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Analysis of the compromise between cutting tool life, productivity and roughness during turning of C45 hardened steel

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Abstract

Tool wear and surface roughness as performance indexes are considered to be the most important in terms of hardened materials' machinability. The best combination of cutting parameters which enhances the compromise between tool life, productivity and machined surface quality contribute to benefice on production cost, which makes manufacturing industry interested in it. The aim of this research is to investigate the life of ceramic cutting tool and machining productivity together with surface roughness during turning of hardened steel C45, with focus on the selection of the optimal cutting parameter combination. The experiments are carried out based on uni-factorial planning methodology of cutting speeds and feed rates. The results show that the mixed ceramic tool is suitable for turning hardened steel C45 (40 HRC) and the conclusion is that it performed well in terms of tool life, productivity and surface quality at a combination of cutting speed (200 m/min), feed (0.08 mm/rev) and depth of cut (0.3 mm). Additionally, a tool life model has been proposed which is presented very high coefficient of determination.

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1. Introduction

In recent years, hard turning which uses a single point cutting tool has replaced grinding to some extent in order to limit machining time consuming and produce a large range of geometries. This attention to hard machining was imperatively accompanied by continuous improvements in tool quality and choice of cutting conditions. It has led to the introduction of extremely hard tools such as ceramics and cubic boron nitride (CBN) on the one hand, and optimization of cutting conditions on the other. Machining of hardened steel is of immense importance for present day industrialized research due to its good machinability, but this performance is affected by such issues as, for example, tool wear.

The tool wear results from friction which causes high temperature at interface tool-chip-workpiece during dry hard machining (Grzesik, 2008). This important technological characteristic is commonly used to evaluate cutting performance, which makes it the main preoccupation for the most researchers in order to increase production and reduce the cost. Some researchers are interested in studying the parameters influencing tool wear, others in studying the wear natures, while others are interested in tool life modeling.

Different wear mechanisms can be developed on tool cutting edge during machining of hardened materials caused by some parameters as temperature which generated under the effect cutting conditions. The magnitude of the temperature at interfaces tool-chip- workpiece can cause a wear mechanism to change from abrasion to adhesion or from adhesion to diffusion wear process (Bhattacharya, 2004). Generally, abrasion, adhesion, and diffusion are considered to be the main tool wear mechanisms in CBN hard turning (Huanget al., 2007). This is confirmed also by Chinchanikar et al. (2015) and explaining that the abrasive wear as more prominent for harder and adhesive wear for the softerworkpiece.

Industry is much more interested in a longer tool life in order to maximize production. As the rapid wear of cutting tool leads to tool life decrease and influences the integrity of the machined surface (Kumar et al., 2017), thus, its reduction will improve the productivity and quality. Therefore, the important machining conditions that must be optimized are the cutting parameters (speed, feed and depth).

Generally, a significant cutting parameter which affects tool wear development in hard turning is cutting speed (Das et al., 2015; Alok et al., 2019) which influences the tool life and the removed material volume when it affects the flank wear mechanism by abrasive phenomena (Attanasio et al., 2012; Abidi et al., 2018). It is similar to the findings of Benga et al., (2003). Motorcu (2011) found that cutting speed followed by cutting tool's hardness have the greatest effects on tool life. Fnides et al., (2013) ascertains that cutting speed influences tool life more significantly than the feed rate. Gordon et al., (2019) claims that flank wear rate grows with increasing cutting speed, but crater depth decreases with increasing speed when hard turning using polycrystalline cubic boron nitride (PCBN) tool.

In another research, Poulachon et al., (2001) discovered that tool life depends on the cutting parameters and workpiece hardness. Subbaiah et al., (2019) later found out that workpiece hardness is the major parameter affecting tool wear. Gaitonde et al., (2009) presented the performance of the ceramic tool in hard turning, they found that the mixed ceramic tool (CC650 type) managed to get good surface qualities when machining at shallow depth of cut and machining times.

Moreover, it has been observed that a significant emphasis has been placed by researchers on modeling of wear tool which is related to tool life. Huang et al., (2007) presented a generalized relation of the flank wear and crater wear in function wear types, tool geometry, tool hardness, part hardness, cutting speed, cutting forces and temperature at the tool-workpiece interface. From experimental tests, several researchers have developed prediction models giving the wear as function of cutting parameters, workpiece hardness and tool hardness during hard turning (Gaitonde et al., 2009; Rathod et al., 2017; Mir et al., 2018). Others offer models for tool life (Chinchanikar et al., 2013; Varaprasad et al., 2014; Abidi et al., 2017).

It has been observed that researchers are more and more focused on the tool wear study in order to ensure maximum performance in hard machining.

In the present study, the influence of cutting speed and feed rate on the wear of mixed ceramic tool and chip removal when turning of hardened steel C45 (40HRC) are analyzed in order to optimize the combination of cutting parameters to benefit on production cost.

2. Experimental work

2.1. Materials

Experiments operations of dry turning are conducted on a SN40 parallel lathe machine which has a maximum spindle speed of 2000 rpm and a maximum power of 6.6 kW. Wear follow-up was achieved using an optical Hund (W-AD) microscope equipped with a digital display and a color charge-coupled device camera, with 1μm precision. The type of cutting tool used was mixed alumina ceramic with an Al_2O_3 (70%) and TiC (30%) matrix, which is designated by CC650 and manufactured by Sandvik. The cutting inserts are removable and offered eight squared working edges of ISO designation SNGN 120408. Geometry angles of inserts: nominal rake angle −6°, back rake angle −6°, clearance angle 6°, approach angle 75° and 0.8 mm nose radius. The insert was rigidly attached to a tool holder of ISO designation of PSBNR2525M12.

The material used throughout this investigation was a C45 steel (according to DIN standard), it is classified as unalloyed tool steel, containing C (0.45%), Mn (0.72%), Si (0.24%), Cr (0.09%), Ni (0.06%), Ti (0.01%) and Fe as balance. This steel is commonly used in mechanical engineering for various uses (molds for plastic material, several pieces for automotive sector, axes, gears...).

Hardening of the material has been achieved on a round bar blank of 60mm diameter and 400 mm length by austenization at 850°C for 30min, quenched in water bath and then tempering at 200 °C (Fig.1). The steel hardness is increased from 220 HB to 40 ∓ 1 HRC.

The overview of the experimental setup, measurement process and analysis procedure is presented in Fig.2.

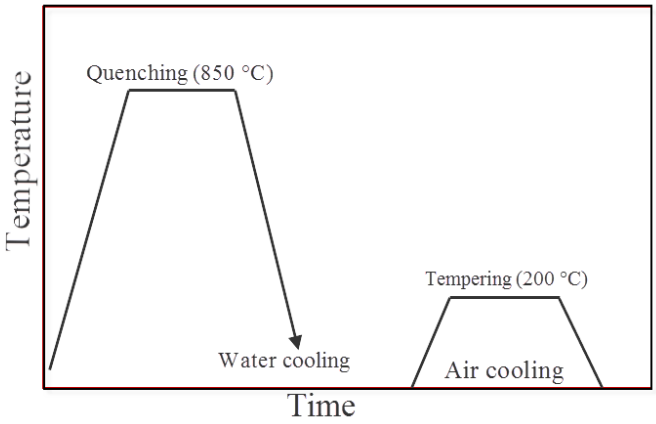

Fig. 1. Heat treatments cycle for Experimental material

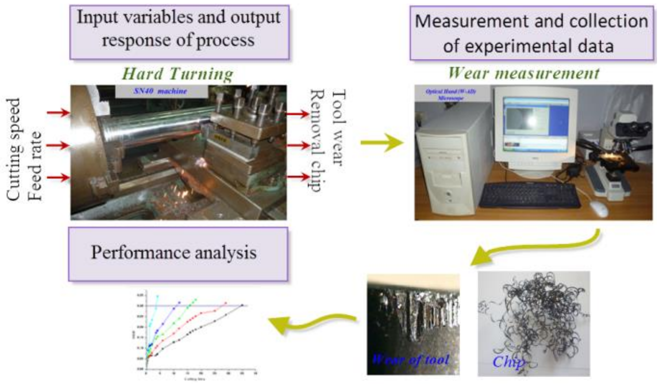

Fig. 2. The flowchart for modeling of hard turning parameters

2.2. Experimental design

The main aim was the determination of the lifetime of the cutting tool and, then, selecting the best cutting parameters combination tool life with productivity. The latter has been conducted using uni-factorial experiment plan where the independent variables were cutting speed and feed rate. The depth of cut is maintained constant with a small value equal to 0.3 mm; this value was selected from previous studies (Abidi et al., 2017). Table 1 summarizes the cutting conditions. The experiments were carried out to analyze the influence of speed and feed on tool life for turning hardened C45 steel. The procedure to determine tool life from wear evolution is shown in Fig.3. The wear behavior of the mixed ceramic CC650 was assessed on the basis of allowable flank wear limits of [Vb] = 0.3mm.

Table 1. Uni-factorial plan for mixed ceramic (CC650) wear investigation (depth of cut, D =0.3 mm)

Cutting parameters	Unit	Levels of parameters				
Cutting speed (*V*)	m/min	140	200	200	200	280
Feed rate (*f*)	mm/rev	0.08	0.08	0.16	0.22	0.08

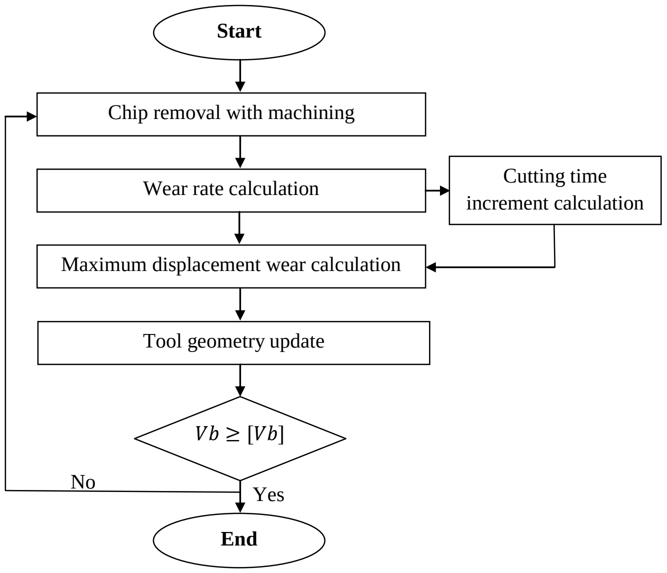

Fig. 3. Procedure for predicting the tool life

3. Results and discussion

3.1. Tool wear effect

Wear is a machining technological parameter which is commonly used to evaluate the performance of a cutting tool. It has influence on the machined surface quality and productivity. Additionally, as wear phenomenon, it is extremely complex due to the interaction of numerous parameters, and, therefore, inspired much scientific interest. Hence, the target of this investigation is to determine the impact of cutting parameters (cutting speed (*V*) and feed rate (*f*)) variation, on mixed ceramic tool wear when dry turning of hardened steel C45. Depth of cut is maintained constant with a small value (equal to 0.3 mm) to neglect its effect on surface quality machined as suggested in the references (Varaprasad et al., 2014; Abidi et al., 2017).

The main wear focus is a flank wear because it is developed in all conventional cutting operations and its direct impact on the machined surface quality. It has also been observed that the influence of workpiece hardness on the crater wear becomes very limited as it reaches 45 HRC (Tang et al., 2019).

Fig. 4 shows the flank wear rate changes with time at different cutting speeds (low, medium and high), feed is kept constant at 0.08 mm/rev. Firstly, it is remarkable that wear is proportional to the machining time. Secondly, the wear increased slowly for low and medium speed (140 and 200 m/min) at a steady rate until a wear limit reached ([Vb] = 0.3 mm) comparing to high cutting speed (280 m/min). The increase of the distance slid in a given machining time increased the abrasion between tool edge and hard workpiece when material particles are removed from the tool. The increase of cutting speed to higher level leads to higher temperature in the cutting zone (Alok et al., 2019) which means that activate tool wear due to drop of material tool hardness. Regarding the wear morphology, when the cutting speed increases, the abrasion streaks of the tool edge collapse become deeper which means that the loss of material on the flank face becomes important due to increase of abrasion aggressiveness. Only abrasion mechanism wear appeared when turning at 140 and 200 m/min cutting speeds, but under 280 m/min cutting speed, a small adhesive wear rate contributes with abrasion due to important increase of cutting temperature. These results are in good agreementwith the previous research (Rathod et al., 2018; Abidi et al., 2018; Augusto et al., 2011).

And as abrasive wear depends on the distance slid (in a given time), the reduction of the last one can be effective to control it. This can be achieved by increasing the feed. Therefore, the analysis of the impact of the feed rate on the tool wear is necessary.

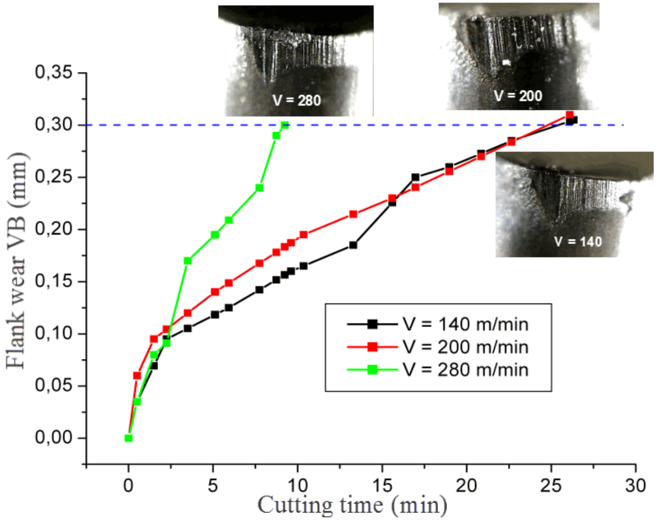

Fig. 4. Effect of cutting speed on flank wear in mixed ceramics (CC650) when turning of hardened steel C45 (*f* = 0.08 mm/rev and *D* = 0.3mm)

Fig. 5 shows the feed rate impact on the tool wear at the medium cutting speed (V= 200 m/min) and depth of cut is kept constant at 0.3 mm. It is remarkable that with increasing of feed, the cutting edge degradation increased and flank wear reached its limit faster. Regarding the wear morphology, the degradation in the tool nose occurs in the form of a cavity characterized by streaks and burns. This is in good agreement with results given in references (Bouchelaghem et al., 2010; Abidi et al., 2018).

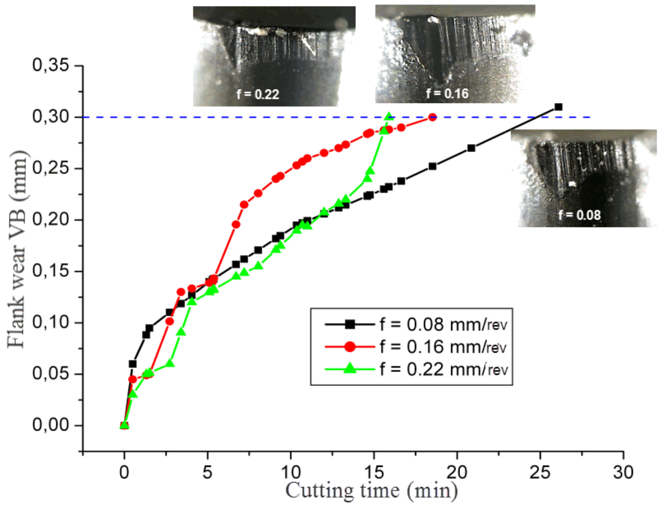

Fig. 5. Effect of feed rate on flank wear in mixed ceramics (CC650) when finish turning of hardened steel C45 (V = 200 m/min and D= 0.3 mm)

On the basis of results taken from Fig 4 and 5, the absence of chipping or breakage on the cutting edges at admissible flank wear, indicate that the ceramic tool CC650 is favorable for this level of machining, this is supported by its good thermal conductivity and chemical stability. This advantage concluded also by Saikaewet al., (2020).

3.2. Tool life effect

Tool life is the most common criterion used to rate cutting tool performance. Considering that the flank wear is the first tool life criterion (Subbaiahet al., 2019), the life of mixed ceramic CC650 was obtained by measuring the flank wear Vbmax. On the basis of allowable wear criteria [Vb] = 0.3 mm (Bouchelaghemet al., 2010).

The tool life values corresponding to the experimental design were gathered from Figs. 4 and 5, and presented in Table 2.

Table 2. Evolution of tool lifetimes (D =0.3 mm)

V (m/min)	*f* (mm/rev)	*T* (min)
140	0.08	25.41
200	0.08	24.78
280	0.08	9.24
200	0.16	18.5
200	0.22	15.9

It was noted that tool life is pronounced low for highest cutting speeds (280 m/min), while the tool lives for the speeds range 140 to 200 m/min are reconciled. Regarding speeds variation, tool life decreased only by about 2.5% while cutting speeds increased from 140 to 200 m/min, while it decreased by 63.6% when speed increased from 140 to 280 m/min. In regards to feeds variation, tool life decreased by about 36% while feed increased from 0.08 to 0.22 mm/rev.

It is remarkable that the wear is more influenced by cutting speed than by a feed rate, which complies with literature (Benga et al., 2003; De Godoy et al., 2011; Das et al., 2013; Alok et al., 2019), which means that the cutting speed has a substantial effect on tool life in comparison to feed rate. This result is clearly shown in the 3D surface plot of tool life (Fig. 6).

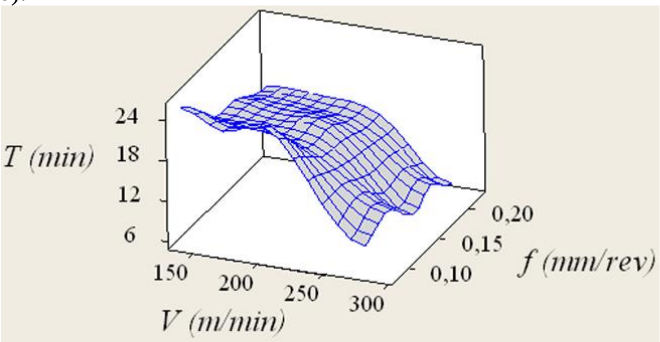

Fig. 6. Surface plot of Tool life vs cutting speed and feed rate

Fig. 6 showed the 3D surface plot of Tool life in function of cutting speed and feed rate. A remarkable fall of tool life when cutting speed increases double in comparison to tool life decreasing when the feed increases about triple.

Since tool life has a strong economic impact on production, the prediction of it is considered as an important goal for the manufacturing research. The most widely used tool life equation is the Taylor tool life equation.

$$VT^{n} = C \tag{1}$$

Where:

T: tool life (min), *V*: cutting speed (m/min), *n*: exponent determines the slope of the tool life curve, *C*: constant.

The first-order mathematical model can be written in the form:

$$Ln(T) = b_1 Ln(V) + b_0 \tag{2}$$

So, from experimental results are shown in Table 2, the prediction model becomes:

$$VT^{0.692} = 1461.47 \tag{3}$$

With: $R^2 = 76\%$.

The layer value of R^2 is desirable.

Equation 3 expresses the relationship between tool life and cutting speed. It reflects the dominant influence of the cutting speed on tool life define from basic Taylor Equation. However, it does not account for the smaller effect of the feed rate. Consequently, a multiple second order regression model was implemented at 95% confidence level to obtain the correlation between tool life and cutting parameters (Speed and feed). The equation is:

$$T = -0.374762 - 0.0013125V^2 + 251.19f^2 + 0.43575V - 138.786f \tag{4}$$

With: $R^2 = 100\%$.

The determination coefficient R^2 value confirms the suitability of the multiple regression equation and correctness of the calculated constants. It implies agreement with experimental results.

3.3. Material removal rate effect

The material removal rate (MRR) was considered as the factor directly affects the machining cost through the machining time rate. The economists' objectives are to maximize it in order to improve the productivity. MRR is the amount of material erosion from the workpiece per time unit. It is given by the Equation:

$$MRR = V \cdot f \cdot D \tag{5}$$

Where:

MRR: material removal rate in (cm^3/min).

At the equation 5 basis and as depth of cut is constant, MRR is linearly related to both feed rate and cutting speed.

And we can also deduce the equation giving the MR:

$$MR = MRR \cdot T \tag{6}$$

Where:

MR: total material removal during tool life in (cm^3).

Fig. 7 shows the variation of MRR and MR in function of cutting parameters combinations. It can be observed that increasing speed or feed leads to increased *MRR*. As seen also by comparing between cutting conditions, the MMR growth rate between two conditions is equivalent to the multiplication of the growth rates of cutting speed and feed rate. For example, between the condition (V, f) equal to (280, 0.08) and the condition (200, 0.22), the MRR growth rate equals to:

$$MRR = (6.72/13.2) = 0.509 = \\ (280/200) \cdot (0.08/0.22) = 1.4 \cdot 0.3636 = 0.509 \tag{7}$$

Therefore, a trade-off exists between tool life and Material Removal (MR) with taking into account the cutting parameters. The lowest MR is recorded at the lowest tool life although the cutting speed was high. It can be seen that MR is linearly related to feed rate at constant cutting speed.

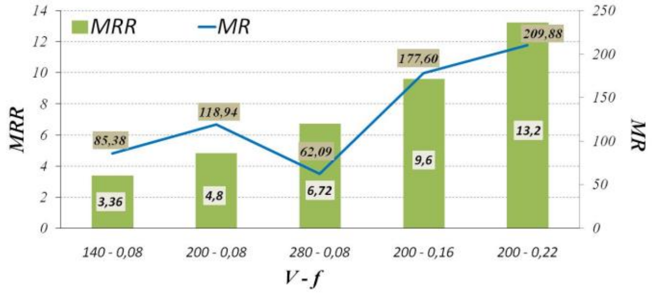

Fig. 7. Effect of cutting parameters on MRR and MR

3.4. Best cutting parameter combination

The best tool lifetime is considered for cutting speeds V = 140 m/min and V = 200 m/min with feed rate f = 0.08 mm/rev. On the other hand, the best surface quality is recorded for the medium cutting speed value which equivalent to V = 200 m/min as reported by Abidi et al., (2017), with feed rate equivalent to 0.08 mm/min which favors the formation of fragmented helical chip leads to a best machined surface quality (Abidi, 2020). The machining productivity defined by the flow of removal chip at the cutting combination V = 200 m/min, f = 0.08 mm/rev and D = 0.3 mm is about 119 cm^3, this value is more than 40% compared to cutting condition V = 140 m/min, f = 0.08 mm/rev and D = 0.3 mm which could reduce the total machining cost by 30%. Hence, the best cutting parameter combination that can be selected is 200 m/min, 0.08 mm/rev and 0.3 mm for cutting speed, feed rate and depth of cut respectively.

4. Summary and conclusion

The present work aims to determine the best cutting parameter combination improving the performance of mixed ceramic tool (70% Al_2O_3 + 30% TiC) when turning of hardened steel C45 (40 HRC) in term of tool life and productivity as well as their correlation with machined surface quality. From this study, following conclusions could be drawn:

- Mixed ceramic tool (CC650) has given a good performance in machining of the hardened C45 steel (40HRC) regarding tool life and surface quality which is very competitive for the grinding.
- It has been proven that tool wear is more affected by cutting speed than feed rate.
- The main wear mechanism of the mixed ceramic tool was abrasion at low and medium cutting speed but at high cutting speed it found that the abrasive wear contributed with small quantity of adhesive wear.
- Accelerated tool wear at high cutting speed (280 m/min) translated by an important reduction in tool life will limit the tool productivity. Tool life drops by about 270% when cutting speed increased by 40% from 200 m/min to 280 m/min.
- The domination of abrasive wear mechanism with absence the chipping or breakage on the cutting edges indicate that the mixed ceramic tool CC650 is favorable for this machining conditions.
- The relationship between machining parameters (cutting speed and feed rate) and tool life are expressed by a multiple quadratic regression model. R^2 value for response is equivalent to unity which ensures an agreement with actual results.
- The best combination of cutting conditions (V = 200 m/min; f = 0.08 mm/rev; D = 0.3 mm) resulted in a good tool life and best productivity with a good machined surface quality.

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C45淬火钢车削时刀具寿命，生产率和粗糙度之间的折衷分析

關鍵詞

相关性 硬加工 工具磨损

生产率 表面粗糙度

摘要

刀具磨损和表面粗糙度被认为是性能指标，对硬化材料的可加工性更为重要。它们在制造业中具有极大的实际意义，这意味着固定切削参数的最佳组合可增强工具寿命，生产率和机械加工表面质量之间的折衷，从而有助于提高生产成本。本文旨在通过混合陶瓷工具车削淬硬钢C45时实现这一目标。为此，采用了实验性单因素计划方法，其切削速度和进给是变量，而刀具磨损，刀具寿命，生产率和表面质量则是响应。结果表明，该混合陶瓷刀具适用于车削C45（40 HRC）淬硬钢，并得出结论，在切削速度（200 m / min），进给量（ 0.08毫米/转）和切深（0.3毫米）。另外，提出了一种刀具寿命模型，该模型具有很高的确定系数。