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Full Length Article

Correlation between vibration amplitude and tool wear in turning: Numerical and experimental analysis

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ABSTRACT

In this paper, a correlation between vibration amplitude and tool wear when in dry turning of AISI 4140 steel using uncoated carbide insert DNMA 432 is analyzed via experiments and finite element simulations. 3D Finite element simulations results are utilized to predict the evolution of cutting forces, vibration displacement amplitudes and tool wear in vibration induced turning. In the present paper, the primary concern is to find the relative vibration and tool wear with the variation of process parameters. These changes lead to accelerated tool wear and even breakage. The cutting forces in the feed direction are also predicted and compared with the experimental trends. A laser Doppler vibrometer is used to detect vibration amplitudes and the usage of Kistler 9272 dynamometer for recording the cutting forces during the cutting process is well demonstrated. A sincere effort is put to investigate the influence of spindle speed, feed rate, depth of cut on vibration amplitude and tool flank wear at different levels of workpiece hardness. Empirical models have been developed using second order polynomial equations for correlating the interaction and higher order influences of various process parameters. Analysis of variance (ANOVA) is carried out to identify the significant factors that are affecting the vibration amplitude and tool flank wear. Response surface methodology (RSM) is implemented to investigate the progression of flank wear and displacement amplitude based on experimental data. While measuring the displacement amplitude, *R*-square values for experimental and numerical methods are 98.6 and 97.8. Based on the *R*-square values of ANOVA it is found that the numerical values show good agreement with the experimental values and are helpful in estimating displacement amplitude. In the case of predicting the tool wear, *R*-square values were found to be 97.69 and 96.08, respectively for numerical and experimental measures while determining the tool wear. By taking *R*-square values into account, ANOVA confirms the close relation between experimental values and numerical values in evaluating the tool wear.

1. Introduction

In turning operations, vibration is a frequent problem, which affects the result of machining, in particular, the tool wear. Vibration can be defined as an object being repeatedly displaced at a very high frequency [1]. In turning process, three types of mechanical vibrations are present. They are free, forced and self-excited vibrations. They occur due to lack of dynamic stiffness/rigidity of the machine tool system comprising tool, tool holder, workpiece and machine tool. Machining vibrations, also called as chatter, correspond to the relative movement between the workpiece and the cutting tool. These vibrations affect typical machining processes, such as turning, milling and drilling. Relative vibration amplitude between the workpiece and cutting tool influences the tool life [2]. Cutting tool and tool holder shank are subjected to dynamic excitation due to the deformation of the work material during the cutting operation. The dynamic relative motion between the cutting tool and workpiece will affect the quality of the machining, in particular, the surface finish. Furthermore, the tool life is correlated with the amount of vibration [3]. In turning, the presence of tool vibration is a major factor which leads to poor surface finish, cutting tool damage, increase in tool wear and unacceptable noise [4]. Metal cutting processes can entail three different types of mechanical vibrations. They arise due to the lack of dynamic stiffness of one or several elements of the system comprising the machine tool, the tool holder, the cutting tool and the workpiece material [5]. Zhou et al. [6] presented a systematic approach based on Areal Power Spectral Density (APSD) method to identify the effect of relative vibratory motions between the tool and workpiece in diamond turning. The vibration amplitude, is the

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Nomenclature

Disp	displacement due to vibration (microns)	*d*	depth of cut (mm)
N	rotational speed (rpm)	VB	flank wear (mm)
$Disp_{exp}$	experimental displacement value (microns)	ANOVA	analysis of variance (ANOVA)
$Disp_{num}$	numerical displacement value (microns)	RSM	response surface methodology
VB_{exp}	experimental flank wear (mm)	V_c	cutting speed (m/min)
VB_{num}	numerical flank wear (mm)	VB	flank wear (mm)
f	feed rate (mm/rev)		
H	workpiece hardness (Bhn)		

characteristic which describes the severity of the vibration, which can be quantified in several ways. In the present work, displacement is chosen to quantify the vibration amplitude during turning operation. Hence, the possibility of predicting the amount of the relative displacement amplitude and tool wear in machining processes is an interesting topic for industries. Most machining operations have two distinct motions: rotary motion and translation that is either straight or curvilinear. In operations such as milling and drilling, the tool is under motion and, thus, is the only component that vibrates [7]. In turning process, on the other hand, the workpiece has a rotary motion whereas the tool translates linearly. Both tool and workpiece vibrate in the process of material removal. However, throughout the years, researchers considered only tool vibration in cutting dynamics [8]. An exception to the previous i.e., workpiece deflection due to the exertion of 3D cutting forces and correlated dimensional errors has been recently considered [9,10]. Machining failures attributable to induced workpiece vibration that is often observed in the real world [11]. Workpiece vibration affects not only cutting instability but also product surface roughness and tool wear. Machine tool components are subjected to wide range of loads, due to the modification in cutter geometry, workpiece hardness, speed, feed and depth of cuts. Determination of machine tool vibration is highly critical and instrumental in increasing the quality of machining [12]. Most models developed for surface roughness [13] do not consider workpiece vibration, either. The cutting process actions applied to the machining system cause relative tool/workpiece displacements that can generate vibration. Consequently, instability in the cutting process can cause instability in the dynamic system of the machine tool resulting vibrations. Major directions in this field of research work aimed towards the advancement of productivity and cost-effectiveness. However, in automated manufacturing systems are focused on vibrations, detection of tool breakage and monitoring of cutting tool wear [14]. According to Paurobally et al. [15] chatter always indicates defects on the machined surface; vibration especially self-excited vibration is associated with the increased flank wear and machined surface roughness.

Chatter vibrations of the machining operation will damage the cutting tool if not addressed properly. Vibration displacement has a significant role in metal cutting. The displacement is a critical parameter for the predictive modeling of load distribution in cutting tool as well as for developing robust temperature prediction models [16]. Various other parameters may affect displacement amplitude while turning. However, there is still the lack of fundamental understanding of the phenomenon occurring at the tool-chip interfaces [17]. For these reasons, it is important for optimizing a machining process to be able to predict the amount of the tool wear. Antic et al. [18] presented the experimental investigation to study the influence of tool wear on the tool vibration and chip segmentation. This approach based on the assumption that a relationship exists between the high-frequency vibrations measured and tool wear degree. Antic et al. [19] demonstrated the procedure for acquiring high quality and timely information on vibration condition in real time with a particular emphasis on the module for acquisition and processing vibration signals. This investigation gives a clear understanding about the mechanism of the chip formation and segmentation type as well. They are used in the development of a system for identifying the tool wear. Zimmermann et al. [20] identified that workpiece and tool are subjected to severe mechanical and thermal loads while turning. The loads in turning can cause thermal expansions and mechanically induced deflections (vibrations) of the tool and the workpiece. They have presented the analysis of dry turning via experiments and 3D finite element simulations by using experimental results. Simulations with FEM in 3D case are performed recently, owing to advancements in re-meshing techniques in commercial FE codes, like Deform™ and Abaqus™, used in the present work [21,22].

Ozel et al. [23] investigated the effects of workpiece hardness, cutting edge geometry, cutting speed and feed rate on surface roughness and resultant forces in the finish hard turning of AISI H13 steel. Erol Zeren and Tuğrul Özel [24] demonstrated a 3D finite element method (FEM) modeling approach with arbitrary Lagrangian Eulerian (ALE) fully coupled thermal-stress analysis to simulate realistically high speed turning. Fazar et al. [25] used a finite element method (FEM) to simulate chip formation in the turning process and presented analytical as well as numerical analyses. This model is then used to predict machining attributes that are affected by the heat partition.

In conjunction with experiential investigations, tool wear prediction in machining is a constant preoccupation among researchers. Haddag et al. [26] presented a discussion on a phenomenological Usui's model to predict tool wear. According to Usui's model, tool wear is defined as a function of the tool–chip interface parameters, such as pressure, temperature and sliding velocity. The main advantage of such laws is the implantation ease.

Tugrul Ozel and Yigit Karpat [27] presented a comparison of neural network models with regression models. Predictive neural network modeling is also extended to predict tool wear, and surface roughness patterns observed in finish hard turning processes [28]. Hence, to predict the factors that can affect the vibration amplitude and tool life a tool condition monitoring system is needed. An experimental evaluation of the tool wear parameters during turning process is a very expensive and time-consuming work, owing to the influence of many uncontrollable variables. There are several techniques for answering this problem like RSM [29] and ANNs. Feng and Wang [30] conducted testing and used regression analysis to develop a complete empirical model for traditional turning. Fang et al. [31] presented finite element simulations of machining for Ti-6Al-4V. In particular, the thermodynamic constitutive equation in FEA is applied for both workpiece material and tool material. The comparison between the experi-