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Analysis and optimization of micro-geometry of miniature spur gears manufactured by wire electric discharge machining

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ABSTRACT

This paper reports about the analysis and optimization of micro-geometry parameters (i.e. total profile deviation 'F_a' and accumulated pitch deviation 'F_p') of the wire electric discharge machined (WEDMed) fine-pitch miniature spur gears made of brass. Effects of four WEDM process parameters namely voltage, pulse-on time, pulse-off time and wire feed rate on the micro-geometry of the miniature gears were analyzed by conducting the experiments designed using Box–Behnken approach of response surface methodology (RSM). Analysis of variance study found all four input parameters significant. Larger deviations in profile and pitch were observed with higher values of the voltage and pulse-on time, and with lower values of wire feed rate and pulse-off time. Multi-performance optimization of WEDM parameters was done using the desirability analysis to minimize profile deviation and pitch deviation simultaneously. The values of F_a and F_p of the gear obtained by the confirmation experiment conducted at the optimized WEDM parameters were as 11.5 μm and 9.1 μm respectively. These values categorize the WEDMed gear having DIN quality number as 7 and 5 respectively for profile and pitch which are better than those obtained by the conventional miniature gear manufacturing processes.

1. Introduction

Miniature gears can either be *meso-gears* (outside diameter in the range of 1–10 mm) or *micro-gears* (outside diameter <1 mm). The present work deals with the *meso-gears*. Miniature gears are the key components in various miniaturized devices such as miniature motors and pumps, electronic and home appliances, business machines, automotive parts, timing devices, sophisticated toys, etc. Brass, bronze, aluminium, stainless steel are the most commonly used materials for these gears [1,2]. Gears made of brass are primarily used as motion transmitting gears which run at very high speed. Therefore, minimum running noise and accurate motion transfer are the two important desirable characteristics for these gears which, depend on the amount of errors or deviations in the two relevant micro-geometry parameters i.e. the deviations in profile and pitch of the miniature gears. Profile deviation affects the noise behaviour, whereas pitch deviation determines the accuracy in the motion transfer. Profile deviation is a type of *form error* which decides the intended nominal shape of the tooth surface, whereas pitch deviation is a type of *location error* and is related to the location of teeth on a gear [1,3]. Profile deviation is the difference between the measured and the theoretical involute surface as shown in Fig. 1a. It includes deviations in the form and angle (slope) of a gear tooth profile and measured perpendicular to the functional profile i.e. the portion of the profile which is in contact with the meshing tooth. The *profile form deviation* is the difference between the nominal involute form and the actual involute form, while *profile angle deviation* is the difference between the nominal involute angle and the actual involute angle [1,3]. The *total profile deviation* (F_a) is the sum of profile form and profile angle deviations.

The pitch is the distance between the corresponding points on two adjacent teeth of a gear along the pitch circle. Deviations in the pitch include single pitch deviation and accumulated pitch deviation which are measured at the middle of the tooth height along the pitch circle. *Single pitch deviation* is the algebraic difference between the theoretical and actual measured values of the pitch for a pair of teeth as depicted in Fig. 1b. It indicates the location accuracy of a tooth on the periphery of a gear. The *accumulated pitch deviation* 'F_p' is defined as the difference between the summation of the theoretical values of pitches and summation of the actual values of the pitches over all the teeth of a gear. This is an important parameter in those applications where absolute trueness of angular motion is required, such as robotic drives, high speed gears, radar gears, etc.

The quality of a gear is defined in the German standard DIN 3962, based on the amount of deviations in its micro-geometry by

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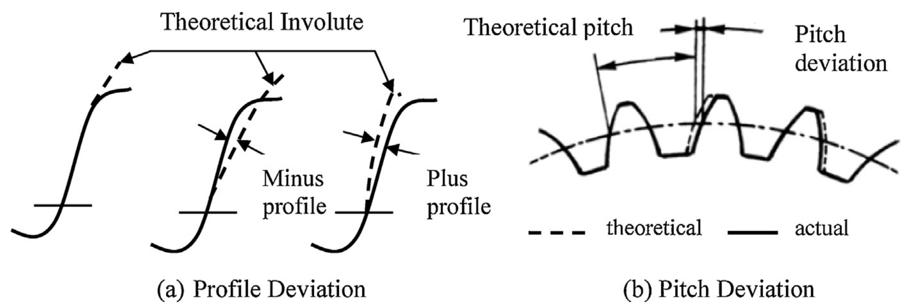

Fig. 1. Concept of deviations in profile and pitch for an external gear. (a) Profile deviation; (b) Pitch deviation.

a value ranging from 1 to 12 [4], with lower DIN numbers indicating better quality of a gear and vice versa. Hobbing, stamping, die casting, extrusion and powder metallurgy are the most commonly used conventional processes for manufacturing the meso-gears. However, all of them have certain limitations as described in Table 1. Moreover, all these processes manufacture gears of low quality i.e. with a DIN quality number in the range of 9–12 [1,2].

These limitations of conventional processes necessitate the exploration of an alternative process which can manufacture high quality miniature gears. Wire electric discharge machining (WEDM) has become a preferred choice for manufacturing the miniaturized components [5–7] and can be a potential alternative to the conventional manufacturing processes. Although processes reported in Table 1 have quality and cost drawbacks, they are more productive than WEDM.

Research has been reported on optimizing WEDM using different statistical and evolutionary techniques for various applications. Some worth-mentioning work include the use of a combination of neural network and simulated annealing by Tarng et al. [8], Taguchi's L_{18} orthogonal array by Liao et al. [9], a combination of grey relational analysis and Taguchi's L_{18} orthogonal array by Huang and Liao [10], Taguchi's L_{16} orthogonal array by Ramakrishnan and Karunamoorthy [11], a combination of Taguchi method and genetic algorithms by Mahapatra and Patnaik [12], and a combination of response surface methodology and desirability analysis by Kanlayasiri and Jattakul [13]. But, there are very few references available on manufacturing of miniature gears by EDM or WEDM. Takeuchi et al. [14] used *micro-EDM* to manufacture *micro-gears* of 0.03 mm module for a micro-planetary gear system using SKS3 tool steel and WC-Ni-Cr cermets as gear material. The manufactured micro-gears were found to perform well for torque transmission. Benavides et al. [15] also used *micro-WEDM* to manufacture *meso-sized* ratchet wheels of different materials and achieved submicron level surface finish, minimum recast layer and consistent micro-geometry. Di et al. [16] used *micro-WEDM* to manufacture *micro-gears* of 40 μm module with seven teeth from stainless steel plates of 1 mm thickness, achieving an accuracy of ±0.2 μm. Ali and Mohammed [17] used *WEDM* to manufacture *meso-sized* external spur gears of beryllium-copper. They achieved 1.8 μm as R_a and 7 μm as R_{max} and advised using low discharge energy parameters to get better surface finish for the miniature gears. Ali et al. [18] compared the surface finish of miniature external spur gears manufactured by WEDM and mirco-WEDM and achieved better results with micro-WEDM.

It is evident from the review of the available literature that all the past work was mainly focused on the surface roughness and surface integrity aspects of the WEDMed miniature gears and not much work have been carried out on the investigation and optimization of micro-geometry parameters of WEDMed miniature gears. This paper reports detailed study of the effects of four important WEDM parameters (i.e. voltage, pulse-on time, pulse-off time and wire feed rate) on the two most important micro-geometry parameters (i.e. total profile deviation and accumulated pitch deviation) of the WEDMed miniature gears and presents a multi-performance optimization of the WEDM parameters by desirability analysis.

The specific objectives of the present work were (i) to explore the use of WEDM as a superior alternative process for manufacturing high quality miniature gears, (ii) to know the trends of the micro-geometry parameters of the miniature gears with the WEDM parameters, and (iii) to optimize the WEDM parameters for achieving minimum deviation in profile and pitch of the miniature gears. Based on preliminary investigations [19–21], the authors conclude that WEDM process is capable enough to manufacture high quality miniature gears.

In WEDM, the material is removed by the thermoelectric erosion process involving melting and vaporization caused by the electric spark generated by a pulsed DC power supply between the wire electrode and the workpiece in the presence of a dielectric [22,23]. Deviations in micro-geometry and dimensional accuracy of the WEDMed components mainly depend on the size, shape

Table 1
Limitations of conventional processes for manufacturing of miniature gear with corresponding quality number according to DIN 3962 [1,2].

Sr. No.	Miniature gear manufacturing process	Limitations	DIN quality number
1.	Hobbing	• Replicates tool marks on gear teeth; • Needs subsequent polishing operation for high quality gears; • Requires long set-up time.	9
2.	Stamping	• Necessitates shaving operation for final finishing of gears; • Cannot manufacture gears with higher tooth thickness; • Wear and tear of die and punch is a problem in stamping.	10
3.	Die-casting	• Cannot be used where extreme accuracy is needed; • Subsequent trimming operations are necessary after the gear has been removed from the die.	11
4.	Extrusion	• Requires secondary drawing operation for improving accuracy of gears; • Wear of die is a major problem.	12
5.	Powder metallurgy	• De-binding of part from mould is difficult; • Arrangement of fine metal powder of all types is difficult; • Not suitable for gears other than spur type.	10