. Therefore, the observation in our study corroborates well with previous studies and the proposed tool-work for thermocouple produces satisfactory results for measuring the cutting temperature.

3.2. Modeling the average cutting temperature

The average cutting temperature is obtained and a mathematical relationship with the process parameters is formulated. A quadratic equation is fitted using MINITAB software considering the individual parameters, their interactions, and squared terms. Based on the significance of the terms, the following equation is obtained by fitting a quadratic equation using the data in Table 2:

$$T = 864.81 - 18.215 \times A - 361.667 \times B + 233.333 \times C + 0.110741 \times A^2 + 654.167 \times B^2 - 258.333 \times C^2, \tag{3.1}$$

where T is the mean cutting temperature in °C, and A, B, C are defined and presented in Table 2. The actual temperature versus predicted temperature is shown in Fig. 7. The coefficient of determination, i.e., R^2 is 0.99, which is significantly high and indicates the acceptability of the model. The actual and anticipated values of the model are closely related and, therefore, may be used for further prediction within the experimental domain considered. The MAPE is 3.02%. Hence, it may be finally concluded that the model has accurate prediction capabilities with a low range of error.

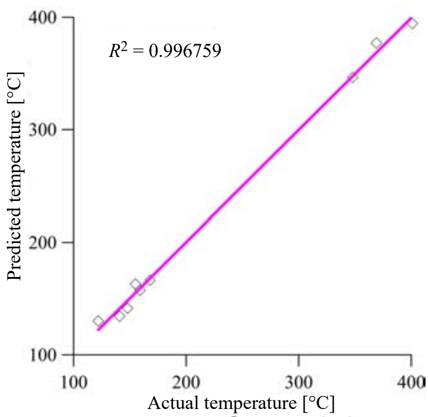

FIG. 7. Correlation between actual and anticipated values of cutting temperature.

The results obtained from the ANOVA of the regression model are tabulated in Table 3. An insight into the true significance of statistics for the parameters is obtained from ANOVA. It is observed from the results that cutting speed was most influential in controlling the temperature at the tool-work interface. The squared term of cutting speed also has some contribution. But low contribution is observed for both feed rate and the depth of cut. Higher cutting speed results in higher friction generated at the tool due to higher material removal per unit time [8]. Higher speed also results in insufficient cooling time for the tool, resulting in higher cutting temperature. This adversely affects the tool making it dull and a consequent higher area of contact and friction. Most of the research indicates a higher contribution from cutting speed and feed and the least contribution from the depth of cut [4, 8, 32]. From surface plots and ANOVA, it was concluded by Rajarajan *et al.* [32] that the interface was influenced mainly by cutting speed. This was followed by feed rate and depth of cut. In fact, it was concluded by Gupta *et al.* [11] that the significance of the depth of cut is very predictable in increasing the average cutting temperature. The ANOVA results agree well with the surface and contour plots (Fig. 6), where speed and feed were observed to have a predominant influence on the temperature. Also, the higher F-value and % contribution of the model indicates its acceptability in making further predictions. Thus, it can be subsequently used for optimization using GA.

Table 3. ANOVA result analysis of average temperature of cutting.

Source	DOF	Seq SS	Adj MS	F-ratio	% Contr.
Regression	6.00	102585.00	17097.40	102.52	99.68
A	1.00	80736.00	13434.80	80.56	78.45
B	1.00	228.00	1121.20	6.72	0.22
C	1.00	171.00	266.70	1.60	0.17
$A \times A$	1.00	19867.00	19866.90	119.12	19.30
$B \times B$	1.00	1369.00	1369.40	8.21	1.33
$C \times C$	1.00	11214.00	213.60	1.28	0.21
Error	2.00	334.00	166.80		0.32
Total	8.00	102918.00			100.00

3.3. Optimization of tool-work interface temperature

An optimal parametric setting to minimize the tool-work interface temperature has been carried out using GA. Compared to the grey or Taguchi method, GA has the ability to predict parameters between the discrete set of combinations in OA. The equation generated by fitting a quadratic equation is used as the objective function (Eq. (1)). The aim is to minimize the temperature T

within the experimental domain considered. The corresponding optimization problem formulation is given as follows:

Minimize: $T\ (A,\ B,\ C)$

Subject to: $70\ \text{m/min} < A < 130\ \text{m/min}$

$0.1\ \text{mm/rev} < B < 0.5\ \text{mm/rev}$

$0.2\ \text{mm} < C < 0.6\ \text{mm}.$

The problem is fed to the MATLAB genetic algorithm toolbox along with the proper GA parameters. In general, there is no instance of a particular set of GA parameters that would result in the best possible combination. But the important criteria that have been considered [30] are presented in Table 4. Major consideration has been given to the size of population, the number of generations, mutation rate, crossover rate, etc. The final setting of the operators that led to the optimum result in minimum iterations is given in Table 4. The fitness value with generations is shown in Fig. 8. After almost 30 generations, there was no significant change in the objective function, and hence the stopping criteria reached after 112 iterations.

Table 4. Genetic algorithm parameters and operators.

Parameter	Setting
Population size	50
Maximum iterations	500
Function tolerance	10^{-12}
Creation function	Uniform
Fitness scaling function	Rank
Selection function	Uniform stochastic
Crossover function	Scattered
Crossover fraction	80
Mutation function	Adaptive feasible

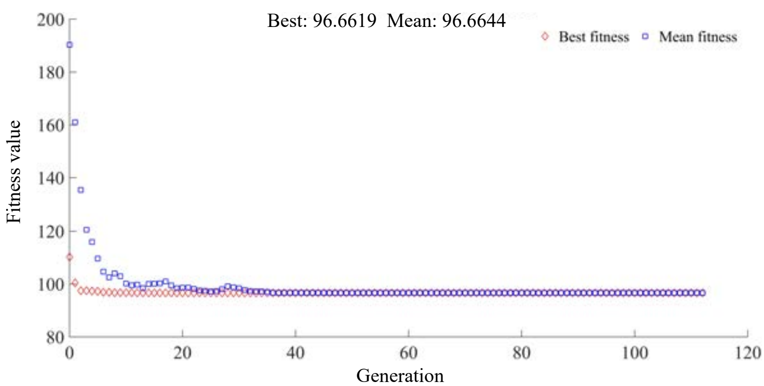

FIG. 8. Variation of fitness with iterations.

It was predicted by GA that a cutting speed of 82.542 m/min, feed rate of 0.276 mm/rev, and 0.2 mm depth of cut was the optimal setting for turning parameters. The optimal GA predicted temperature is 96.66°C. In the surface plots, it could be seen that up to the mid-level value of speed versus feed and speed versus cutting depth, the temperature generated was quite low and steady. But no clear trend was observed for feed versus cutting. So, the optimization using GA comes in handy in such cases where the variation is non-linear. Due to the limitations of the parametric settings of the lathe, a confirmation test was conducted at the given cutting speed of 70 m/min, feed rate of 0.3 mm/rev with a depth of cut of 0.2 mm. The regression predicted temperature is 114.44°C, whereas the experimentally obtained interface temperature is ∼116°C. A simplistic regression-based GA obtained from fewer trials yields results similar to other research works, thereby saving computation time [30].

4. Conclusion

This work examined the dependence of temperature at the interface of tool-work on the cutting parameters in dry non-lubricated conditions for AISI 1040 steel. Machining was accomplished using a conventional HSS tool. The calibration of a tool-work thermocouple was conducted with fair accuracy to determine the temperature of cutting generated at the cutting zone. The following conclusions derived based on the investigation are:

1) The interface temperature exhibited a steep rise with speed versus cut-depth and speed versus feed at higher parametric combinations. But up to 100 m/min feed rate, the temperature was quite low and a steady rise was noticed. The variation of temperature with feed versus depth of cut did not follow any trend and exhibited a random nature.
2) A quadratic equation of order two was fitted for the average tool-work temperature with a high R^2 of 0.99 and a low MAPE of 3.02%.
3) ANOVA results displayed the maximum contribution of cutting speed to control the temperature at the junction of tool and work.
4) Due to the non-linear nature of variations of temperature with the process parameters, GA was employed for optimization. GA predicted a combination of cutting speed of 82.542 m/min, depth of cut 0.2 mm, and feed rate of 0.276 mm/rev. The minimum temperature predicted was 96.66°C. The confirmation test indicated good correlation between anticipated values and test results.
5) The present work can be beneficial in improving machining capabilities of AISI 1040 steel in conventional turning, reducing costs, and improving system performance. Future research may be conducted to explore the effect

of work piece hardness, variation of tool materials, cutting environment, etc., on the tool-work interface temperature.

Acknowledgments

The authors gratefully acknowledge the facilities provided by the Central Instrumentation Facility and Mechanical Engineering Department of Birla Institute of Technology, Mesra, Ranchi.

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Received December 22, 2021; accepted version April 28, 2022.
