Parametric Optimization and Modeling for Flank Wear of TiSiN-TiAlN Nanolaminate Cutting Insert

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ABSTRACT

Selection of machining parameters and better prediction for cutting tool flank wear is indispensable in hard machining as flank wear is directly influences the quality of machined surface. In the current study, parametric optimization and predictive model were carried out for the flank wear of TiSiN-TiAlN nanolaminate cutting insert in hard turning of 58 HRC AISI 1045 medium carbon steel which is an unexplored area. Taguchi's method was employed for parametric optimization and predictive model was established for flank wear by response surface methodology (RSM) based regression analysis. Cutting speed: 40m/min, feed rate: 0.3 mm/rev and depth of cut: 75 µm generates optimum value of flank wear 0.07 mm. In conclusion, verification test was carried out to validate the optimal set of parameters and the result was shown a great reduction of 81.42% in the flank wear. The predictive model elaborated for flank wear was dependable and helps to make better prediction to the manufacturing industries within specified range of the experimentation.

Keywords: *Flank wear; Taguchi method; RSM based Modeling; optimization; Nanolaminate cutting insert.*

Introduction

The highest importance has been given to surface quality of the machined parts as it plays a crucial role in the functioning of the parts. Surface roughness during machining is mainly due to the cutting tool geometry and cutting environment. Tool wear is an added factor for influencing surface finish of work piece in hard turning process where the cutting tool deals with

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already hardened material [1, 2]. To improve the surface quality, a cutting tool ought to have certain properties like good wear resistance, mechanical strength and thermal stability. In the process of achieving these, tool substrate material, type of surface coating material and method of coating are very important. As the work piece material hardness increases, selection of cutting tool material is more significant. Usually, cubic boron nitride (CBN) tipped (HRC > 60), ceramic materials (50-55 HRC) and carbide (up to 50 HRC) tools are choices for hard turning [2-6]. On demand of cost effectiveness and eco-friendly environment, manufacturing industries inclining towards coated carbide tools. Nevertheless, during machining of harder materials, higher temperatures are generated due to the higher cutting forces which cause higher tool wear. There are different tool wears that exists during turning, particularly, flank wear which is the major hindrance to the use of coated carbide tool as it is unfavorable to the product quality and dimensional accuracy [6, 7].

However, on-line tool monitoring techniques are available which are costly and tedious; parametric optimization and developing predictive models for flank wear with a good accuracy is a good way to use the coated tools for the purpose of cost reduction and improvement of product quality. Being aware of this fact, a good amount work related to prediction and parametric optimization using RSM, multiple regression techniques and Taguchi method was carried out. Senthil Kumar et al. [8] used RSM to optimize the process parameters considering the output responses flank wear, surface roughness and material removal rate during turning of AISI 1045 steel using tungsten carbide insert. They found that the increment in cutting speed lead to the increment in the chosen output responses up to certain level. Later, further increment in cutting speeds result the decrement in the responses. As far as flank wear is concerned, feed rate was the most dominating parameter. The quadratic models were developed for all the responses using RSM. All the RSM models had good agreement with experimental values. Senthil Kumar et al. [9] employed a grey-fuzzy approach for optimization in turning of AISI 1045 steel using uncoated carbide insert. Maruda et al. [10] conducted experimental investigation to know the effect of extreme pressure and anti-wear additives (EP/AW) on tool wear during minimum quantity cooling lubrication (MQCL) turning of AISI 1045 steel using tungsten carbide insert. They concluded that the MQCL+EP/AW method was useful to reduce the flank wear of cutting insert about 8% in comparison with MQCL method alone and 23% in contrast with that under dry machining. Maruda et al. [11] conducted the experiments under dry, MQCL and EP/AW method during turning of AISI 1045 steel using cemented carbide insert. They noted that using MQCL/EP/AW method, the value of flank wear was reduced by around 20% at the lowest cutting speed to 51% at the highest speed as compared to dry turning.

González et al. [12] performed experimental investigation in high speed machining of AISI 1045 using CVD coated TiN $+Al_2O_3$+Ti(N,C) layer insert, CVD coated Ti(C,N)$+Al_2O_3$ and uncoated cermet insert. In this work, RSM methodology was applied to determine optimal set of cutting parameters for obtaining minimum flank wear. The CVD three layer insert was effective followed by the CVD two layer insert. In this work, the coefficients of determination of the RSM based predictive models were below 75% which cannot yield better prediction. The second order or quadratic model may give better prediction. Thangarasu et al. [13] conducted experiments on EN8 steel using Tin coated cemented carbide insert to predict the flank wear using artificial neural network. The feed rate (21.33%) and the interaction of cutting speed and depth of cut (26.67%) were mostly influenced the flank wear. Qasim et al. [14] employed both uncoated and coated cement carbide cutting inserts to machine AISI 1045 to find optimum machining parameters for surface roughness, power consumption, and temperature. The study concluded that the carbide cutting tools were better than the uncoated tools. In this study, the authors did not consider the important response tool flank wear. The predictive models were also not covered. Abbas et al. [15] investigated the influence of dry, flood and minimum quantity lubrication (MQL)-nano fluid environments surface roughness and power consumption in turning of AISI 1045 steel. Finally, MQL-nano fluid environment provided promising results over the remaining. In order to understand the machinabity performance of AISI 1045 steel, tool wear analysis would have been added. It was observed from the literature review, some of the researchers were not considering the tool wear analysis in their investigations [16-22].

Davies et al. [23] conducted experiments to record the temperature during the turning of AISI 1045 steel at higher speeds. They used a high-bandwidth thermal imaging system to measure the temperature. They would have been included the tool wear analysis along with the temperature measurement as it is very predominant in tool design. Soroush Masoudi et al. [24] AISI1045 steel investigated to make out the effect of nozzle positions, work piece hardness and tool type on cutting force, surface roughness and tool wear under MQL environment. The position of nozzle, work piece hardness and tool type showed significant impact on performance measures. This kind of research definitely would reduce machining cost and the take care of the health of the operator. Selvam et al. [25] also used MQL environment for turning of AISI 1045 steel. They aimed to explore the effect of three kinds of cutting fluids on surface quality of the work piece. Among the chosen cutting fluids, vegetable based emulsified cutting fluids were shown best performance. From ANOVA, feed rate was significantly influence on surface roughness. Surprisingly, this study shows cutting fluids impact was least insignificant among all the parameters whose probability value was 0.2780.

Sobron et al. [26] focused on built up edge formation on cutting tool with respect to cutting speed variation during turning of AISI 1045 steel. They observed that BUE formation was not directly persuade by cutting speed. They also found that the size of BUE was directly influenced by cutting force. The authors ignored the tool wear analysis in their study as it is accompanied by BUE and cutting forces which are covered. The study could have been strengthened by adding tool wear analysis which influences the surface quality of machined surface.

The present work employed the Taguchi method which is a powerful technique to satisfy the industrial goals: reduction in product development cycle, lower cost and higher profits [27]. This method greatly improves profits by reducing cost and time. In order to optimize machining parameters, Taguchi method provides a simple, systematic and competent methodology [28]. It provides a high off-line quality system through a small number of experiments [29, 30]. If more than one output response is needed to optimize simultaneously, the Taguchi method does not work, in particular if the output responses contend with each other [31]. On the other side, the RSM is very much useful for the predictive modeling and problem analysis. Moreover, RSM models helps to optimize, simulate the machining process behavior within the chosen experimental range [32]. In recent time, the Taguchi and RSM methods are widely used in industries and research works. Vijay et al. [33] employed heuristic optimization methods Genetics Algorithm (GA), Particle Swarm Optimization (PSO) and Simulated Annealing (SA) to optimize mathematical model developed for surface roughness by RSM. They stated that PSO and GA performance was better than SA. Both PSO and GA produced the same result. Moreover these methods performed 0.03% better than SA. In reality, this percentage of improvement is insignificant. The authors did not give enough explanation in this regard.

Trong Quyet et al. [34] conducted experiments to investigate the effect of cutting fluid on some machinability issues in turning of AISI 1045 steel under MQL environment. Further, Taguchi’s single objective method and Taguchi based grey relational analysis (GRA) multi-objective optimization method were adopted. Generally, the analysis of variance conducts to know the influence input parameter on responses. However, this study completely overlooked this analysis. In addition, during mathematical modeling coefficient of determination (R^2) value is essential to determine whether the prediction is good or not. The current study totally missed it. It was effectively applied for prediction and optimization of machining parameters [35, 36].

It is observed from the literature review, researchers conducted experimental investigations using various coated, uncoated, cermet, CBN and PCBN cutting inserts during the hard turning of AISI 1045 steel. Due to the advancement of surface coating technology, tool manufacturers develop new coated tools which are effective than the previously developed one. Under this scenario, the present work focused on TiSiN-TiAlN nanolaminate PVD-coated insert which is newly developed by Seco tools Manufacturers Company. The insert possess high toughness and wear resistance. Moreover, it is an alternative to CBN and PcBN inserts from the cost point of view. In the current work, AISI 1045 steel was chosen as work piece material which is medium carbon steel suitable for construction and engineering applications. Engineering applications comprise crank shafts, connecting rods, shafts, pins, bolts, gears. There are no studies available regarding hard turning of AISI 1045 steel using a newly developed TiSiN-TiAlN nanolaminate PVD-coated insert. The plan of the current work is to optimize the cutting parameters and developing predictive model using RSM for flank wear while turning AISI 1045 steel which was hardened at 58 HRC. An orthogonal array (OA) L_9 of Taguchi technique was applied for experimentation and signal-to-noise (S/N) ratio was employed to determine optimal set of cutting parameters.

Experimental Procedures

Experimental details

Once the orthogonal array was chosen, the next one was to perform the turning trials. In this regard, LOKESH TL250 CNC lathe was used. Some of the specifications of the machine are: spindle power 11 kW, spindle speed up to 4000 RPM, maximum turning diameter up to 440 mm and turning length 540 mm (maximum). AISI 1045 medium carbon steel was used as work piece specimen and hardened up to 58 HRC using heat treatment process (hardening & tempering).The chemical composition of AISI 1045 is shown in Table 1. For turning tests, the work piece material of 200 mm length and 50 mm diameter of nine pieces were cut from a single bar. A single nanolayer of TiSiN-TiAlN PVD-coated, graded as SECO TH 1000, TNMG 120404 cutting tool was used. The details of geometry of cutting insert are: relief angle 0^o, approach angle 95^o, inclination angle 6^o, including angle 60^o, clearance angle 6^o and nose radius 0.4 mm. An ISO designated PCLNL 2020 K12 right hand side tool holder was employed for mounting the cutting tool. The flank wear of the worn out tool was quantified using a profile projector (Optomech pp 300T) comprises high magnification capabilities up to 10X. The measurement was repeated for three times and their average was considered as the resulted one. The entire view of the work is shown in Figure 1. In the ensuing section, the outcome of the experimental trials is presented and discussed.

Table 1: Chemical composition of AISI 1045

C	Mn	P	S	Si	Al
0.45	0.50	0.356	0.06	0.35	0.04

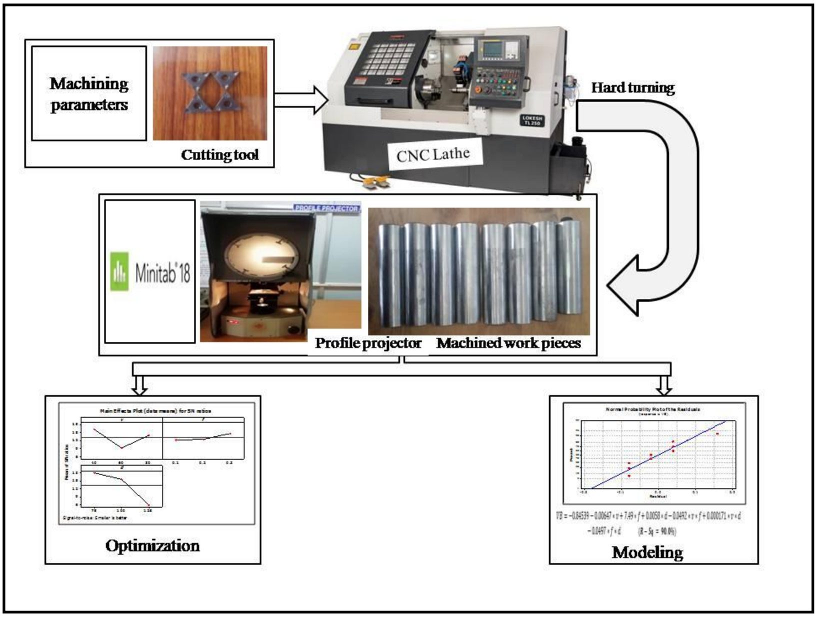

Figure 1: Entire experimental view.

Design with Taguchi method

Taguchi method greatly reduces no experimental trails using specially constructed tables named as orthogonal array. As a consequence of this, this method has become cost effective. In the Taguchi technique, the experimental results are converted as S/N ratio to know the deviation of measured response from the desired value. Taguchi categorized the quality characteristics in to three types: the smaller-the-better, the larger-the-better and the nominal-the-better. After selecting one of the quality characteristics, the ratio is calculated for each input parameter. Subsequently, the highest value of the ratio is taken as better quality characteristic irrespective of category. Thus, the greatest ratio of each process parameter represents optimal level. In this experimental investigation, L_9 Taguchi's OA was chosen for three machining parameters namely cutting speed, feed rate and depth of cut which varies three levels (3^3). The set of machining parameters and its attribution of the levels are shown in Table 2. In order to obtain, the minimum value of flank wear, the smaller-the-better quality attribute was taken. S/N ratio for this quality characteristic can be computed by [27, 28].

S/N ratio = N = -10 Log10 [mean of sum of squares of measured data of flank wear]

This norm used in this study to find out the set of optimal cutting parameters.

Table 2: Machining parameters levels

Machining Parameter	Symbol	Levels		
		1	2	3
Speed (m/min)	*v*	40	60	80
Feed (mm/rev)	*f*	0.1	0.2	0.3
DoC (µm)	*d*	75	100	125

Results and Analysis

The measured flank wear results are summarized in Table 3. ANOVA results for flank wear are shown Table 4. These results reveal that the depth of cut is the most dominant factor followed by cutting speed for flank wear during hard turning by their percentage of contribution i.e.73.38% and 15.77%. The response graph (S/N ratio) for the flank tool wear is used to select the best combination a level (v1-f3-d1) to achieve minimum flank wear is shown in Figure 2. In other words, an optimum value of flank wear was obtained with the combination of 40 mm/min cutting speed, 0.3 mm/rev feed rate and 75 µm depth of cut.

Table 3: Experimental outcomes including S/N ratio

Trials no.	v	f	d	V_B (mm)	S/N ratio (dB)
1.	40	0.1	75	0.07	23.0980
2.	40	0.2	100	0.2	13.9794
3.	40	0.3	125	0.26	11.7005
4.	60	0.1	100	0.26	11.7005
5.	60	0.2	125	0.61	4.2934
6.	60	0.3	75	0.26	11.7005
7.	80	0.1	125	0.8	1.9382
8.	80	0.2	75	0.11	19.1721
9.	80	0.3	100	0.09	20.9151

Table 4: Analysis of variance for S/N ratio-V_B

Parameters	Degrees of freedom	Sum of squares	Mean squares	F-value	Conti. (%)
v (mm/min)	2	0.0664	0.0332		15.77
f (mm/rev)	2	0.0456	0.0228		10.83
d (mm)	2	0.3088	0.1544		73.38
Total	6	0.4208	-	-	-
Error	2	0.07302	-	-	-

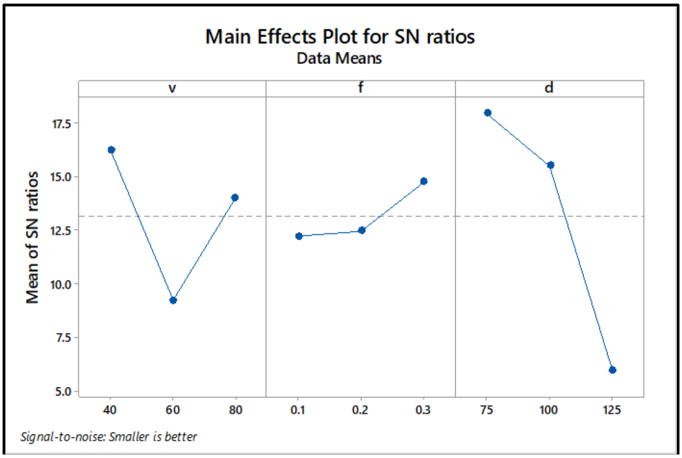

Figure 2: S/N ratio plot for flank wear.

As it is observed from Figure 2, the depth of cut is established which has significantly affected to the flank wear followed by cutting speed. It was seen that as the cutting speed and depth of cut increases, flank wear increases. This concurs with the studies of Gabriel & Milton [37], Dureja et al. [38], Lopez-Luiz et al. [39], Das et al. [40], Singh & Kumar [41], Rajesh Kumar Bhushan [42], Varaprasad et al. [43], Suresh et al. [44], and Tian-Syung Lan [45], the increment in cutting speed remarkably increases temperature at the interaction of tool tip and work piece and leads to more flank wear.

Statistical modeling for tool flank wear

The concept of optimization of tool flank wear through predictive models automatically improves the machined surface quality. One of the effective methodologies to obtain optimum result is response surface methodology (RSM). In this method, there are certain models of having relationship between dependent (responses) and independent variables. In this work, for the prediction of flank wear, among the available RSM models, a linear model with cross terms or the main effects model with interaction is chosen:

$$Y = a_0 + \sum_{i\ 1}^{l} a_i X_i + \sum_{ij}^{l} a_{ij} X_i X_{ji} + \cdots + a_i \ldots n X_i X_{ji} \ldots Xn + \varepsilon_{ij}$$

where a_0, a_i, a_{ij}, a_{ii} are the regression coefficients.X_i , denotes process parameters and ε_{ij} represents error of fit of regression equation.

In view of applying RSM, machining parameters, experimental design and output response is required. Cutting speed (*v*), feed rate (*f*) and depth of cut (*d*) were taken as input parameters in the present study. The flank wear (VB) of the cutting insert was taken as output response. The association between input and output response in the present work can be written as [27]:

$$Y = C\ v\hat{}k\ f\hat{}l\ d\hat{}m$$

where *k*, *l*, *m* are the constants of corresponding input parameters and Y is proposed response i.e flank wear using quadratic (non-linear) regression model which is an appropriate to study the effects of second order terms of input parameters and its cross product terms on flank wear.

In the present work, a linear model with cross terms was hypothesized in acquiring the association between the flank wear (VB) and the turning parameter. The model equation is given as:

$$VB = -0.84539 - 0.00647 * v + 7.49 * f + 0.0058 * d - 0.0492 * v * f + 0.000171 * v * d - 0.0497 * f * d$$
$$(R - Sq\ =\ 90.0\%)$$

Coefficient of determination (R-sq) is used to determine the potentiality of predicted model and dependent variable (Flank wear in this work) on an appropriate scale of 0-100%. Higher R-sq value represents the strong correlation [27]. In the current study the obtained value of R-sq is 90.0% means 90.0% variations in flank wear is explained by the machining parameters. Therefore the fitness of the model for flank wear is good. From the normal plot (Figure 3), the data points in the plot should in approximate linear form. The plot follows the normality as the residuals are very close to the straight line as shown in the plot. Finally, the anticipated model for flank wear is satisfactory for good prediction.

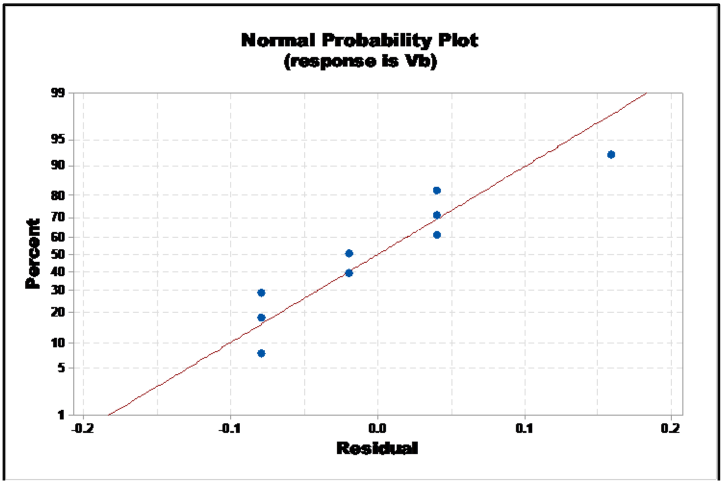

Figure 3: Normal plots for VB.

Response table for S/N ratio at all levels of are presented in Table 5 for flank wear. It provides the highest range values of parameters depth of cut and cutting speed i.e.17.99 and 16.25. This represents that these two factors effect on flank wear more significantly. ANOVA in Table 4 also confirms that the depth of cut and cutting speed during hard turning greatly influenced the cutting tool flank wear by their contribution i.e 73.38% and 15.77%. This kind of trend was observed in the previous works of López-Luiz et al. [39], Singh & Kumar [41], Rajesh Kumar Bhushan [42], Varaprasad et al. [43], Nilrudra Mandal et al. [46], and Meenu Sahu & Komesh Sahu [47].

Table 5: S/N Ratio for flank wear

Level	v	f	d
1	**16.25**	12.24	**17.99**
2	9.23	12.48	15.53
3	14.08	**14.77**	5.97
Range (Max-Min)	7.02	2.52	12.01
Rank	2	3	1

Confirmation test

Confirmation test is the last stage in Taguchi method which is to be conducted after obtaining the optimal set of machining parameters. In the current work, 9 experiments were conducted and through S/N ratio analysis, it was found that the optimal machining parameters are *v*1-*f*3-*d*1 i.e the optimal machining parameters are the cutting speed of 40 m/min, feed rate of

0.3 mm/rev and depth of cut of 75 µm. A conformation test was conducted according to the optimal set of parameters and the flank wear value was obtained as 0.07 mm. In order to envisage the S/N ratio $\eta_{pred.}$ for flank wear by using Table 5, the following equation can be employed as [40]:

$$\eta_{pred.} = \eta_{msn.} + \sum_{k\ 1}^{j} (\overline{\eta_k} - \eta_{msn})$$

where $\eta_{msn.}$ the total mean of S/N ratio is, $\overline{\eta_k}$ represents mean S/N ratio at optimal set, and j represents the number of input parameter that appreciably affect the flank wear. The result of the confirmation experiments and estimated values are shown in the Table 6. From the results, a notable improvement (18.8 dB) in S/N ratio to the response (flank wear) was observed. Hence, the tool flank wear was greatly improved through the use of Taguchi method.

Table 6: Comparison of outcomes among of confirmation experiment for VB

	Initial machining parameters	Optimal set of parameters	
		Predicted value (Taguchi method)	Experimental value (Confirmation test)
Level	*v2-f2-d*3	*v*1-*f*3-*d*1	*v*1-*f*3-
VB (mm)	0.61	--	
S/N ratio	4.29	22.67	23.09
Improvement	**18.8**		

Conclusions

To fill the research gap in hard turning of 58 HRC AISI 1045, the current study was carried out on hard turning of AISI 1045 by nano laminated PVD grade cutting insert. In this process, Taguchi technique was employed for parametric optimization and RSM based model was developed for flank wear. As per the aforesaid discussions, subsequent conclusions can be summarized as:

a. The optimum levels of the cutting parameters to minimize the flank wear using S/N ratios were established. The optimal cutting parameters for flank wear were found at v1-f3-d1 (i.e., cutting speed: 40 m/min, feed rate: 0.3 mm/rev and depth of cut: 75 µm), respectively.
b. The flank wear of tool is directly proportional to the depth of cut. The study demonstrates that a higher tool wear rate is reported at cutting speed 60 m/min and depth of cut of 125 µm. The depth of cut is greatly

influenced on the flank wear (73.38%) followed by cutting speed (15.77%).

c. Verification test was carried out to validate the optimal set of parameters and the result was shown a great reduction of 81.42% in the flank wear.
d. A linear model with cross terms RSM based model was established. The accuracy of the model was checked by R-square (90.0%) and normal probability plot. All these confirmed that the developed model demonstrate excellent fit and is capable of predicting the flank wear values which are reasonably close to the experimental values.
e. The study has confirmed the feasibility of an inexpensive cutting insert for hard turning of AISI 1045 steel in the specified range. This cutting insert is cost effective choice to costlier CBN and PCBN tools.
f. In future, researchers may investigate with this cutting insert for other grades of hardened steels, Inconel and various grades of stainless steels. Furthermore, the behavior of chip formation, cutting forces and surface roughness analysis can also be included to understand the machinability performance of hardened steels.

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