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OPTIMAL PARAMETERS SELECTION TO REDUCE CUTTING TEMPERATURE OF MILD STEEL USING PARTICLE SWARM OPTIMIZATION INTELLIGENT TECHNIQUE

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ABSTRACT

The temperature evolution, which happened in cutting operations due to heat, influences the properties of the cutting tool and work piece materials. This study focuses on the primary heat zone so called shear zone and secondary heat zone which also called tool-chip interface zone temperatures during turning a mild steel work piece via carbide insert cutting tool in process of CNC turning operation in dry machining. The temperature between the tool and the work piece can be neglected because it is small and also can be reduced using cutting tool with sharp cutting edge. Two new objective functions are proposed to optimize the cutting temperature problems. The proposed system uses particle swarm optimization (PSO) methodology to find the ideal cutting parameters which help in finding the optimal temperatures. This research shows that there is lack of machining conditions optimization studies especially in the field of the cutting tool temperature optimization. The study also shows that the feed rate has a major affect on the cutting temperature compared with other parameters.

Keywords: *particle swarm optimization (PSO), temperature optimization, CNC turning machine, shear zone temperature, tool-chip interface temperature.*

1. INTRODUCTION

In today's manufacturing, finding the ideal parameters of turning processes is one of the most crucial factors which aim to increase competitiveness and product fineness. In fact, the selection of ideal machining parameters is difficult and complex. The trial and error method that is used traditionally in this operation is tedious and unreliable. Metaheuristics methods have been proposed over the last decade to overcome these problems. Many researchers showed that the most of the power of cutting process is converted to heat in the primary heat zone (shearing zone) and secondary heat zone (chip- cutting tool) sliding area. There is a heat appear on the tertiary zone where the tool relief face slides on the actual machined surface but has not been considered in calculations either for simplicity or because it is very small when using sharp cutting edges [1],[2],[3]. The total wear rate and crater wear on the rake face are strongly influenced by the temperature at chip-tool interface [4]. The cutting tool temperature if not controlled properly, cutting tools undergo severe flank wear and notch wear and loose sharpness of the cutting edge or become blunt by welded built –up edge and weaken the product quality , [5].

High temperature affects the cutting tool and work piece properties, thus increases the cutting tool wear, reduce tool life and bad work piece integrity surface. As a result, the attempts to reduce the amount of heat between work piece and cutting tool are still remain continue. Three zones of heat generation can be distinguished in turning operation, shear zone temperature which represents (60٪) of total heat generation and it depends on shear angle and affects the mechanical properties of the work piece-chip material, chip-tool interface zone which represents (30٪) of total heat generation and depends on the friction between the chip and tool rake face and influence tool wear, and work piece - tool interface zone which represents (10٪) and depends on the sharpness of cutting tool [1] as shown in Figure (1).

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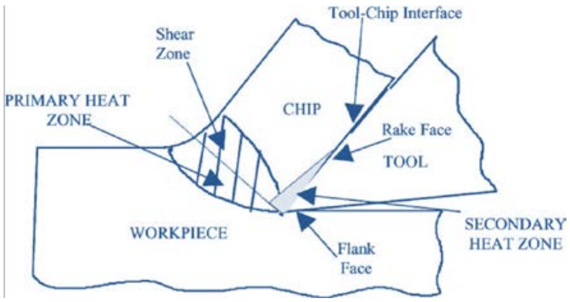

Figure 1: Heat Generation Zones (Sullivan, 2001).

In recent years there has been increasing interest in the hybrid algorithms to optimize the machining parameters and machining economic problems [6]. Particle swarm optimization (PSO) describes the candidate solution as an active particles working together travelling towards the optimum solution through the D-dimensional search-space. According to the value of the objective function, each particle keeps track of its best-achieved position (personal best, pbesti) and the best position ever achieved in the group (group best, gbesti) among all personal best. PSO algorithm, in this paper, is used to find the optimum cutting parameters to optimize (minimize) the turning operation temperature. The influence of cutting parameters such as cutting speed, feed rate and depth of cut on tool temperature, cutting forces, tool wear and surface roughness using hardened steel work piece and multilayer coated carbide tools at high cutting speeds was achieved by [2]. The temperature was measured using a thermocouple positioned at the lowest insert face and underneath it and using the gradient to calculate the values of temperature near the cutting tool rake face. They showed that the cutting temperature affects on the cutting tool wear, work piece surface safety and machining accuracy. The final results showed that the critical parameters on chip-tool interface temperature in turning these types of work piece and cutting tool were the cutting speed, feed rate but the depth of cut has the greatest influence on it. However to get a successful cutting operation, the tool material must be harder than the work material and able to maintain that hardness at elevated temperatures, beside that and although 60% of heat is generated in the shear region and 80% of the total heat goes to the chips, most temperature increases in the tool because it remains constant in the work piece [3]. The mechanical wear (abrasion) and chemical wear (diffusion) interactions increase the diffusion and oxidation processes between the cutting tool and work piece when the cutting tool heats up to 1000 C° or more, also, the mark of the chemical wear became clearer at the higher cutting speeds [7]. The study of tool-chip interface temperature of EN-31 steel alloy work piece in turning operation using tungsten insert cutting tool showed that the increment in the values of speed, feed rate and depth of cut increase the cutting temperature, while increasing tool nose radius will reduce it [4]. A steel work piece, cemented carbide insert and a tool-work thermocouple technique were used in [8] to study the optimization operation of the cutting parameters in turning process that leads to minimize the temperature generated between the cutting tool and chip. The author concluded that among all parameters, cutting speed and feed were the most significant parameters that affects on chip-tool interface temperature. PSO algorithm can be used for estimating the parameters based on nonlinear regressive curve of cutting tool temperature [9]. The empirical model used is as Eq. (1):-

$$Tr = K \cdot a_{p} \cdot f \cdot v \quad (1)$$

Whereas:-
Tr :- Output of temperature (C^{o}).
K :- Coefficient depending on work piece material.
a_p :- Depth of cut (mm).
f :- Feed rate (mm/rev).
v :- Cutting speed (m/min).

The objective function aims to minimize the model simulation output temperature and actual temperature. The results showed that the PSO algorithm is an effective approach. The optimization of the cutting variables such as feed rate, cutting speed, pressure and flow rate of high pressure coolant to obtain the best machining performances in turning AISI-4320 steel work piece by uncoated carbide insert was achieved[10]. The estimated models of chip reduction coefficient, cutting temperature and surface roughness were considered. Multi-objective optimization methodology has been carried out based on (GA) algorithm for minimizing two conflicting objectives simultaneously; the first is cutting temperature and second is cutting force. The results showed that cutting temperature, chip reduction coefficient and surface roughness can be well estimated through these models. There is a problem of estimating the ephemeral temperature and the heat stream at the tip of a tool during a turning process [11]. The researchers used an inverse approach in order to prevent and avoid the cutting tool damaging or breaking. In this method, two thermocouples are located at two different

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locations in the insert tool. The heat transfer was then described with a model based on the quadruple formulation. The results were tested with simulations performed based on the finite volume method fluent for different temperatures aspects such as Heaviside and exponential solicitations. A pyrometer with two optical fibers can be used for measuring the tool temperature at the flank face in turning operation [12]. In this method, the incidence face of one optical fiber which is embedded in a rotating work piece receives the infrared rays radiated from the cutting tool and sends it to the other face. The infrared energy is accepted by the other optical fiber which is fixed at the pyrometer and lead to the two color detectors. The authors concluded that the temperature was increased with the cutting speed. Measuring the temperature using the thermocouple method during the CNC turning on steel C45 work piece using cutter type ceramic cutting plates MC2 was achieved [13]. The cutting parameters used are: cutting velocity, feed rate, depth of cut and nose radius. The authors concluded that the great amount of temperature was at the chip's contact zone with the front surface; also the cutting speed and feed rate have a great influence on cutting temperature, beside that, when the cutting angle increases, the cutting forces also increase as well as the cutting temperature. Another study showed that the direct temperature measurement at the chip–tool interface is very complex operation [14]. The proposed method to prove this problem was by using a heat flux for temperature estimating at this area via the inverse heat conduction problem technique. The thermal model was obtained by a numerical solution of the transient three-dimensional heat diffusion equation that considers both the tool and the tool holder assembly. Many cutting tests using cemented carbide tools were performed in order to check the model and to verify the influence of the cutting parameters on the temperature field.

2. MOTIVATION OF STUDY

In any event, the human experience and handbook recommendations are used to select the operating parameters in manufacturing industry which may not ensures getting of the optimum cutting conditions. Also because of the complexity of the optimization problem there have not been many studies done in the field of cutting temperature optimization. The cutting temperature increases with the increase in specific energy consumption and material removal rate that is with the increase of cutting velocity, feed rate and depth of cut. The high temperature generated leads to many problems like chip and built- up- edge formation, reducing the magnitude of the cutting forces, reducing the shear strength, dimensional inaccuracy of the work piece, surface damage by oxidation, rapid corrosion and burning, rapid tool wear which reduce tool life, plastic deformation of the cutting edge, thermal flanking and fracturing of the cutting edges due to thermal shocks… etcetera. Therefore and because of the presence of the three areas of heat generation can be noticed in turning operation such as the shear zone, the chip-tool and the tool-work piece interface temperature and because of the temperature at shear zone affect on the mechanical properties of the work piece-chip material and the temperature at the tool-chip zone affect on the cutting tool wear [1]. This paper aims to minimize these temperatures using intelligent PSO algorithm. The most optimization algorithms considered by the researchers at the last time are concentrated on optimization surface roughness followed by machining/production costs and material removal rate and there are no more papers studied the field of cutting temperature optimization [15] as shown in Figure. 2.

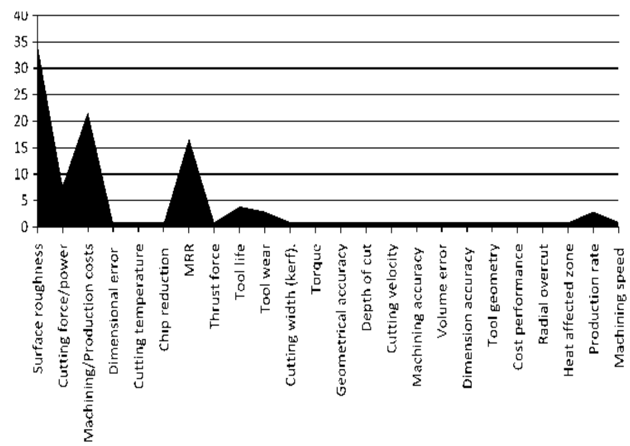

Figure 2: Machining Performance Using GA,SA, PSO, ABC and ACO (Yusup et al. , 2012).

3. PARTICLE SWARM OPTIMIZATION METHODOLOGY

PSO concept consists of regulating the velocity and location of each particle toward its p_{best} and g_{best} locations according to the Eq. (2) and Eq. (3) [9] below:-

$$v_{i+1} = w.\ v_i + a_{1.}\ rand\ (p_{best} - xi) + a_2\ .rand\ (g_{best} - xi) \qquad (2)$$

Whereas:-

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v_{i+1}:-Next particle velocity.
w:- Variable inertia weight.
v_i:- Velocity of particle.
a_1, a_2:- acceleration constants .
rand:- random number between 0 and 1.
Pbest:- personal best of particle i.
x_i:-Actual swarm position.
gbest:- best position in the neighborhood.

Also:-

$$x_{i+1} = x_i + v_{i+1} \quad (3)$$

Whereas:-
x_{i+1}:-Next particles position.
x_i :- Actual swarm position.
v_{i+1}:-Next particle velocity.

In this work, the process for applying PSO for estimation the parameters is as follows:-
Step 1: Initialize related parameters, such as population size of swarm (in this work equal to 30), the acceleration constants a_1 (equal to 0.02) , a_2 (equal to 0.02), the maximum velocity vmax (equal to 4), the stop criterion (maximum iteration equal to 500).
Step 2: Evaluate the desired fitness function values for current each particle.

Step 3: Compare the evaluated fitness value of each particle with its Pbest. If current value is better than Pbest, then set the current location as the Pbest location. Furthermore, if current value is better than gbest, then reset gbest to the current index in the particle array.

Step 4: Change the velocity and location of the particle.

Step 5: Loop to Step 2 until a stop criterion is met.

4. METHODOLOGY AND APPROACH

4.1 Objective Functions

PSO algorithm needs an objective function to be maximized or minimized. In this paper, two objective functions are employed to minimize the shear and chip-tool interface zones temperature.

4.2 Shear Zone Temperature (Ts)

This area also called primary heat zone. In this zone, the major part of the energy is converted into heat. The objective function that estimates the temperature of this zone derived from many equations as shown in Eq. (4) [16]:-

$$Ts= B.C.Vc.(Fz.a2 – F.f .\sin (\phi) /a2) / (J .\theta .Vc .a .f) + Ta \quad (4)$$

Whereas:
Ts:-Shear zone temperature (Cº).
B:- Shear energy that is converted into heat, equal to (0.95~1) in turning operation.
C:- Heat that goes to the chip from the shear zone , equal to (0.7~0.9) in turning operation.
Vc:-Main cutting velocity (m/min).
Fz:-Main cutting force (N).
a2:-Chip thickness (m).
F:- Friction force at the rake surface (N).
f :- Feed rate (m/rev).
ϕ :- Cutting tool edge angle (degree).
J :- Mechanical equivalent of heat of the chip / work material (J/cal), (dependent on work piece material).
θ:- Volume specific heat (cal/m^3/Cº), (dependent on work piece material).
a :- Depth of cut (m).
Ta:- Ambient temperature (Cº).

4.3 Chip – Tool Interface Temperature (Ti)

This area also called as secondary heat zone. In this zone, the heat is generated due to rubbing or shearing between the chip and cutting tool rake face. The objective function that estimates the temperature of this zone derived from many equations as shown in Eq. (5) [16]:-

$$Ti= C_1.Ec. \sqrt{(Vc.f .\sin (\phi) / (\theta.\lambda))} \quad (5)$$

Whereas:-
Ti: - Chip-tool interface temperature (Cº).
C_1:- Constant equal to (121) in turning operation.
Ec:- Specific cutting energy of the work material by a given environment (Kg/m^2).
Vc:- Main cutting velocity (m / min).
f :- Feed rate (m/rev) .
ϕ :- Cutting tool edge angle (degree).
θ :- Volume specific heat (Kcal/m^3/Cº),(dependent on work piece material).
λ:- Thermal conductivity (cal/m.s.Cº) , (dependent on work piece material).

So, the main objective function that should be minimized can be shown in Eq. (6):-

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$$T_{main} = Ts + Ti \quad (6)$$

Whereas:-

T_{main}:- Main cutting temperature (C°).

Ts:- Shear zone temperature (C°).

Ti:- Chip-tool interface temperature (C°).

In other words, the main objective function can be expressed in Eq. (7) below:-

$$T_{main} = [B *C *Vc*(Fz*a2 - F* f * \sin (\phi)) /a2/ J *\theta *Vc *a *f +Ta] + [C_1* Ec * \sqrt{(Vc *f *\sin (\phi) / (\theta*\lambda))}]. \quad (7)$$

Therefore, the main objective function is to minimize the main cutting temperature (T_{main}) which represents the summation of shear zone temperature (Ts) and chip – tool interface temperature (Ti).

There are many parameters that affect the cutting temperature such as cutting speed (Vc), feed rate (f), depth of cut (a), main cutting force (Fz) and friction force at the rake surface (F). So, it is necessary to consider these parameters as constraints for the operation because its effects on the selection of the optimal cutting conditions as shown below [11]:-

$$a\ min \leq a \leq a\ max$$
$$f\ min \leq f \leq f\ max$$
$$a2\ min \leq a2 \leq a2\ max$$
$$Fz\ min \leq Fz \leq Fzmax$$
$$F\ min \leq F \leq F\ max$$

The flow chart that minimizes the cutting tool temperature using PSO methodology is shown in Figure (3):-

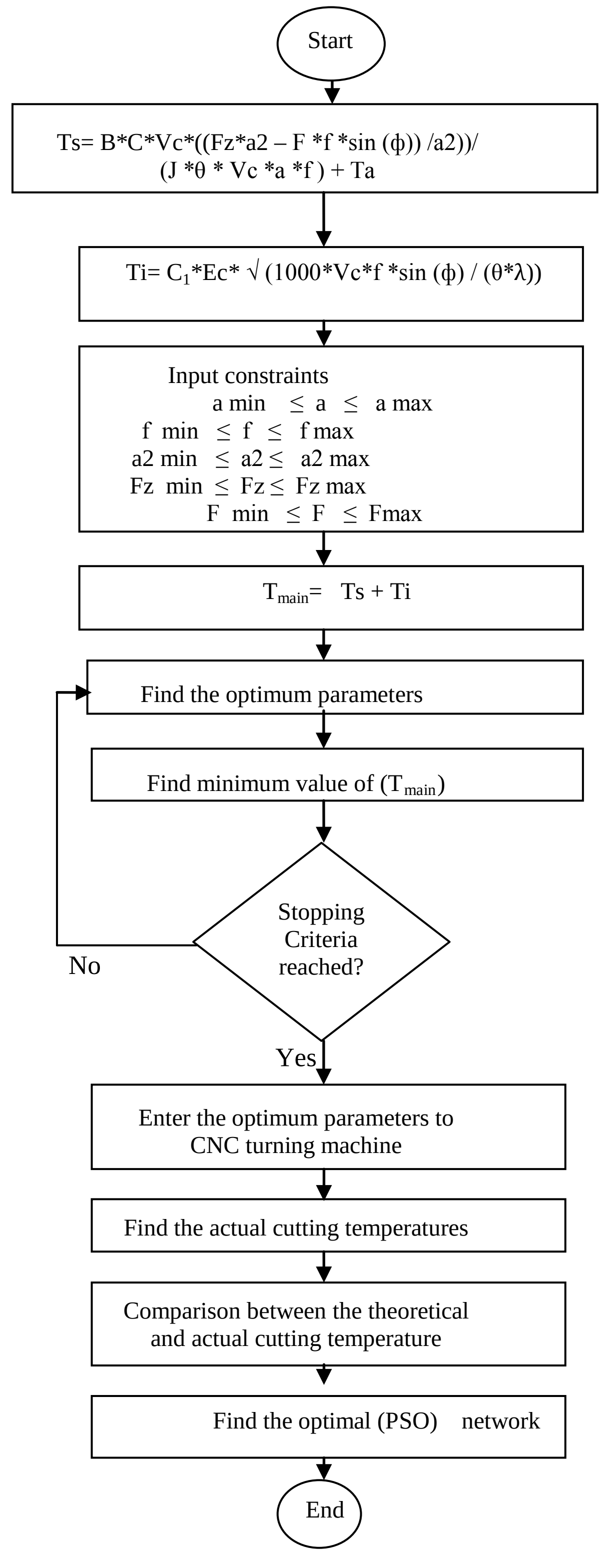

Figure 3: Flow Chart Minimizes Cutting Temperature Using Pso Methodology.

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The ideal parameters can be used as inputs to the CNC turning machine directly to calculate the actual cutting temperatures and compare the results with theoretical temperatures.

5. CASE STUDY

A case study was taken to estimate the main cutting temperature (T_{main}) when turning a mild steel rod work piece using a carbide insert cutting tool and dry turning operation. This work includes three steps, the first step is to estimate a shear zone temperature (Ts), the second one is to estimate the chip-tool interface temperature (Ti) while the last step is to find the total of shear and chip-tool temperatures which represents the main cutting temperature (T_{main}).

5.1 Shear Zone Temperature (Ts) Estimation

Using Eq. (1) , the constants and the constraints will be considered as; B = 0.95, C = 0.70, Vc = 125.6 (m/min), $\phi = 20^o$, J = 4.2 J/Cal for mild steel, θ = 825 Kcal/m^3/C^o for mild steel, Ta = 25 (C^o).

The constraints of the operation will be considered as below:-

$$0.002 \text{ m} \le a \le 0.006 \text{ m}$$
$$0.00010 \text{ m/rev} \le f \le 0.00015 \text{ m/rev}$$
$$0.0015 \text{ m} \le a2 \le 0.0060 \text{ m}$$
$$1000 \text{ N} \le Fz \le 1300 \text{ N}$$
$$400 \text{ N} \le F \le 700 \text{ N}$$

After using PSO methodology, the following results are obtained as shown in Table (1):-

Table 1: Shear Zone Temperature Estimation.

Depth of cut (a) m	Feed rate (f) m / rev	Chip thickness (a2) m	Main cutting force (Fz) N	Friction cutting force (F) N	Shear zone temperat-ure Ts (C^o)
0.00200	0.000100	0.00150	1000	800	417.06
0.00257	0.000138	0.00555	1057.37	521.89	793.28
0.00260	0.000134	0.00211	1042.20	643.85	750.91
0.00317	0.000100	0.00172	1001.72	673.94	660.31
0.00224	0.000100	0.00173	1240.42	513.46	587.29
0.00208	0.000101	0.00778	1171.78	554.94	532.14

The optimum machining parameters that achieve less shear zone temperature are shown in the last row of Table (1) as shown:-

The optimal shear zone temperature selection is illustrated in Figure (4):-

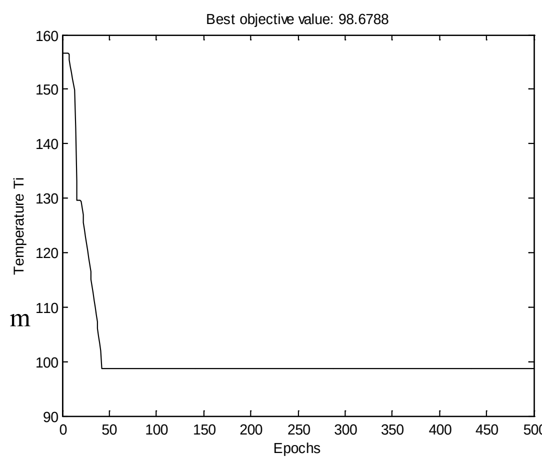

Figure 4: Optimal Shear Zone Temperature.

Table (1) shows that increasing the depth of cut (a) and decreasing the friction force at rake face (F) , feed rate (f), chip thickness (a2), main cutting force (Fz)], the shear zone temperature decreases significantly. However, in some periods of cutting operation, at a constant value of depth of cut, feed rate and main cutting force and increasing the value of friction force, the shear zone temperature decreases lightly.

5.2 Chip-Tool Interface Zone Temperature (Ti) Estimation.

Using Eq. (2), the constants and the constraints will be considered as; C_1= 121 , Vc = 125.6 (m/min), $\phi = 20^o$, θ = 825 Kcal/m^3/C^o for mild steel, λ = 40 (cal/m.s.C^o) for mild steel.

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The specific cutting energy (Ec) is calculated as Eq. (8) Kharargpur e-book (2009) as shown below:-

$$Ec = Fz / f * a \quad (8)$$

Whereas:-

Fz:- Main cutting force (N).
f :- Feed rate (m/rev).
a :- Depth of cut (m).

After remuneration Eq. (8) in Eq. (5), the resultant equation becomes:-

$$Ti = C_1 * (Fz / f * a) * \sqrt{(1000*Vc*f *\sin(\phi) / (\theta*\lambda))} \quad (9)$$

The constraints of the operation will take as:-

$0.002\ m \leq a \leq 0.006\ m$
$0.00010\ m/rev \leq f \leq 0.00015\ m/rev$
$1000\ N \leq Fz \leq 1300\ N$

After using PSO methodology, the following results were obtained as shown in Table (2):-

Table 2: Chip-Tool Interface Temperature Estimation

Depth of cut (a)m	Feed rate (f) m/rev	Main cutting force (Fz) N	Chip-tool temperature (Ti) C°
0.00635	0.000108	1130.56	158.42
0.00763	0.000114	1208.83	153.16
0.00800	0.000106	1288.27	150.34
0.00597	0.000100	1036.28	149.97
0.00625	0.000100	1079.08	147.39
0.00633	0.000100	1021.93	137.61
0.00670	0.000100	1000	127.31
0.00707	0.000100	1000	120.72
0.00743	0.000100	1000	114.78
0.00780	0.000100	1000	109.40
0.00800	0.000100	1000	98.678

The optimal temperature selection is illustrated in

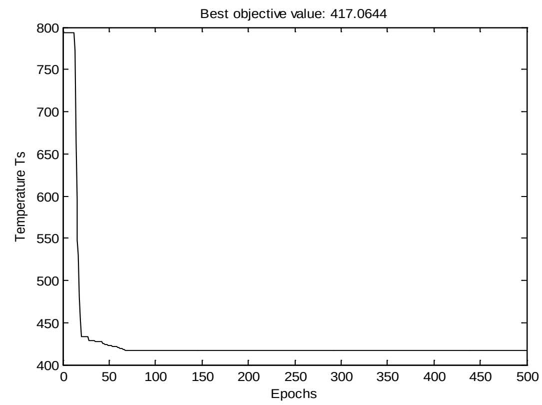

Figure (5):-
Fig 5: Optimal Chip-Tool Zone Temperature

The optimum machining parameters that achieve less chip-tool interface temperature are shown in the last row of Table (2).

Depth of cut (a) m	Feed rate (f) m / rev	Main cutting force (Fz) N	Chip-tool temperature Ti (C°)
0.00800	0.000100	1000	98.678

Table (2) shows that increasing in depth of cut (a), feed rate (f) and main cutting force (Fz) leads to chip - tool interface temperature decreasing lightly. However, at some periods of cutting operation, the increasing in depth of cut value with constant values of other parameters leads to chip-tool temperature decreasing largely.

5.3 Total (Shear Zone And Chip-Tool Interface Zone Temperatures (Ts + Ti) Estimation.

Using Eq. (4), Eq. (5) the constants and constraints will be considered as; B = 0.95, C = 0.70 , Vc = 125.6 (m/min), ϕ = 20° , J = 4.2 J/Cal for mild steel, θ = 825 Kcal/m3/Co for mild steel, Ta = 25 (C°), C1= 121, λ = 40 (cal/m.s.Co) for mild steel.

The constraints of the operation isconsidered as below:-

$0.002\ m \leq a \leq 0.006\ m$
$0.00010\ m/rev \leq f \leq 0.00015\ m/rev$
$0.0015\ m \leq a2 \leq 0.0060\ m$
$1000\ N \leq Fz \leq 1300\ N$
$400\ N \leq F \leq 700\ N$

After using PSO methodology, the following results are obtained as shown in Table (3):-

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Table: 3 Total Shear and Chip-Tool Interface Zones Temperature Estimation

Depth of cut (a) m	Feed rate (f) m/rev	Chip thickness (a2) m	Main cutting force (Fz) N	Friction force (F) N	Combine temperature T_{main} (Ts+Ti) C°
0.00350	0.000102	0.00379	1076.84	585.11	1068.44
0.00319	0.000100	0.00600	1075.67	468.16	993.64
0.00319	0.000100	0.00600	1057.86	479.52	978.31
0.00320	0.000100	0.00600	1040.04	490.88	962.96
0.00321	0.000100	0.00600	1022.23	502.24	947.57
0.00321	0.000100	0.00600	1004.42	513.60	932.15
0.00322	0.000100	0.00600	1000	524.96	928.89
0.00305	0.000100	0.00600	1015.65	408.37	922.56
0.00278	0.000100	0.00600	1000	400	879.26
0.00239	0.000100	0.00600	1000	400	845.08
0.00213	0.000100	0.00600	1000	400	831.90
0.00200	0.000100	0.00600	1000	700	827.45

The optimal shear and chip-tool zones temperature selection is illustrated in Figure (6):-

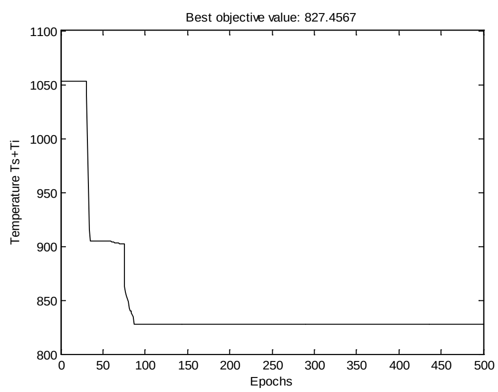

Figure 6: Optimal Shear and Chip-Tool Zones Temperatures

The optimum machining conditions that achieve less shear zone temperature are shown in the last row of table 3.

Depth of cut(a) m	Feed rate (f) m / rev	Chip thickness (a2) m	Main cutting force (Fz) N	Friction cutting force (F) N	Combine temperature (Ts+Ti) C°
0.00200	0.000100	0.00600	1000	700	827.45

Table.3 shows that decreasing the values of depth of cut, feed rate, main cutting force and friction force at the rake face and increasing the value of chip thickness decrease temperature significantly. However, at some periods of cutting operation, decreasing the value of depth of cut with constant other parameters, the total temperature can also decrease. But, at constant depth of cut, feed rate and chip thickness and decreasing the value of and main cutting force and increasing the value of friction force, the total temperature can be lightly decreased.

6. CONCLUSION

The manual selection of optimal machining parameters based on hand books and personal experience may not ensure of getting the optimum performance and minimization of costs. Moreover, the complexity of the optimization problem has not

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been exploited yet. This study concluded that there is lack in the field of the cutting temperature optimizations and up to date the most of optimization algorithms are concentrated on optimize another parameters and there are a few papers focus on the cutting temperature optimization. Therefore, this paper is proposed a new objective functions to achieve this purpose using PSO.

The major amount of the energy is converted into heat in shear zone, while the further heat is generated due to rubbing at the chip-tool interface zone. The distribution of heat depends on the size and thermal conductivity of the tool-work material and the cutting conditions. All cutting parameters affect on cutting temperature in different levels. When using a mild steel work piece and carbide insert cutting tool in dry turning operation, the depth of cut, feed rate and main cutting force have a great affect on the shear zone temperature, while chip thickness and friction force at the cutting tool rake face have lower effect. Also, at the chip-tool interface zone, increasing the depth of cut at constant feed rate and main cutting force leads to chip-tool interface temperature decrement. In this zone also, the increasing in feed rate and main cutting force at variable values of depth of cut leads to chip- tool interface temperature increment. Finally, it is clearly that the feed rate has a huge effect on shear zone and chip-tool interface zone compared with other parameters. Thus, generation of heat at the cutting zone need to be controlled to an optimum level in order to achieve better machining performance.

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