Advanced process limits by rolling of helical gears

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ABSTRACT: A new developed method describes the gear-rolling-process and an alternative pitch design of forming tools. A model was created to analyze rolling processes which determined that in contrast to flat rolling tools, round tools for helical gears need additional kinematic compensation during diameter-related variable pitch forming processes. The new method shows up to a 50% improvement in pitch accuracy and the ability to roll high teeth gears (up to 10 mm in height and a tooth-height-coefficient larger than 2,7). The Fraunhofer Institute IWU has carried out research for many years to provide insight in generating high gearing typical of transmissions with rolling techniques and surpassing the limits of forming feasibility.

Key words: Forming, Rolling, Gears, Rolling tools, Pitch accuracy

1 INTRODUCTION

Rolling of helical gears is a competitive alternative to metal-cutting production processes due to the benefits derived from forming manufacturing processes such:

- no loss of material and no need to dispose of chips,
- very short processing times,
- over 60% boost in strength in the flank zone,
- highest surface quality ($R_a = 0.2$ µm; $R_z = 1.4$ µm),
- improved load capacity caused by contour-related fiber orientation.

The basic prerequisite for applying rolling processes to manufacturing higher tooth profiles is enhancing the potential gear qualities in terms of flank shape, accuracy of pitch concerning the assessment criteria formulated in the DIN 3960 through 3962 quality standards [1] and economical tool life qualities.

2 ROLLING OF HELICAL GEARS

Rolling has found the widest range of application among the forming techniques for teeth shaping. There is a distinction made between forming techniques and generating techniques [2], [3]. The foremost generating techniques are rolling with flat tools and rolling with round tools.

2.1 Flat Rolling Technique

Cold rolling with flat tools consists of two rolling rods moving in opposite directions that mesh with the rolling blank symmetric to rotation. It is centered between tips on both ends and can rotate freely. The upper and lower rolling rods have translatory and synchronous motion in relation to one another, they encounter the rolling blank simultaneously and they set it into rotation by means of friction and form closure.

2.2 Round Rolling Technique

The round rolling technique clamps the original form that is symmetric to rotation between the tips in the axial direction. Depending upon the technique, two or three round tools with the same direction of rotation and a constant speed form the toothed geometry into the blank (Figure 1).

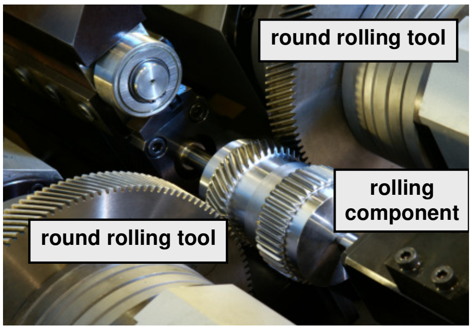

Figure 1: Round rolling technique with two rolling tools

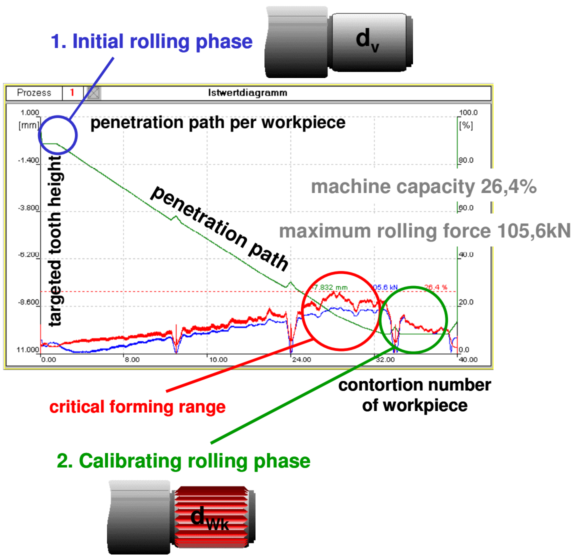

Figure 2: Penetration path into the workpiece

The penetration into the workpiece (Figure 2) is done by reducing the axle base of the round tools in the radial direction. And since the workpiece can be seamed several times, the round rolling technique can be deemed as forming at an infinite tool length. This is an advantage it has in relation to rolling with flat tools that are limited in their length and it explains the challenge presented by rolling with round rolling tools. In other words, the design of the round rolling technique does not make it possible to give tools variable pitches (i.e., with variable spaces from one tooth to another) to ensure a pitch-precision process of penetration of tool teeth into the rolling blank which is dependent upon the diameter.

2.3 *Pitch-variable Rolling Process*

State-of-the-art are engineering flat tools with a constant tooth pitch over the entire length while rounded tools also roll at a constant tooth pitch since the tools and rolling component seam several times. The idea of designing rolling techniques with variable pitches arises from the fact that the rolling process is dependent upon the diameter over its entire length. That means, the tool initially rolls to the preliminary dimension of the original shape that is symmetric to rotation both with round tools and flat tools. The longer the process of the tool teeth penetrating into the rolling blank, the more the penetrating diameters change with one another [4].

Figure 3 shows 6 workpiece seamings for rolling a targeted z=12 teeth as an example of the penetration process dependant upon diameter. The diameter before lathing (d_v) determines the beginning of rolling into the rolling blank based on the pitch (p_A) while the rolling or reference circle diameter d_{Wk} or d_0 determines the end of rolling (p_K) when the toothed wheeled works are fully formed. A rolling circle diameter of the tool and workpiece gear cutting develops at every point in time of the rolling process that is dependent upon penetration. This gradual change in the corresponding rolling circles has to be accommodated not only in the design of the rolling tools but also in the design of the process routine. This is the reason why a differentiated procedure is called for with the rolling techniques being investigated.

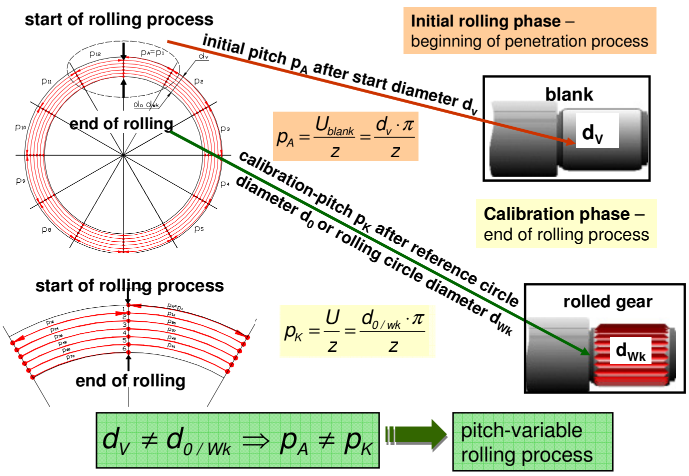

Figure 3: Pitch-specific penetration process into a rolling blank depending upon diameter

Correcting the pitch with the flat-rolling technique is a linearization of adjusting the toothed pitches from the first tooth of the tool run-in p_A to the tooth pitch p_K when the calibrating zone has been reached. Pitch correction in the rolling process with round tools uses a Speed-Controlled Forced Synchronization.

Speed-Controlled Forced Synchronization

The rolling component is clamped firmly in the speed-controlled synchronous run-in and force driven by a separate drive train for a technique with variable pitches over the penetration process of the rolling tool dependant upon diameter. The calculation rules shown in Figure 4 are used to calculate the workpiece speed at a constant specified tool speed and then it is implemented in the control system as a setpoint curve. The rolling process is broken down into three phases for precision definition of terms.

$$n_{1,Ws} = \frac{n_{1,Wz} \cdot D_{a,Wz}}{d_{v,Ws}}$$

$$n_{2,Ws} = \frac{n_{2,Wz} \cdot D_{Wk,i}}{d_{Wk,i}}$$

$$n_{3,Ws} = \frac{n_{3,Wz} \cdot D_{Wk}}{d_{Wk}}$$

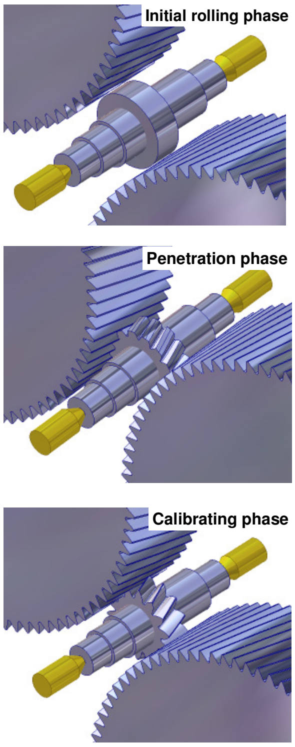

Figure 4: Diameter-dependant speed adjustment in the round rolling process

At the beginning of the initial rolling phase, the tip circle diameter $D_{a,Wz}$ of the rolling tools and the diameter before lathing d_V of the rolling blank generate with one another. The tip circle pitch of the tool forms the initial rolling number z_A on the circumference of the blank. The same procedure can be determined with mathematical precision for phase 3 of the rolling process, i.e. the calibrating process as well as the ratios of speeds to diameter can also be precisely defined in the zone of full formation. The rolling circle diameter of the tool (D_{Wk}) and the workpiece (d_{Wk}) generate with one another in the calibrating zone of forming. The speed of the rolling tools n_{Wz} is specified as a constant target speed over the entire process while the rolling circle diameter of the tool ($D_{Wk,i}$) and the workpiece ($d_{Wk,i}$), each generated in forming phase i, roll in the zone of the penetration phase [6].

3 TESTS

Various helical gears were formed with round and flat tools to verify the tool and process designs described here. The selected gears were rolled both with round and flat tools to compare rolling techniques. Hardened steel 16MnCr5 was used as the reference material because MnCr-alloyed hardened steels are suited for high-stress wear-resistant components in automobile manufacture and mechanical engineering, especially for gear cutting. These experimental tests on the pitch-dynamic rolling process with the flat-tool technique were carried out on a flat-profile-rolling machine and the rolling tests with the round rolling technique were realized on the PWZ Spezial Two-Roller Machine at the Fraunhofer Institute for Machine Tools and Forming Technology IWU in Chemnitz.

Test Findings

The gear-geometry measurements of ten pitch-constant (state-of-the-art) and pitch-variable rolling workpieces were broken down into the geometrically relevant gear variations as per DIN 3962, flank shape, flank line, true running and pitch accuracy. Pitch accuracy was accorded a higher priority since these findings are directly impacted by the pitch-variable modification in techniques while flank formation and true running accuracy are only impacted indirectly. Figure 5 shows a compressed summary and comparison of findings from pitch-constant and pitch-variable tool design when rolling a high gear module m_n=1.6 tooth number z=10 with flat tools.

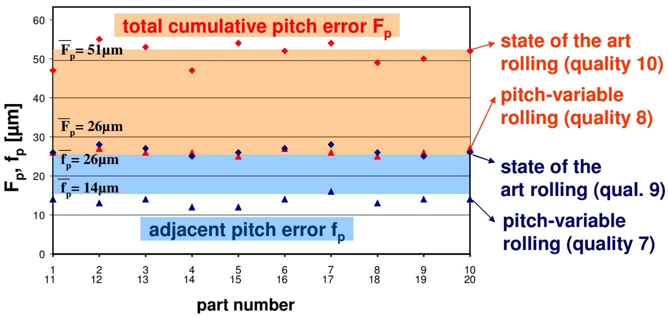

Figure 5: Pitch accuracy with state-of-the-art rolling and pitch-variable rolling (high gear m_n=1.6 z=10 - flat tools)

Concerning flat tool rolling, the resulting pitch-precision penetration process alone was able to drive down the pitch variations, reducing quality nearly 50% (f_p-improvement from 26µm to 14µm) and improving gear quality by 2 quality classes (9 to 7). The geometric variation as per DIN 3962 was also

scaled back by approximately 50% (F_p-improvement from 51µm to 26 µm).
Figure 6 shows a summary and comparison of findings of pitch-constant and pitch-variable process design when rolling the high gearing module m_n=1.6 mm, tooth number z=10 with round tools. The pitch-precision penetration process of the tool teeth into the rolling component reduced pitch variations by approximately 30% (f_p decrease from 26µm to 18 µm) and gear quality improved by one quality class (9 to 8). The geometric variation was driven down by approximately 40% with the described total cumulative pitch error F_p from 44µm to 27µm. That means that the qualitative improvement potential increases (due to diameter-dependent and a pitch-precision process) with the resulting increasing discrepancies between initial rolling and calibration pitch when rolling into the full material.

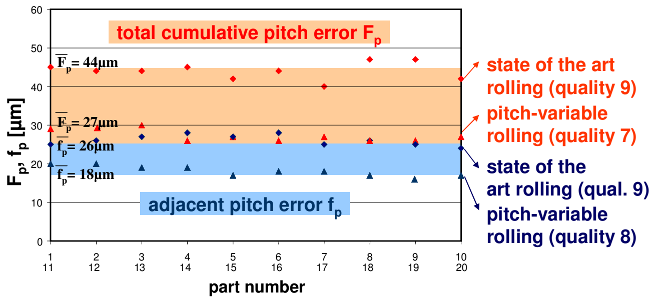

Figure 6: Pitch accuracy with state-of-the-art rolling and pitch-variable rolling (high gear m_n=1.6 z=10 - round tools)

4 OUTLOOK

Conclusions can be drawn on large-module gears from the qualitative findings of rolling processes for their pitch-variable process design using measurements to assess them.

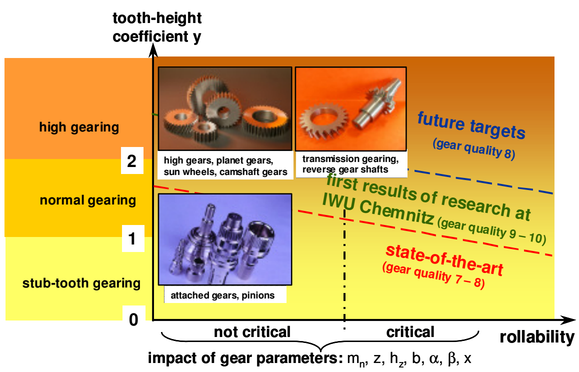

Figure 7: State-of-the-art with gear rolling

This is promising since the state-of-the-art practical limit for cross rolling of spur-toothed gear into the full material is approx. module 1.6 (normal gears).

A pitch-adapted forming process based on diameter can make a contribution to rolling high gears since the mathematical discrepancy between the initial rolling and calibrating pitch increases the greater the module and tooth height. Special segments for future manufacture of high gears with rolling processes could be reverse gears (since quality requirements are low), sun wheels and planetary gears (Figure 7). Volkswagen AG has even been successful at proving that extremly high gearing can be rolled with the high gear for the reverse gear where module 3.75 was rolled into the full material (16MnCr5) at an extreme tooth height of 10.3 mm and a tooth height coefficient of y=2.7 (refer to Figure 8).

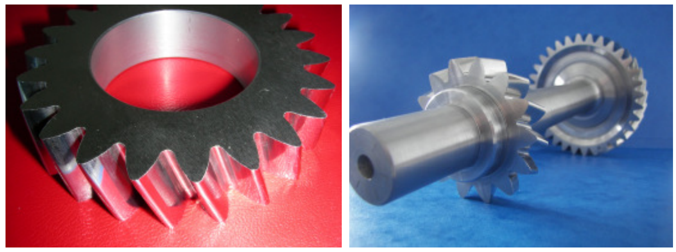

Figure 8: Transmission helical gear rolling into the full material for the first time at IWU (reverse gear at VW AG)

In conclusion, gear quality 10 as per DIN 3962 were achieved and greater potential was found for enhancing this process in geometrically exact rolling tools in a process design specifically adapted by varying machine setting parameters. Next steps will be proving that gear geometries provide better component properties due to its process-oriented property advantages (adapted fiber orientation and increased hardness in the load-bearing flanks and tooth base zone) in comparison to conventional cutting processes.

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