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Analysis of Optimized Total and Specific Manufacturing Costs in Medium Longitudinal Turning of C45E Steel

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Abstract: Given the significance of manufacturing cost estimation, the present study is focused on the analysis of total and specific manufacturing costs in medium longitudinal turning of C45E steel using coated carbide inserts under optimized cutting conditions. To this aim, a single-objective optimization model with process constraints, related to available cutting power and favourable chip slenderness ratio, was developed and solved using a generalized reduced gradient algorithm. In the proposed optimization model, a dimensional analysis-based model for cutting force prediction was developed and used for the estimation of the cutting power, while the Taylor model was used for estimating the tool life. In order to analyse total and specific manufacturing costs under optimized cutting conditions, four machining operations with different volumes of material to be removed, performed using lathes with different available cutting power and two alternative coated carbide inserts were considered. In addition, an analysis of the share of cutting insert cost and labour and overhead cost, as well as their ratios, under optimized cutting conditions for both cutting inserts and lathes and different volumes of material to be removed was performed.

Keywords: C45E steel; costs; modelling; optimization; turning

1 INTRODUCTION

The selection of machining regimes has multiple impacts on machining performances, including quality, productivity, and manufacturing cost [1, 2]. The manufacturing cost per part is affected by the machine tool technology, manufacturing systems management and cutting tool characteristics, as these directly determine machining and auxiliary times as well as tool life [3]. In turning, the manufacturing cost depends on a number of factors, including workpiece material type, stock and part dimensions, lot size, quality and dimensional accuracy requirements, machine tool characteristics, cutting tool characteristics (type, grade, material, geometry, price), cooling and lubrication conditions during machining, and particularly, selected machining regime, i.e., combination of cutting speed, feed rate and depth of cut. Their significant influence stems from the fact that these technological parameters determine the material removal rate (MRR) and the number of passes in a multi-pass turning process, both of which have a direct impact on the overall machining time. Given multiple influential factors, which influence to a greater or lesser extent, analyses of their influence and estimates of manufacturing cost and associated manufacturing price are of practical importance in process planning.

Determining the optimal machining regime in turning is of great importance for improving the overall efficiency of machining system which ultimately have diverse positive effects including machining economics. Due to all the aforementioned, the optimization of machining regimes with respect to costs in turning is a constant focus of both manufacturers and researchers in the field, who are looking for ways, methods and approaches to analyse and optimize turning processes. The optimization of the turning process has long been an actual topic, but in the recent literature, one can also find studies in which the optimal cutting regimes are determined with regard to different cost criteria, such as production cost, manufacturing cost, machining cost, profit rate, specific profit rate, specific cost, etc. Mellal and Williams [4] applied a cuckoo optimization algorithm for the minimization of unit production cost in the multi-pass turning process. The authors confirmed the robustness and efficiency of the applied metaheuristic algorithm. The application of another metaheuristic, i.e., subpopulation firefly algorithm, was proposed for determining optimal cutting parameter values in multi-pass turning, resulting in minimal production cost [5]. With the use of stochastic programming, Torres et al. [6] analysed the effects of machining conditions and industrial variables on manufacturing cost in hard turning of AISI 52100 steel using coated mixed ceramic inserts. Given that the resulting manufacturing costs are influenced by specified surface roughness, Schultheiss et al. [7] proposed a modelling approach for cost estimation with respect to required surface finish, workpiece material properties, cutting tool geometry and machining conditions in longitudinal turning of AISI 4140 steel. Chung et al. [8] proposed a robust integer optimization approach for determining cutting parameter values in order to minimize production cost in a discrete production environment, while considering the number of workpieces to be machined and cutting tool wear probability. A profiling turning of AISI 304 stainless steel of single and multiple parts using a single cutting insert highlighted that the number of parts to be processed significantly impacts production cost. García-Martínez et al. [9] performed economic analyses, including estimates of manufacturing cost and analysis of maximal profit rate, in turning of Ti48Al2Cr2Nb aluminide under different lubricating conditions (dry, MQL, cryogenic). Analytical modelling and analysis of manufacturing costs in turning LM25Al/VC composite material using coated carbide inserts were discussed by Tolcha et al. [10]. In addition, a deep artificial neural network model was developed for the prediction of manufacturing costs. Ameur [11] proposed the use of a multi-objective particle swarm algorithm based on the concept of dynamic neighbourhood for the selection of Pareto solutions and minimization of production cost in the multi-pass turning process. The discussed approach was intended to determine simultaneously the number of needed passes and machining parameter values for each pass. Frumuşanu and Epureanu [12] developed a novel concept for optimal control of machining parameters based on process sequencing and cutting force monitoring in order to achieve maximal specific profit rate (EUR/min) in turning. The same authors also presented a holistic approach for turning optimization analysis by defining different optimization criteria, including specific cost (EUR/cm^3)

[13]. Accompanying numerical simulation confirmed the relevance and potential efficiency of the proposed approach in practice. Cheng et al. [14] proposed an integrated modelling approach for production planning and maintenance scheduling in order to minimize production cost per unit. A case study with sensitivity analysis was conducted to identify the most significant influencing variables.

Given the complexity of the turning process, its multiple input-output nature and the pursuit to consider several goal functions, the literature shows a trend of research that investigates optimal machining conditions regarding the combined cost and quality, as well as environmental, energy and productivity criteria. These approaches aim to address current challenges in energy efficiency and improve resource utilization, thereby promoting cleaner and more sustainable machining strategies [15]. Bagaber and Yusoff [16] developed a multi-objective turning optimization model considering three objectives (machining cost, energy and surface roughness) in turning stainless steel using uncoated carbide inserts under dry and wet cutting conditions. Prediction models, developed in terms of cutting speed, feed rate and depth of cut, were used in the formulation of a multi-objective optimization model, which was then solved using two approaches, i.e., desirability function approach and non-sorted genetic algorithm II (NSGA-II). Lin et al. [17] solved a multi-objective optimization problem using a teaching-learning-based optimization algorithm, while considering three objectives, i.e., carbon emissions, operation time, and machining cost. Likewise, Jiang et al. [18] developed a multi-objective optimization model for simultaneous minimization of carbon emissions and cost in turning and solved it with the application of NSGA II. Trifunović et al. [19] developed a constrained Pareto optimization model of multi-pass turning of grey cast iron for simultaneous minimization of unit production cost and consumed energy. The Pareto sets for roughing and finishing, containing optimal values of cutting speed, depth of cut, feed rate and number of passes, were determined using a brute force optimization algorithm. Sahali et al. [20] proposed a robust multi-objective optimization model for simultaneous minimization of manufacturing cost and maximization of production rate, while considering uncertainties of uncontrollable and noise factors in multi-pass roughing and finishing operations in turning. Probabilistic NSGA-II was used for the determination of Pareto fronts. Amorim et al. [21] proposed a multi-objective optimization approach based on models, derived using response surface methodology, and a normal boundary intersection algorithm for simultaneous minimization of unit manufacturing cost, tool life, and minimal variance for both responses. The proposed approach was illustrated while solving two case studies, i.e., the hard turning of AISI52100 steel and AISI H13 steel using CC6050 and CC670 mixed ceramic inserts. La Fé Perdomo et al. [22] proposed a constrained multi-objective optimization model by considering manufacturing cost, CO_2emission, and operational safety as objective functions for the multi-pass turning of AISI 1045 steel. NSGA-II algorithm was applied to determine the most sustainable machining conditions. Radovanović [23] studied the multi-objective optimization of material removal rate and machining cost in turning AISI 1064 steel using a carbide cutting tool. Optimal machining conditions, in terms of cutting speed, feed rate and depth of cut, under the presence of five process constraints, were determined using three optimization algorithms, i.e., iterative search, genetic algorithm and multi-objective genetic algorithm (MOGA). Widhiarso and Rosyidi [24] developed a multi-objective optimization model for the minimization of manufacturing cost and environmental impact, measured using the Eco-indicator 99 score, in the turning of AISI 1045 carbon steel. The model considered feed rate and cutting speed as decision variables, surface roughness, cutting force and cutting power as process constraints and was solved using OptQuest of Oracle Crystal Ball software. Pujiyanto et al. [25] proposed a multi-objective optimization model for multi-pass turning processes, while considering five objective functions (total energy, surface roughness, total noise, total cost, and carbon emission) and four decision variables (depth of cut, feed rate, cutting speed and number of passes). A set of non-dominated machining parameter combinations towards sustainable machining was determined using MOGA, while the final solution was selected with the application of the TOPSIS method. Pangestu et al. [26] proposed an analytical optimization model for multi-pass turning of AISI 1045 carbon steel for simultaneous minimization of energy consumption, carbon emissions, manufacturing time and manufacturing costs. The model considered spindle speed, feed rate, depth of cut and number of passes as decision variables and several constraints (tool life, cutting force, cutting power, chip-tool interface temperature, stable cutting region, surface roughness, and machining parameter relations). The optimized machining conditions were determined using MOGA, while sensitivity analysis was applied to analyse the effects of decision variables on objective functions.

As could be observed from literature review, improving machining efficiency, including manufacturing cost minimization, necessitates carefully planned experiments, supported by appropriate modelling and optimization methods. However, there are no universal or generally accepted rules for selection of these methods [27]. In addition, in contemporary manufacturing, the integration of the Internet of Things (IoT), machine learning models, big data analytics, and advanced sensors integrated into machine tools enables continuous monitoring and optimization of manufacturing processes [28]. The goal of the present study is to analyse the optimized total and specific manufacturing costs in medium longitudinal turning of C45E steel (1.1191; AISI 1045) using coated carbide inserts. For determining the optimized machining conditions, a single-objective optimization model with constraints (inequality constraint for cutting power and interval constraint for chip slenderness ratio) was proposed and solved using a generalized reduced gradient (GRG) algorithm. To this aim, based on conducted experimental research, a dimensional analysis-based model for cutting force prediction was developed, while the Taylor model, developed based on collected data from referential literature, was used for estimating the tool life. In order to analyse total and specific manufacturing costs, as well as a share of cutting insert cost and labour and overhead cost under optimized machining conditions, four machining operations with different volumes of material to be removed, performed using lathes with different available cutting power and two alternative coated carbide inserts were considered. Moreover, an analysis of the share of cutting insert cost and labour and overhead cost, as well as their ratios, under optimized cutting conditions was performed.

2 CASE STUDIES

The estimation of total manufacturing cost was carried out in the following way. Namely, through integration of two objective functions proposed in previous research [29], i.e., production rate (τ) and tool life consumed during machining (ε) and using case-specific parameters and constants, one can estimate tool cost (c_t) and labour and overhead cost (c_{lo}), i.e., total manufacturing cost (c_{tot}). Practical constraints related to the technical limitations of the used machining system, as well as the machining process, should be considered in optimizing manufacturing costs [10, 12]. Therefore, in order to ensure stable cutting conditions and favourable chip form [30], as well as to consider the given lathe cutting power capacity, two process constraints were introduced: allowable cutting power (P) and chip slenderness (ξ). Therefore, a single-objective optimization model with constraints for the analysis of optimized total manufacturing cost is proposed in the following form:

$$\text{Minimize:} c_{\text{tot}} = \varepsilon \cdot \frac{c_{\text{ins}}}{n_{\text{ce}}} + \tau \cdot c_{\text{slo}} = c_{\text{t}} + c_{\text{lo}}$$

$$\text{Subject to:} P = \frac{F_{\text{c}} \cdot v}{6 \cdot 10^3} \le P_{\text{M}} \cdot \eta \tag{1}$$

$$\xi_{\min} \le \frac{a_p}{f} \le \xi_{\max}$$

where c_{tot} (EUR) is total manufacturing cost, c_{ins} (EUR) is cutting insert cost, c_{t} (EUR) is tool cost, c_{lo} (EUR) is labour and overhead cost, n_{ce} is the number of cutting edges, c_{slo} (EUR/h) is specific labour and overhead cost, P (kW) is the maximal allowable cutting power, v (m/min) is cutting speed, F_{c} (N) is the main cutting force, P_{M} (kW) is lathe motor power, η is transmission efficiency and $\xi_{\min}$ and $\xi_{\max}$ are minimal and maximal preferable chip slenderness ratios, respectively, which depend on workpiece material being machined. Minimal and maximal preferable chip slenderness ratios for steel C45E are $\xi_{\min} = 4$ and $\xi_{\max} = 16$ [31].

The experiment in a dry medium longitudinal turning of C45E steel (tensile strength of R_m = 680 N/mm^2) was realized using Sandvik Coromant PCLNR 3225P 12 tool holder (cutting edge angle of κ = 95°, rake angle of γ_{oh} = –6°) with cutting inserts PrametCNMG 120408E-NF T8430 (nose radius r_ε = 0.8 mm, γ_{oi} = 25°) and Prame tCNMG 120408E-SF T8430 (r_ε = 0.8 mm, γ_{oi} = 14.5°). Chemical composition of the workpiece material is shown in Tab. 1. It has to be noted that although dry turning is environmentally cleaner, the deterioration of machined surface quality and shorter cutting tool life are the main drawbacks [32]. The experiment was performed on POTISJE PA-C 30 universal lathe using round bars of 60 mm in diameter and 250 mm in length.

Table 1 Chemical composition of the C45E steel

Chemical composition / %					
C	Mn	Si	Cr	Ni	Cu
0.4653	0.6947	0.1182	0.0859	0.0734	0.1783

In the present study, the cutting force was estimated by using the dimensional analysis-based prediction model developed using the methodology described in the literature [33]. The developed multiplicative power model was defined in terms of three dimensionless groups (cutting speed to feed velocity ratio, chip slenderness ratio and cutting edge angle to rake angle ratio). It should be noted that in the realization of the experiment for estimating model unknown coefficients, depth of cut, feed rate, and rake angle were varied, while cutting speed and cutting edge angle were kept constant. Likewise, for the estimation of production rate (τ) and tool life consumed during machining (ε), tool life in the form of the Taylor model was developed using the available experimental data [34]. Finally, in order to analyse total and specific manufacturing cost, under optimized machining conditions, four machining operations with different volumes of material to be removed (V_1 = 84 cm^3, V_2 = 154 cm^3, V_3 = 210 cm^3 and V_4 = 253 cm^3) were considered. This corresponds to multi-pass roughing with a start diameter of 80 mm, machining length of 60 mm, and different end diameters (D_1 = 68 mm, D_2 = 56 mm, D_3 = 44 mm, and D_4 = 32 mm). In the analysis, two lathes with different power levels were considered: lathe M1 (HAAS ST-10) with the motor power of P_{M1} = 11.2 kW, and lathe M2 (HAAS ST-20) with the motor power of P_{M2} = 14.9 kW.

The values of other constants, which figure in the proposed constrained turning optimization problem, case study-specific data, and value ranges of machining parameters, are given in Tab. 2. The developed constrained single-objective turning optimization model was solved using a generalized reduced gradient (GRG) algorithm. This algorithm was chosen as being perceived as one of the most robust and reliable for solving non-linear optimization problems [35]. It is a gradient-based algorithm in which the objective function, to be minimized or maximized, and imposed constraints can have a nonlinear nature [36]. The search direction during the optimization process is usually guided by using a quasi-Newton method [37]. The applied experimental, modelling and optimization approach for the analysis of optimized total and specific manufacturing costs in medium longitudinal turning of C45E steel is illustrated in Fig. 1.

Table 2 Optimization model parameter data

Parameter	Value	Parameter	Value	Parameter	Value
c_{ins}	11.16 EUR	c_{slo}	30 EUR/h	v*	246 m/min
n_{ce}	4	τ_{s}	0.15 min	η	0.8
τ_{TC}	0.5 min	τ_0	$i \cdot 0.024$ min	i**	2, 4, 6, 8

τ_{s} - setup time, τ_{TC} - cutting tool change time, η - motor efficiency, i - number of passes, τ_0 - tool idle time

* Cutting speed (v) is considered constant, given that in the experiment for cutting force modelling, it was not considered as an influential parameter.

** The number of passes is dependent on the volume of material to be removed. For V_1 number of passes is assumed as 2.

Range of machining parameters:

PrametCNMG 120408E-NF T8430: depth of cut, a_p = [0.8, 3.5] mm, feed rate, f = [0.15, 0.35] mm/rev, cutting speed, v = [160, 325] m/min

PrametCNMG 120408E-SF T8430: depth of cut, a_p = [0.8, 3] mm, feed rate, f = [0.12, 0.3] mm/rev, cutting speed, v = [149, 337] m/min

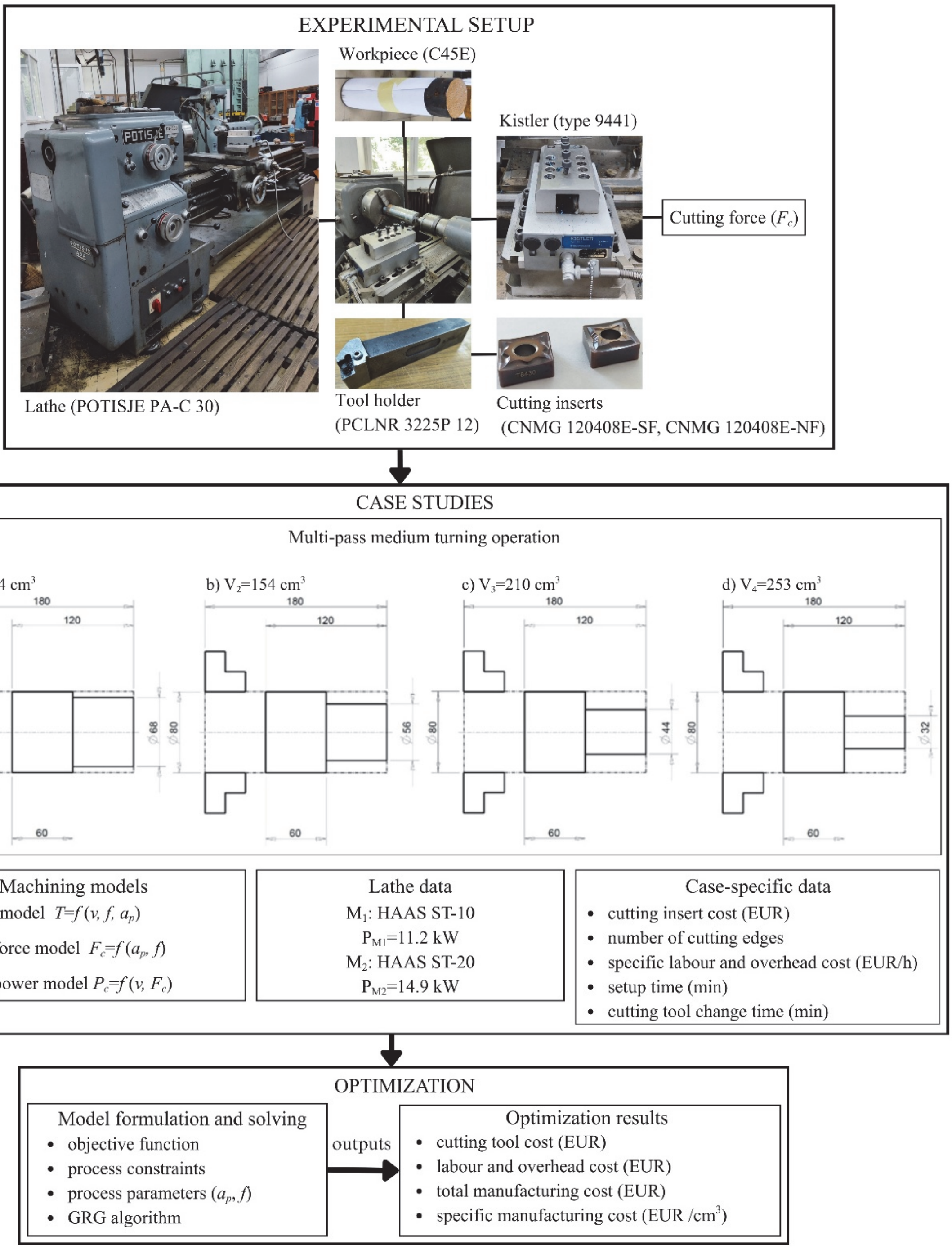


Figure 1 Scheme of the applied experimental, modelling and optimization approach

3 RESULTS AND DISCUSSION

Tab. 3 gives the optimized machining conditions for minimal total manufacturing cost in the medium longitudinal turning of C45E steel for both cutting inserts and lathes with different power levels determined using GRG algorithm.

If one uses CNMG 120408E-SF cutting insert, optimized machining conditions for both lathes are the same. Namely, due to the smaller ranges of the depth of cut and feed rate values, lathe M1 (HAAS ST-10) has enough available cutting power to use more intensive machining regimes. On the other hand, machining regimes that can be used according to the recommendations for the CNMG 120408E-NF cutting insert can only be fully realized using lathe M2(HAAS ST-20), which has more cutting power available. It can be concluded that, for a given case study condition, the optimal machining parameter combinations for minimal total manufacturing costs are characterized by higher material removal rates, constrained by the allowable cutting power of the used lathe.

Table 3 Optimal machining parameter combinations for minimal total manufacturing cost

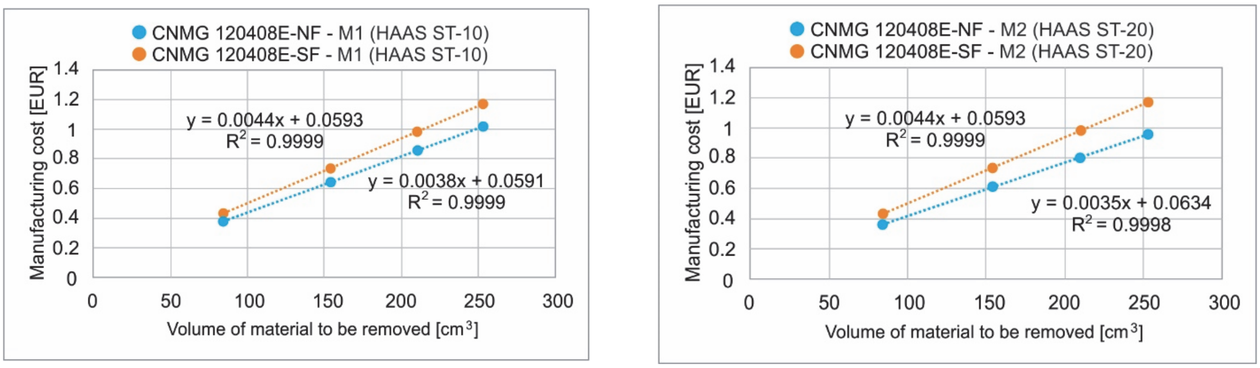
Cutting parameters	CNMG 120408E-Nf cutting insert		CNMG 120408E-Sf cutting insert	
	Lathe M1 (11.2 kW)	Lathe M2 (14.9 kW)	Lathe M1 (11.2 kW)	Lathe M2 (14.9 kW)
a_p / mm	3.5	3.5	3	3
f / mm/rev	0.313	0.35	0.3	0.3

From the aspect of the cutting tool used, material removal rates are directly related to cutting tool life. However, considering the ratio between cutting tool costs and labour and overhead costs, the optimal machining regimes from the standpoint of manufacturing costs tend to shift toward more intensive machining conditions with higher material removal rates, regardless of the significantly reduced tool life. On the other hand, it can be shown that the highest manufacturing cost corresponds to the use of the smallest allowed feed rate and depth of cut, and, compared to the optimal machining conditions, they yield five to six times higher manufacturing costs for different volumes of material to be removed. Likewise, in comparison to the optimized machining conditions, the recommended machining regimes not only do not fully exploit the lathe's motor capacities, but may result in manufacturing costs that are approximately two times higher in the present case studies.

It should be emphasized that the optimal machining parameter values for both cutting inserts are the same for all volumes of material to be removed. However, as one might expect, as the volume of material to be removed is increased, manufacturing costs increase. Actually, under optimized conditions, there is a linear relationship between manufacturing costs and the volume of material to be removed (Fig. 2).

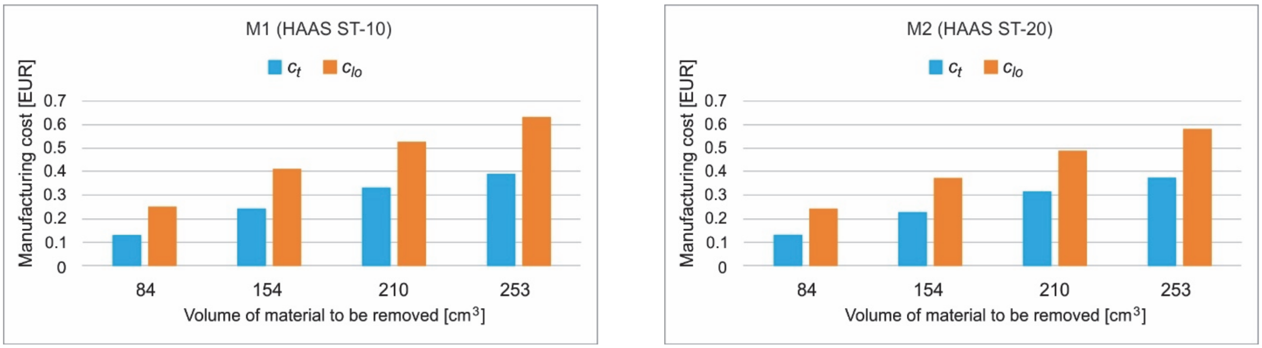
From Fig. 2, it can be observed that if the CNMG 120408E-SF cutting insert is used and the optimal machining regimes are determined and applied, the use of a lathe with higher cutting power does not ensure additional manufacturing cost reduction. On the other hand, the use of CNMG 120408E-NF cutting insert and a lathe with a higher available cutting power, in optimized machining conditions, reduces manufacturing costs by about 5-7%, depending on the volume of material to be removed.

For minimal total manufacturing costs and different volumes of material to be removed, the share of cutting insert cost (c_t) and labour and overhead cost (c_{lo}) for both cutting inserts and lathes are given in Fig. 3.

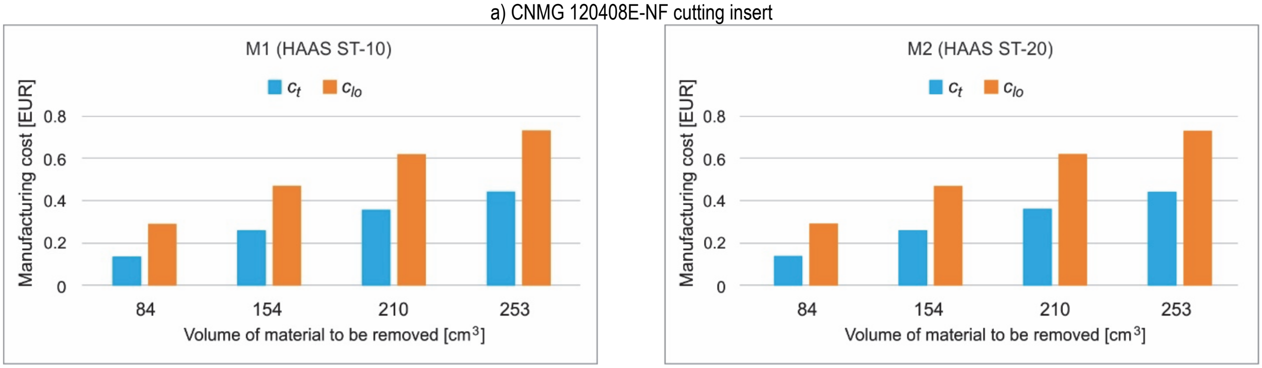


a) Lathe M1 (P_{M1} = 11.2 kW) b) Lathe M2 (P_{M2} = 14.9 kW)

Figure 2 Dependence of the total manufacturing cost on the volume of material to be removed under the optimized machining conditions



a) CNMG 120408E-NF cutting insert

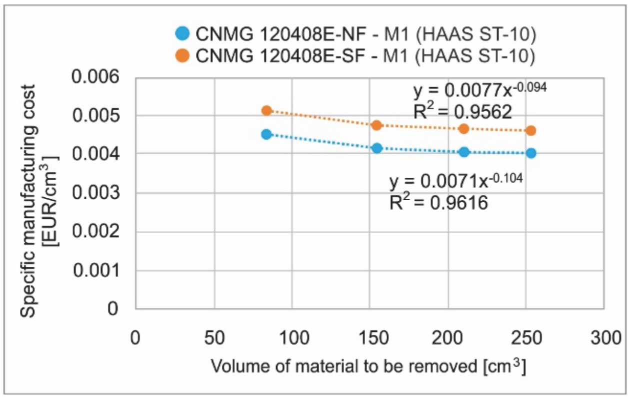


b) CNMG 120408E-SF cutting insert

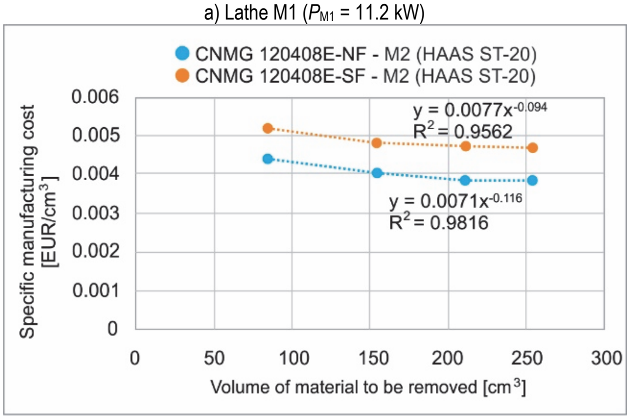
Figure 3 Share of cutting insert cost (c_t) and labour and overhead cost (c_{lo}) under the optimized machining conditions

As could be observed from Fig. 3, cutting insert costs are lower than labour and overhead costs. Previous analyses of cutting tool costs confirm that, in general, the cost of an individual insert represents a relatively smaller share of the total manufacturing cost [38]. Consequently, it could be observed that for both cutting inserts, with an increase in the volume of material to be removed, not only does total manufacturing cost increase, but also the ratio of cutting insert cost and labour and overhead costs, which ensures the lowest manufacturing cost. For the CNMG 120408E-NF cutting insert, this ratio starts from 0.52 for lathe M1(HAAS ST-10) or 0.54 for lathe M2(HAAS ST-20) for the smallest volume of material to be removed and goes up to 0.62 for lathe M1 or 0.66 for lathe M2 for the largest volume of material to be removed. It can therefore be concluded that a lathe with more cutting power available ensures this higher ratio and consequently reduces the total manufacturing costs. In the case of CNMG 120408E-SF cutting insert, this ratio ranges from 0.48 for the smallest volume of material to be removed to 0.6 for the largest volume of material to be removed and is constant for both lathes.

If one divides the total manufacturing cost by the volume of material to be removed, one can estimate the total specific manufacturing cost. These costs for both cutting inserts and both lathes, in optimized cutting conditions, are given in Fig. 4.



a) Lathe M1 (P_{M1} = 11.2 kW)



b) Lathe M2 (P_{M2} = 14.9 kW)

Figure 4 Dependence of the total specific manufacturing cost on the volume of material to be removed for optimized cutting conditions

As could be observed from Fig. 4, with an increase in the volume of material to be removed, there is a decrease in specific manufacturing costs by the power model for both cutting inserts and lathes. This decrease can be attributed to the fact that the non productive time does not increase proportionately with the weight of the component or volume of the material to be removed [39]. Analysis of Fig. 4 indicates that, under optimized machining conditions, a lathe with higher available cutting power provides greater cost efficiency. However, an even more significant potential for manufacturing cost reduction arises from the appropriate selection of cutting inserts.

4 CONCLUSION

The present study was focused on the analysis of total and specific manufacturing costs in medium longitudinal turning of C45E steel under optimized machining conditions. Four machining operations with different volumes of material to be removed were considered. The operations were performed using two lathes with different available cutting power, and two alternative coated carbide inserts. Based on obtained optimization results and conducted analyses, the following conclusions can be drawn:

- Minimal total manufacturing costs are ensured by increasing the ratio of cutting insert cost, and labour and overhead costs. For the studies considered, the optimal ratio is 0.5 and above. It can therefore be concluded that a lathe with higher cutting power available offers better compromise solutions, in terms of machining parameter values, ensures this higher ratio, and consequently reduces the total manufacturing costs.
- Choosing the right cutting insert, preferably with a larger range of allowable values of machining parameters, makes a big difference and the possibility of making cost savings in relation to the selection of a particular lathe. In fact, the key is matching the appropriate cutting tool and the available lathe in a job shop.
- The relationship between the volume of material to be removed and total manufacturing costs follows a linear model, while the relationship between the volume of material to be removed and specific manufacturing costs follows the power law curve.
- Although cost savings due to cutting insert and lathe selection may be limited, determining optimal machining conditions offers significant savings compared to a process that would be realized by implementing arbitrarily chosen machining regimes.
- The cost estimate may, to a greater or lesser extent, depend on the labour and overhead costs, the available cutting tools, and the purchase price of the cutting tool, so there may be certain deviations in cost analysis from company to company.
- It can be shown that, if cutting speed would also be considered as an optimization variable, the optimized machining conditions would correspond to higher values of feed rate and depth of cut along with lower values of cutting speed, and would provide even lower total manufacturing costs (on average about 7% in the case of the CNMG 120408E-NF cutting insert and 3% in the case of the CNMG 120408E-SF cutting insert, for all volumes of material to be removed). Cutting speed affects cutting power, which is one of the process constraints. It also affects material removal rate and tool life, which are present in the production rate and tool life consumed during machining models. It has a positive correlation with the material removal rate and negative correlation with the tool life. However, the effect of the cutting speed on tool life is noticeably more pronounced compared to the effect on material removal rate.

The main limitation of the study is that the cutting speed was not considered as an optimization variable. The cutting speed had a constant value because its influence on the main cutting force is very small. As mentioned earlier, by considering the cutting speed as an optimization variable, the optimized machining conditions would provide even lower total manufacturing costs.

The planned future study will consider manufacturing costs analysis, taking into account several workpiece materials from different machinability groups and other parameters, taken as constants throughout the current study.

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