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Study on ultrasonic-assisted lapping of gears

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Abstract

Ultrasonic-assisted lapping of gears is firstly proposed and compared with conventional lapping in material removal process and mechanism. The material removal mechanisms of the ultrasonic lapping include hammering, impacting and acoustic cavitation. The experiments showed that the material removal rate of ultrasonic lapping is nearly three times that of the conventional lapping in the same condition, and the ultrasonic lapping can produce a better tooth surface quality ($Ra = 0.2\,\mu m$ and the section height $c = 1.2\,\mu m$) than the conventional lapping ($Ra = 0.33\,\mu m$ and $c = 3.2\,\mu m$). Then a set of parametric experiments for the ultrasonic lapping was conducted with the Taguchi experimental design. The results of this set of experiments reveal that the optimum conditions for a high removal rate in the ultrasonic lapping experiments of spiral-bevel gears are of brake torque, 0.12 Nm; pinion rotational speed, 600 rpm; and slurry concentration with 20%. The contributions by percentage of torque, speed and concentration to the removal rate are 8.13, 19.26 and 68.11, respectively.

Keywords: Ultrasonic lapping; Material removal rate; Spiral bevel gears; Hypoid; Taguchi method

1. Introduction

Ultrasonic machining (USM) is a non-conventional mechanical material removal process that has been widely used for machining both conductive and non-metallic materials, preferably those with low ductility and a hardness above 40 HRC, e.g. inorganic glasses, silicon nitride, nickel/titanium alloys [1]. Also, the rotary ultrasonic machining (RUM) and the ultrasonic-assisted conventional /non-conventional machining have been developed. They are used for machining metallic materials as well as non-metallic materials, such as ultrasonic assisted drilling, turning, grinding, polishing, lapping and honing. They are applied to metal materials and are claimed to be able to reduce machining time, work-piece residual stress and strain hardening, and to improve work-piece surface quality and tool life compared to conventional machining [1–5].

Ultrasonic-assisted hobbing, slotting and shaving of gears have also been studied and are thought to be able to reduce cutting power and cutter wear, and to improve the material machinability, the tooth surface quality and the cutting efficiency compared to the conventional machining of gears [6,7]. It is expected that the ultrasonic-assisted cutting will be used more extensively in machining high hardess tooth surface. At present, gears with a complex curve tooth, such as spiral bevel and hypoid gears, lack a good technique for the final finishing process. The present techniques are limited to grinding and lapping. Owing to the fact that the gear grinding is low in efficiency and high in product cost, and conventional lapping is poor in material removal rate and shows low precision in modifying tooth shape, ultrasonic-assisted lapping of gears (ULG) is proposed in this paper. Follow-up work is presented as follows:

Firstly, rotary ultrasonic system is designed to perform the ULG; conventional lapping and ULG are compared in the material removal process and mechanism. Secondly, a

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set of parametric experiments are conducted. The results of this set of experiments reveal the influences of the controllable process parameters (i.e., the brake torque, rotational speed and slurry concentration) on the process outputs (i.e., MRR). Finally, the experimental results are presented and discussed, and conclusions are made.

2. Conventional lapping of gears

Spiral bevel and hypoid gear sets are lapped to refine the tooth surface finish and to improve the tooth contact pattern. Errors arising in the preceding cutting and heat treatment operation can result in tooth shape errors, thus reducing tooth mating accuracy. The lapping operation may refine tooth contact surface finish and improve tooth mating.

Fig. 1(a) shows the lapping movement manner of the pinion in relation to the gear member. It is necessary to displace the pinion in relation to the gear member in a manner that will move the tooth contact over the entire area of the tooth surface. The magnitude of displacement is controlled by three direction axes: (1) V-Axis (Offset) moves the gear making contact to the toe and heel; (2) H-Axis (pinion cone) moves the pinion making contact to the top and flank; (3) J-Axis (Gear cone) moves the pinion controlling backlash.

The lapping operation is a cutting process where metal is removed and chips are formed. In the case of bevel and hypoid gears, the process may be referred to as equalizing lapping where both the work and the lap mutually improve their shape. Ideally, the tooth surfaces are separated by one layer of abrasive particles, which are suspended in the carrier medium called the vehicle, i.e. slurry. The vehicle also lubricates the work and prevents scoring. The film thickness of the vehicle is less than grain size of the abrasive particles under load (Fig. 2). The combination of relative sliding and normal and tangential forces (F_n and F_r in Fig. 2) between the mating tooth surfaces allow the abrasive particles to remove and microcut metal such that the surfaces are changed.

The process of the conventional lapping of gears has some limitations as follows:

1. Poor material removal rate (MRR)—due to the grain cutting movement and force relying only on the relative sliding and contact action between the two mating tooth surfaces.
2. Non-uniform lapping over tooth surface—due to the relative sliding rate being different for contact moving to the top and flank of tooth surfaces, respectively; especially for the spiral bevel, the pure rolling contact occurred at the pitch position of the tooth surface.
3. Poor correction of profile errors—due to the above two limitations in (1) and (2).

3. Ultrasonic-assisted lapping of gears

ULG is similar to the RUM in configuration. The difference is that the ultrasonic vibration system fitted in the spindle in the RUM is to provide the ultrasonic vibration (about 20,000 Hz) for the tool tip [8], but the same vibration in ULG is to be provided for the pinion (see Fig. 1(b)). In ULG, besides the movement of the pinion relative to the gear member being the same as the above-described lapping (see Fig. 1(a)), the pinion will oscillate

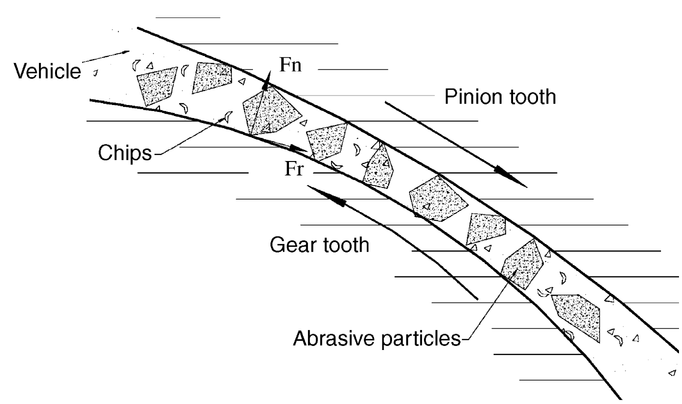

Fig. 2. Conventional lapping process.

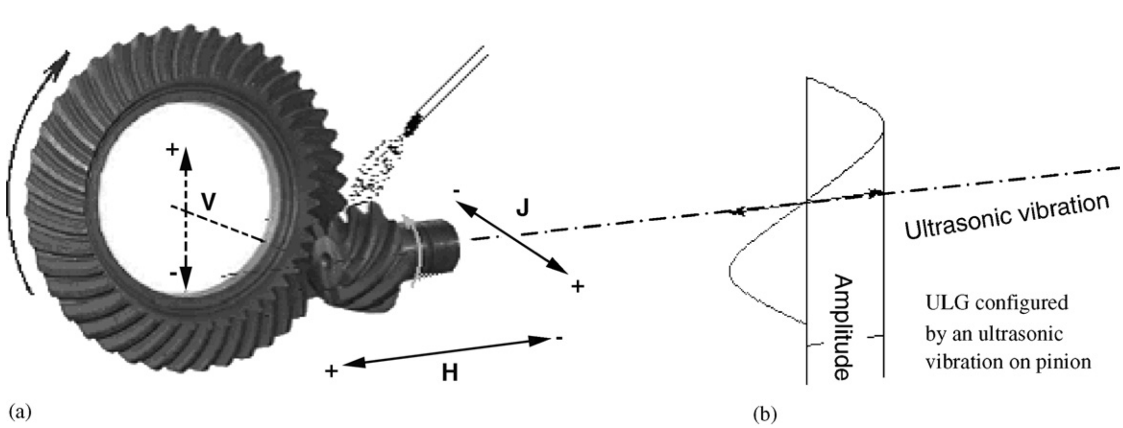

Fig. 1. The method of lapping spiral-bevel or hypoid gears: (a) the lapping movements, (b) the ULG method.