Evaluation of process causes and influences of residual stress on gear distortion

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ARTICLE INFO

Keywords:
Heat treatment
Deformation
Residual stress

ABSTRACT

In the automotive industry, heat treatment of components is implicitly related to distortion. This phenomenon is particularly obvious in the case of gears because of their typical and precise geometry. Even if distortion can be anticipated to an extent by experience, it remains complex to comprehend. This paper presents an approach to estimate the distortion based on the idea of a distortion potential taking into account not only geometry but also the manufacturing process history. Then the idea is developed through simulation and experiments including annealing to understand the impact of residual stress on gear distortion in an industrial case study.

1. Introduction

The inherent phenomena of the manufacturing processes involve some variations of product properties. In the case of gearbox, they affect the product functionalities and quality [1,2]. To improve product quality, it is important to know the causality between Process Key Characteristics and Product Properties. This paper focuses on the heat treatment which is applied to improve mechanical properties and to match specifications. Heat treatment also has side effects such as geometrical variations on global and local scales [3].

Distortion is related to several causes. This study focuses on residual stress, which is one of these factors, and its influences on distortion after heat treatment are evaluated through experiments and simulation.

2. State of the art

Distortion during heat treatment is due to these major phenomena:

- spatial and temporal heterogeneity of temperature during heating and quenching which leads to heterogeneous dilatations [4];
- timing of phase transformations, for example from austenite to martensite [4,5];
- transformation induced plasticity (TRIP) [6];
- decrease of yield strength when temperature increases which causes stress relief by plastic deformation [4].

Distortion after heat treatment can be seen as the result of a distortion potential gradually stored into the material all through the process [7,8]. Each manufacturing step contributes to the distortion potential which is physically related to physical carriers. Carriers present dependencies on each other, as shown in Fig. 1 [9].

In this study, the manufacturing process includes cold forging, machining and heat treatment. First, the relief of residual stress induced by forging affects distortion [10]. Then, during machining steps, turning and gear hobbing modify residual stress distribution and distortion [11,12]. Consequently, amongst all carriers of distortion potential described in Fig. 1, this study mainly deals with residual stress.

3. Objective

The global aim of this project is to improve the understanding of gearbox shaft tooth distortion during heat treatment. Experiments and simulations are carried out with a secondary gearbox shaft coming from automotive industry.

It has been observed that teeth distortion is a consequence of size and shape changes of the base-body [3]. Moreover, metrology software does not always apply the independence principle. Thus, previous works proposed a way to distinguish local and global deformations in measurement analysis [13,14]. As a result, we consider global and local geometry independently.

The first goal of the present study is to prove the influence of the carrier "residual stress" [9] on heat treatment distortion. The second objective is to observe if deformation behaviours on local and global scales are related. Thirdly as manufacturing chronologies sometimes depends on production plants, the impact of the manufacturing chronology on residual stress is investigated by simulation. The overall objective is to know more about residual stress: its consequences on geometry after heat treatment and its causes towards manufacturing history.

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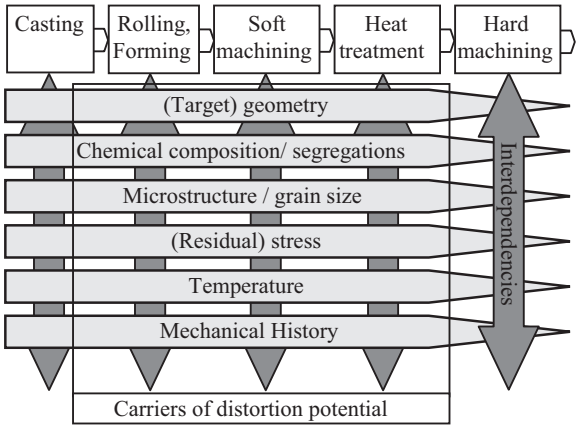

Fig. 1. Process chain prior to operational behaviour and carriers of distortion potential of a typical component for the transmission industry [9].

4. Residual stress experiments

4.1. Experimental procedure

First in order to observe the influence of residual stress after machining on heat treatment distortion, behaviours of various lots are experimentally compared, as shown in Fig. 2. After machining, gearbox shafts are separated in three different lots. Lot A is not stress relieved, lot B is stress relieved during 4 h at 200 °C and lot C is stress relieved during 4 h at 600 °C under an argon atmosphere.

Residual surface stresses in axial and tangential directions are measured by X-ray diffraction on 3 shaft sections at stages 1 and 2. Material contains more than 95% of ferritic steel therefore X-ray diffraction appears as a thin and intense peak. Precision of the measuring takes into account curve-fitting error and reproducibility error. It is estimated to ±30 MPa.

By measuring residual surface stresses before and after stress relieving, the influence of temperature and the efficiency of stress relieving are quantified. On a global scale, the orientation and norm of shaft bending are considered. Then, teeth surface geometry is measured by a Coordinate Measuring Machine dedicated to gear metrology.

Finally we hypothesize that amongst all carriers of distortion, temperature, chemical composition/segregations and microstructure/grain size are supposed identical for the three lots at stages 1, 2 and 3 respectively.

4.2. Residual surface stresses

The residual surface stress levels in tangential and axial directions after machining are scattered and vary approximately from −310 MPa to 370 MPa, as visible in Fig. 3. Lot B residual surface stress (not represented) has been measured only on section 3 and its level is almost the same as after machining. Therefore, the 4 h – 200 °C treatment is not efficient enough to decrease radically residual surface stress. Taking into account uncertainty, difference are significant between lot A and C. In fact, lot C residual stress levels decrease to less than 150 MPa in absolute value, which is less than 20% of the rupture stress of the studied steel. Thus, the residual stress level is hypothesized as not significant after the 4 h – 600 °C stress relieving.

4.3. Global distortions

First, circular runout is measured as a function of axial angle. Radial lubrication holes visible in Fig. 2 are used as an angular reference. In the measuring plan, shaft is considered as an off-centered circle. For each shaft, identification of eccentricity by curve-fitting is made on 4 sections. Then orientation and magnitude of bending is deduced for each shaft.

Thus, by comparing global distortion after machining at stage 1 and after heat treatment at stage 3, bending has the tendency to orientate towards the vertical direction which matches to lubrication holes, see Fig. 4. Moreover, bending increases in magnitude. This distortion of the shaft is described as a "banana distortion" because of its bend profile. Actually, we do not observe any difference between the 3 lots at stage 2, therefore we do not present the results here. Stress relieving has no influence on the bending, in either orientation or magnitude.

4.4. Local distortions

By comparison between stages 1 and 2, lot B distortions are very low on chosen teeth characteristics, as visible in Fig. 5. In fact, variations are smaller than 2 μm, which is the measuring uncertainty of the measuring machine. Therefore, at this point gear distortion is considered as null for these criteria and the 200 °C treatment does not appear as influent on residual stress or gear distortion. On the contrary, lot C workpieces show higher variations, especially for $f_{H\beta}$ which is the helix slope deviation as defined in [1]. The total cumulative pitch deviation on the left flank F_{p_left} has also a greater mean for lot C than lot B. The distortion is low for the profile slope deviation $f_{H\alpha}$ [1]. Finally, the 600 °C treatment leads to distortions that are very close to usual heat treatment distortions.

During heat treatment, lot A shows higher distortions in the mean, especially on total cumulative pitch deviation F_p for both flanks and on the helix slope deviation $f_{H\beta}$, as shown in Fig. 6. Lot B workpieces have scattered results, therefore lot B has high standard deviation. Stress relieved workpieces from lot C have weaker distortions than those from lot A. Therefore, 4 h – 600 °C stress relieving leads to weaker distortion. For all lots, distortions are very weak in the case of profile slope deviation $f_{H\alpha}$.

4.5. Experiment analysis

The experiment presented here allows us to deduce two main results:

- Residual stress level has been decreased by the 600 °C – 4 h heating. During heat treatment, stress relieved shafts have

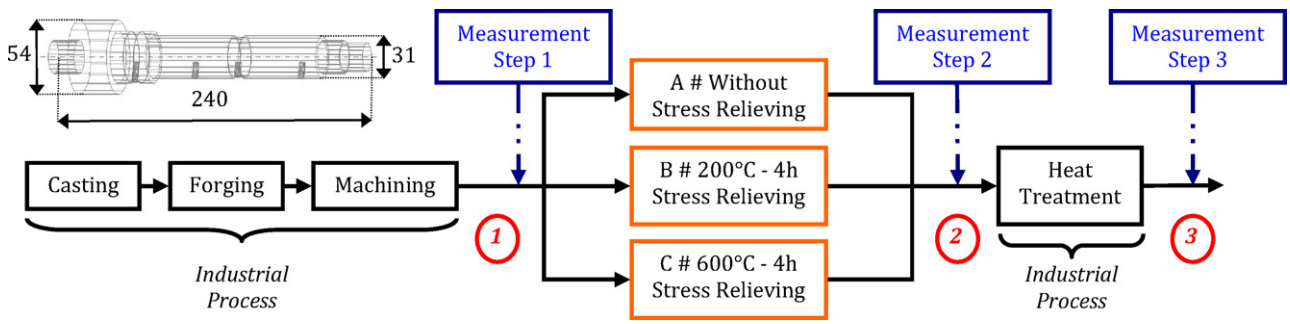

Fig. 2. Experimental plan, 3 different lots (A–C) are set up after machining. Lot A is not stress relieved, lot B is stress relieved during 4 h at 200 °C and lot C is stress relieved during 4 h at 600 °C. Then, these 3 lots are heat treated together. Main dimensions of the shaft are given in mm.

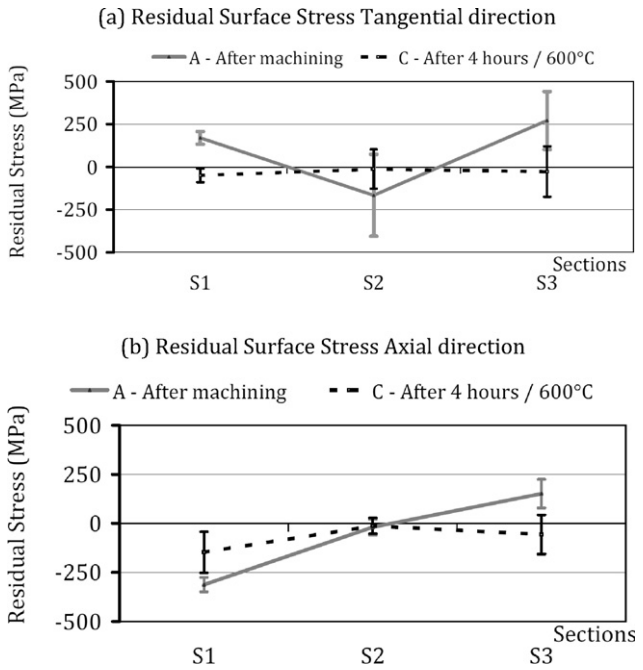

Fig. 3. Residual surface stresses on tangential (a) and axial (b) directions for 3 sections of 2 shafts from lot A and 2 shafts from lot C, represented with standard deviation plus uncertainty. (a) Residual surface stress tangential direction, (b) residual surface stress axial direction.

lower gear distortion than shafts that have undergone no stress relieving. Nevertheless, bending behaviour is identical for all lots.

- Lot B shafts do not undergo gear distortion during stress relieving, therefore they kept the same geometry as lot A shafts. However, heat treatment distortions are lower in the mean for lot B than lot A. Therefore, independently from geometry the "residual stress" and/or "mechanical history" carriers of distortion potential have an influence on gear distortion.

As seen in Fig. 1 [9], dependencies exist between carriers of distortion potential. In the aforementioned experiment, the implicit hypothesis of identical geometry, temperature, chemical composition/segregations, microstructure/grain size has been assumed for the 3 lots at stage 2. However, mechanical history has not been considered. The next section will focus on the influence of mechanical history on the residual stress state.

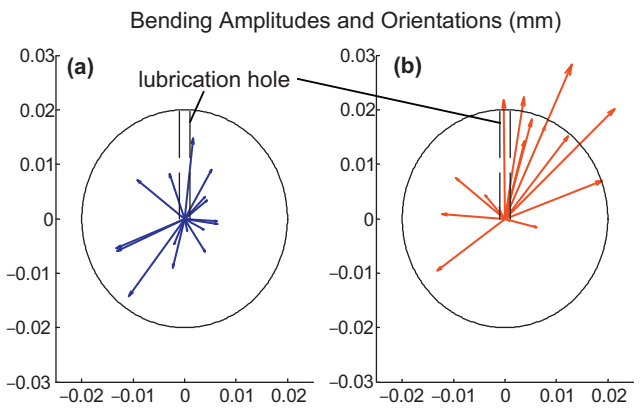

Fig. 4. Angular orientation of bending after machining at stage 1 (a) and after heat treatment at stage 3 (b). Cross section (orthogonal to the shaft axis) of workpieces coming from lots A, B and C. Bending orientation and magnitude are identified from runout measurements.

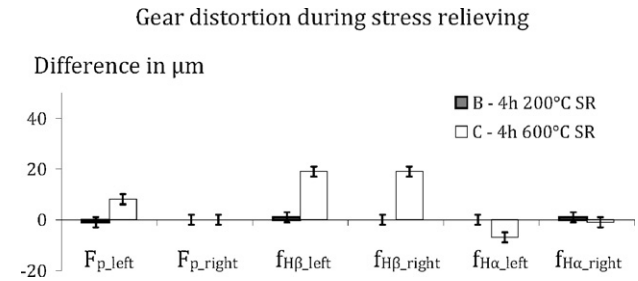

Fig. 5. Gear distortions for 1 shaft from lot B: 4 h – 200 °C stress relieving (SR) and 1 shaft from lot C: 4 h – 600 °C stress relieving, represented with uncertainty. F_p: total cumulative pitch deviation, $f_{H\beta}$: helix slope deviation, $f_{H\alpha}$: profile slope deviation.

5. Residual stress simulation

5.1. Simulation procedure

In order to observe the influence of mechanical history on residual stress, two different virtual manufacturing processes have been computed by FEM simulation on "Forge 2009"® in the case of a *Z* axis 20MnCr5-steel cylinder (length: 100 mm, diameter: 30 mm).

The initial state: first, +700 MPa residual stress in *ZZ* direction for the inside and −600 MPa residual stress in *ZZ* direction for the outside is applied. Initial values of −600 MPa and 700 MPa before balancing have been chosen arbitrarily. In fact, the idea is to apply high residual stress values to ensure the visibility of results.

Then, a geometry/residual stress balance operation takes place in simulation.

- Process 1: the shaft is drilled (12 mm-through hole) then turned (2 mm-depth cutting).
- Process 2: the shaft is turned (2 mm-depth cutting) then drilled (12 mm-through hole).

Machining operations in Forge® do not impact residual stress but only remove material. After that, residual stress is balanced. Drilling and turning are identical and lead to the same geometrical removal. Temperature, microstructure and chemical composition are considered as homogeneous during simulations. Consequently, the only difference between both processes is their history.

5.2. Simulation results

Two processes are applied in parallel, drilling on the one hand and turning on the other hand. Residual stress levels are obtained by simulation. Therefore, uncertainty can be due to numerical errors and due to a difference between models and experiments. Nevertheless, the goal here is to observe if residual stress levels are significantly different; high precision is not required.

Finally by material removal and residual stress balance, the residual stress levels of both parts decrease. Nevertheless, residual stress distributions are different. Drilling – turning process leads to greater magnitudes of *ZZ* direction residual stress, from −20 to

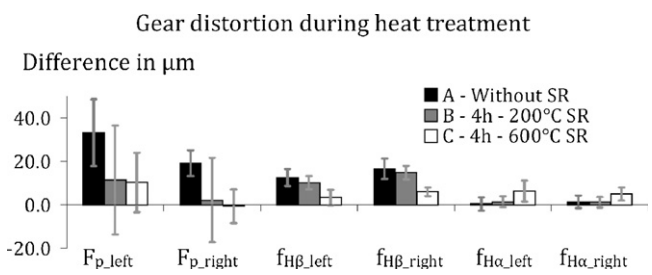

Fig. 6. Gear distortions during heat treatment for lots A (5 shafts), B (5 shafts) and C (3 shafts) represented with standard deviation plus uncertainty. F_p: total cumulative pitch deviation, $f_{H\beta}$: helix slope deviation, $f_{H\alpha}$: profile slope deviation.

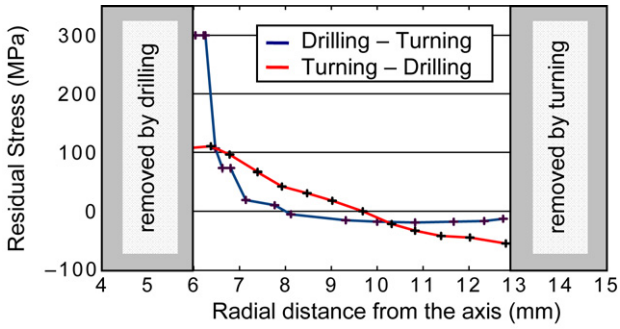

Fig. 7. Residual stress in *ZZ* direction for drilling–turning process shaft and turning–drilling process shaft depending on radial distance from the axis.

300 MPa (see Fig. 7). Decreasing gradient is high within the first hundredths of millimetre from the inside of the shaft. Such a distribution is inherited from the initial state and heart disappearance. In fact, during drilling, the heart of the part disappears, removing high levels of residual stress. Thus, after this manufacturing step, positive stress areas are smaller, and then the part is balanced. On the contrary, the turning – drilling process generates smaller variations. This effect can probably be explained by more progressive residual stress balances within the part during the turning – drilling process.

5.3. Simulation analysis

During this simulation, high residual stress levels and significant machining steps have been chosen to provide visibility. Accordingly, significant differences are observable between both final parts. Geometrically speaking, the manufacturing steps have been identical; history was the only variable under consideration. Thus, process chronology appears to have an influence on final residual stress.

6. Conclusion

Distortion potential is dependent on various factors of influence, also known as carriers of potential. In this study, due to the manufacturing process and state of the art, the focus has been on residual stress.

The experimental plan improves the understanding of the consequences of residual stress on heat treatment distortion:

- Greater magnitudes of residual stress lead to higher tooth distortions. Residual stress is an influent carrier of distortion potential.
- On the other hand, the influence of residual stress on the orientation and magnitude of shaft bending has not been observed. Therefore, influences of the residual stress on distortion are high on a local scale but not on a global scale. No relationship has been observed between the two scales of distortion.
- Simulation revealed the influence of mechanical history on residual stress. Dependencies exist between those two carriers of potential distortion at a significant level.

As a result, residual stress has to be taken into account in the manufacturing process including heat treatment. Residual stress is a highly important carrier of distortion, especially for the tooth surface. As a first consequence, taking into account residual stress in manufacturing processes design and process chronology is a way to limit distortion. Concretely, a solution to decrease distortion could be to apply stress relieving before heat treatment. In this case, distortion occurring during stress relieving should be anticipated or corrected by machining. Secondly, once critical manufacturing steps and required residual stress distribution are identified, cutting conditions can be updated. Therefore, residual stress will be taken into account in-process.

A future work will be to study the consequences of stress relieving before heat treatment in more detail. It has been observed that decreasing residual stress levels is a way to decrease heat treatment distortion. Nevertheless, residual stress also has an impact on the fatigue strength of the workpiece. Both geometry and mechanical characteristics are product properties that are influenced by addition of stress relieving in the manufacturing process.

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