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# Experimental identification of the process influences on gear distortion during heat treatment

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## Résumé :

*Le traitement thermique est utilisé dans l'industrie automobile afin d'améliorer les propriétés mécaniques des pièces fabriquées. Il a également pour effet secondaire de conduire à des déformations géométriques. La littérature scientifique et les retours d'expérience industriels montrent que l'ensemble de la gamme de fabrication en amont du traitement thermique joue un rôle dans l'apparition des défauts. L'objectif des travaux vise à déterminer expérimentalement l'influence de chaque étape de fabrication en amont du traitement thermique sur les déformations des dentures, par neutralisation des contraintes résiduelles. Les résultats permettent de relier chaque type de déformation sur les paramètres géométriques de la denture à une ou plusieurs étapes de fabrication en particulier. Lorsqu'une dérive sur le procédé est détectée sur un critère géométrique, la méthode ainsi développée permet de diagnostiquer l'origine du défaut au sein de la gamme de fabrication amont.*

## Abstract :

*Heat treatment is widely used in automotive industry to improve mechanical properties of workpieces. It also generates side effects such as geometrical distortions. Scientific literature and experience show that the manufacturing process chain has an influence on heat treatment distortion. The purpose of the presented work is to experimentally determine the influence of each pre-heat treatment step on gear distortion. Residual stress is being neutralized and by comparison, connections between gear teeth geometry and manufacturing step are obtained. As a consequence, non-conformities roots can be determined more easily thanks to this diagnosis tool.*

**Keywords :** Heat-treatment ; Gear ; Manufacturing

## 1 Introduction

### 1.1 Context

Geometrical variations during heat treatment are on global and local scales [1]. Distortion is related to several causes. This study focuses on residual stress, which is one of these factors. Its influences on distortion after heat treatment is evaluated through experiments. In our case, majors distortions during heat treatment occur on gear teeth at two geometrical scales. The global aim of this project is to support both the design and the development of the manufacturing process chain. Thus, it will improve the control of gear quality.

### 1.2 State of the art

First of all, distortion during heat treatment is a consequence of these major phenomena :

- spatial and temporal heterogeneity of temperature during heating and quenching which leads to heterogeneous expansion [2] ;
- timing of phase transformations, for example from austenite to martensite [2] ;

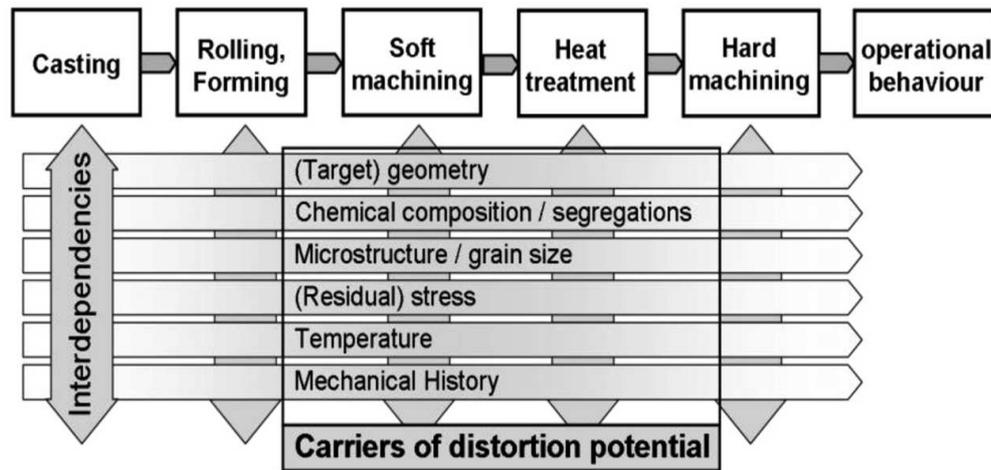


FIGURE 1 – Process chain and carriers of distortion potential of a typical component for the transmission industry before operational behaviour [4].

– decrease of yield strength when temperature increases which causes stress relief by plastic deformation [2].

One idea is to consider distortion after heat treatment as the result of a distortion potential gradually stored into the material all through the process [3]. Each manufacturing step contributes to the distortion potential which is physically related to physical carriers. Carriers present dependencies on each other, as shown in Figure 1 [4].

### 1.3 Objective

In this study, the manufacturing process includes cold forging, machining and heat treatment. First, the relief of residual stress induced by forging affects distortion [5]. Then, during machining steps, gear hobbing modifies residual stress distribution and distortion [6]. Consequently, among all carriers of distortion potential described in Figure 1, this study first focuses on residual stress. The global aim of this project is to improve the understanding of gearbox shafts distortion during heat treatment. Experiments are carried out with a gearbox shaft of automotive industry. During our experiments, the manufacturing process presented in Figure 3 is not necessarily the same as industrial one in terms of technology and chronology. Nevertheless, the manufacturing process has been chosen to emphasise influences of residual stress on heat treatment distortion.

## 2 Experiments

### 2.1 Experimental Procedure

By considering two manufacturing step  $k$  and  $k - 1$  as represented in Figure 2, two lots are compared. In order to observe the influence of a carrier of potential distortion, this carrier is neutralized between these two steps. After manufacturing step  $k - 1$ , both lots  $A$  and  $B$  have the same geometry  $G_{A(k-1)}$  and  $G_{B(k-1)}$ . Then, lot  $A$  goes directly to next manufacturing step  $k$  to obtain geometry  $G_{A(k)}$  while lot  $B$  is being "neutralized". At last, lot  $B$  will pass through manufacturing step  $k$  leading to geometry  $G_{B(k)}$ . In the case of a geometrical deformation due to the neutralization, this variation can be checked thanks to a comparison between  $G_{B(k-1)N}$  and  $G_{B(k-1)}$ . Finally, by comparing geometry of lot  $A$  ( $G_{A(k)}$ ) and lot  $B$  ( $G_{B(k)}$ ) after manufacturing step  $k$ , the influence of the carrier of distortion potential is revealed.

This approach has been applied to an experimental manufacturing process, as presented in Figure 3. The neutralization that has been chosen is a 4-hour 600°C stress relief (designated by "SR"). Its effi-

ciency to decrease significantly residual stress has been checked [7]. 8 lots are considered : 1 lot without any stress relief and 7 lots that are stress relieved once during their manufacturing history. Thus, 131 workpieces are manufactured under similar conditions in terms of time, tools and machines. Some parts have been removed, which explains non homogeneous lots. At last, each workpiece is identified with a letter from its lot name. Gears are measured by a coordinate-measuring machine whose uncertainties are evaluated to  $5 \mu m$  for first scale of gears (cf. Figure 4) and  $3 \mu m$  for second scale (cf. Figure 5).

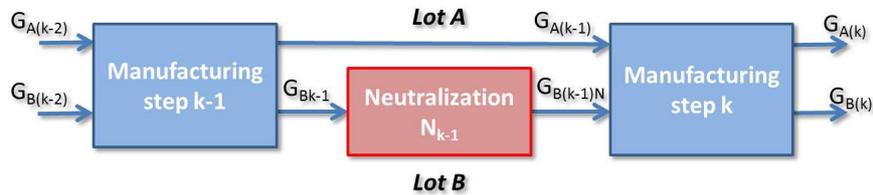


FIGURE 2 – Experimental Principle, 2 different lots ( $A$ ,  $B$ ) are set up after manufacturing step  $k - 1$ . Contrary to lot  $B$ , lot  $A$  is not neutralized. By comparing geometry of lot  $A$  and lot  $B$  after manufacturing step  $k$ , the influence of the carrier of distortion potential is revealed.

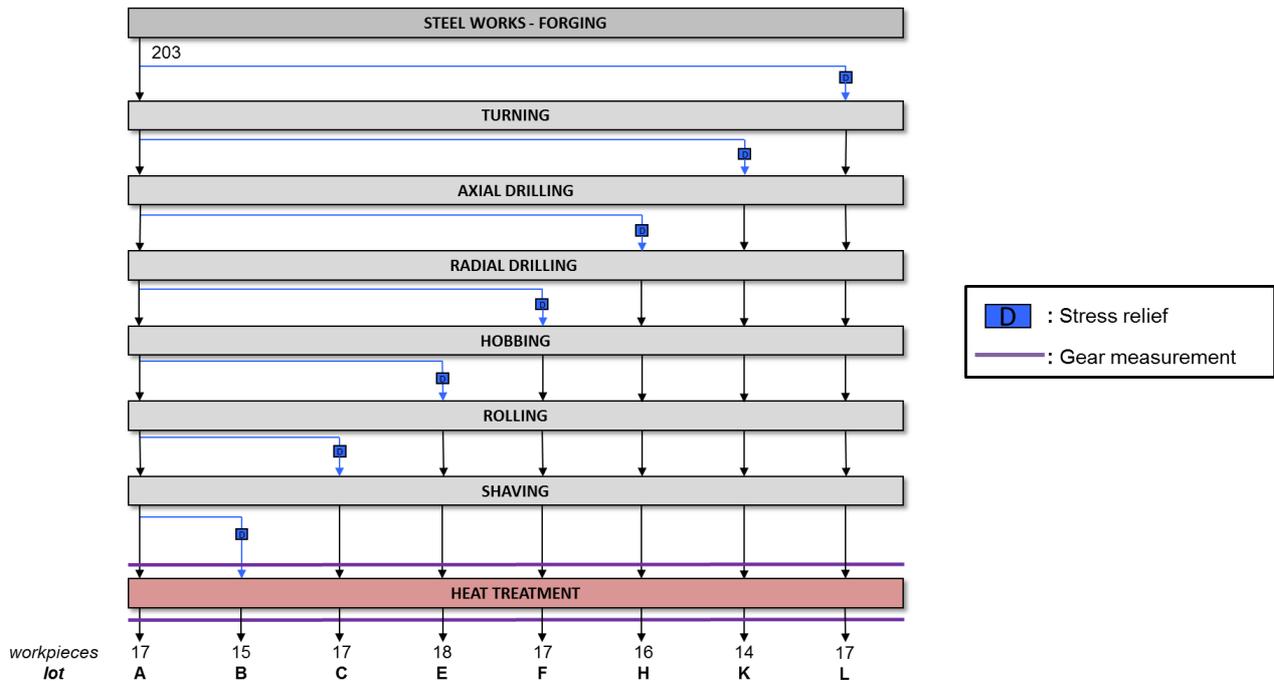


FIGURE 3 – Experimental manufacturing process and procedure. Each one of 7 lots  $B, C, E, F, H, K, L$  is stress relieved once during its history. By comparing geometry of two lots, the influence of the carrier of distortion potential is revealed.

## 2.2 Results

Hobbing process is not capable to deliver gear geometry that is exploitable at a small geometrical scale. For this reason, the evolution of geometry during stress relief for all lots except  $B$  is not presented here. First level of gear parameters results as defined in [8] is presented in Figure 4. The four levels increase during heat treatment. For instance measurement over pins  $MrK$  rises to about 0.15 mm. Dispersion

is high for the other parameters. Nevertheless, it is possible to identify qualitative tendencies and to rank all the lots in two categories for run out over pin  $Fr$  and total cumulative pitch deviation  $Fp$  :

- lots  $B, C, H, K, L$  are stress relieved respectively after shaving, rolling, axial drilling, turning and forging. Values of  $Fr_1, Fp_{l1}$  and  $Fp_{r1}$  are attributed.
- lots  $E$  and  $F$  are stress relieved after hobbing and radial drilling. Values of  $Fr_2, Fp_{l2}$  and  $Fp_{r2}$  are attributed.

Lot  $B$  has small geometrical variations during stress relief for the four considered parameters. However, a small decrease is visible for measurement over pins. In other words, stress relief leads to a slight contraction of the gear. Other first level parameters are not sensible to variations. During heat treatment, lot  $B$  has the lowest run out over pin  $Fr$  and total cumulative pitch deviation  $Fp$ .

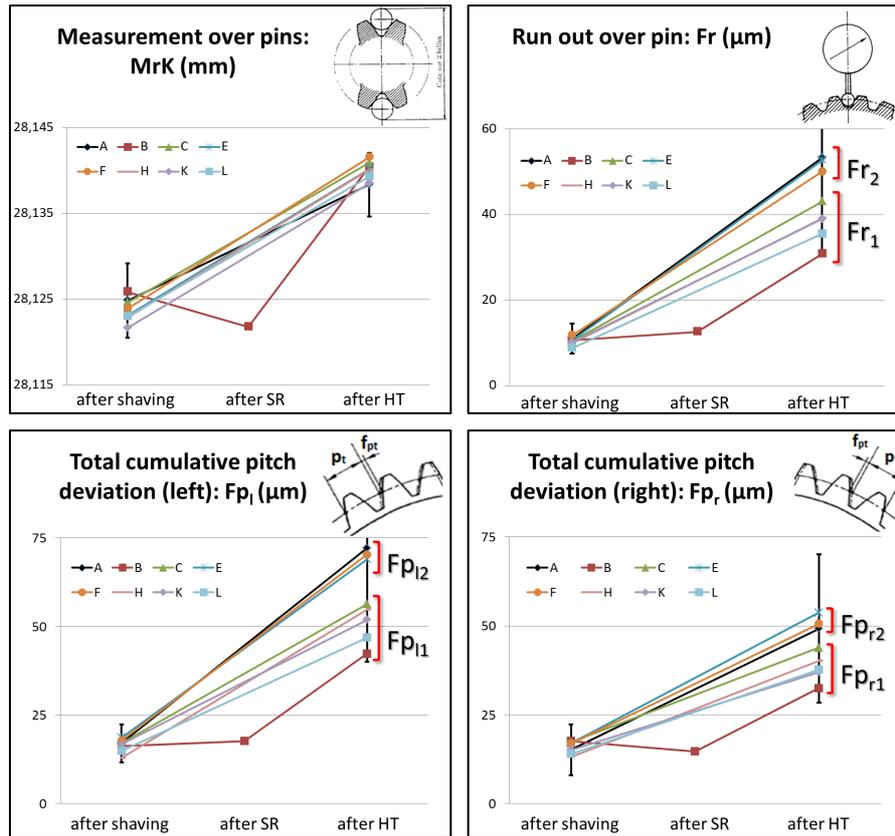


FIGURE 4 – Evolution of measurement over pins  $MrK$ , run out over pin  $Fr$  and total cumulative pitch deviation for left ( $Fp_l$ ) and right flanks ( $Fp_r$ ) of 8 lots during heat treatment (HT). Lot  $B$  is the only one to be stress relieved (SR) after shaving. Lot  $A$  is represented with its uncertainty.

At a second level of analysis, profile and helix slope deviations results are presented in Figure 5. Dispersion is lower than previously and it is easier to distinguish various behaviours. The mean value is calculated on three teeth for lot  $A$  (standard workpieces) and is worth less than  $1 \mu m$  after shaving and less than  $2 \mu m$  after heat treatment, which is below measurement uncertainty. Here, comparison between lots is quantitatively exploitable. Proximity between values regarding the profile slope deviation  $fH_{\alpha r}$  is too small and does not allow a valid classification for this parameter. The right helix can be separated in two groups : lot  $B$  with the value  $fH_{\beta r2}$  and the other lots with the value  $fH_{\beta r1}$ . Profile and helix on the left flank enable a classification visible in Figure 5 :

- lot  $B$  is stress relieved after shaving. Values of  $fH_{\alpha l1}$  and  $fH_{\beta l3}$  are attributed.
- lots  $C$  and  $E$  are stress relieved respectively after rolling and after hobbing. Values of  $fH_{\alpha l2}$  and  $fH_{\beta l1}$  are attributed.

– lots  $F$ ,  $H$ ,  $K$ , and  $L$  are stress relieved respectively after radial drilling, after axial drilling, after turning and after forging. Values of  $fH_{\alpha 13}$  and  $fH_{\beta 12}$  are attributed. Lot  $B$  workpieces have almost similar values for second level parameters after heat treatment than lot  $A$  ones. This means that, stress relief after shaving does not influence the final gear geometry of second level teeth geometry.

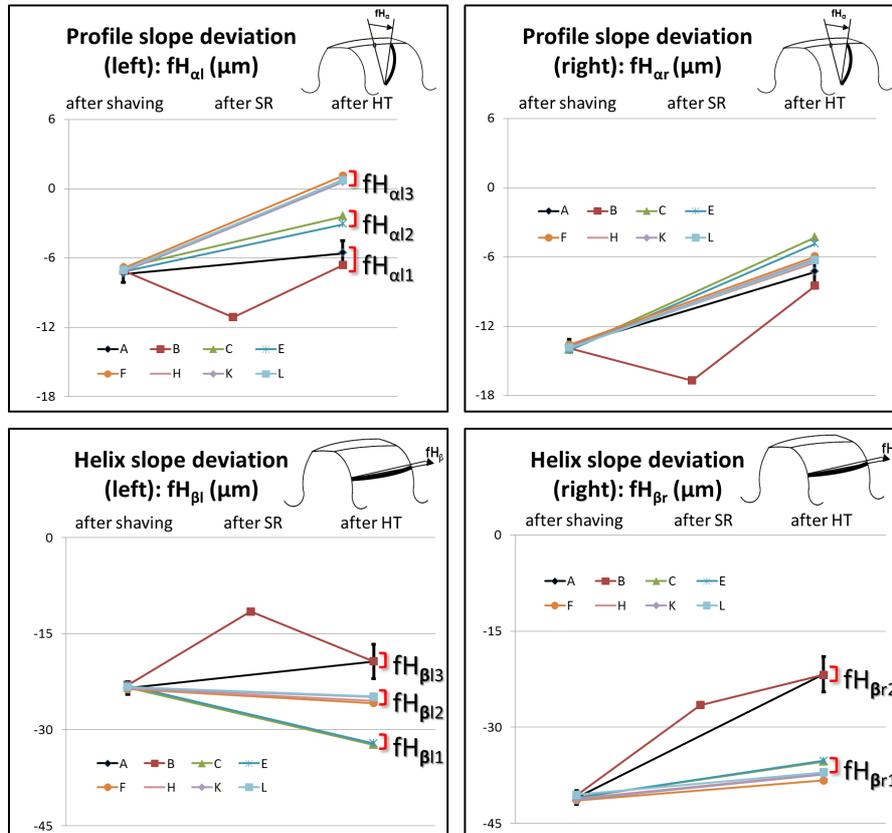


FIGURE 5 – Evolution of profile slope deviation ( $fH_{\alpha}$ ) and helix slope deviation ( $fH_{\beta}$ ) for left and right flanks of 8 lots during heat treatment (HT). Lot  $B$  is the only one to be stress relieved (SR) after shaving. Lot  $A$  is represented with its uncertainty.

### 2.3 Discussion

First, both gear levels showed different classifications. Consequently, gear distortion during heat treatment depends on the geometrical scale. Then, the approach by neutralization and comparison can be applied thanks to previous results. The purpose is to determine the influence of the carrier of distortion potential on the gear distortion. In our case, this carrier is "residual stress" and it is correlated to each manufacturing step. To obtain its influence, differences between previously obtained values are calculated and presented in Table 1.

At first geometrical level, only two manufacturing steps modifies significantly the "residual stress" carrier of distortion : radial drilling and rolling. Radial drilling appears as favourable for first level gear geometry. On the contrary, rolling modifies the residual stress distribution in such a way that it leads to an unfavourable impact on the shaft after heat treatment. Rolling is a cold-press forming process. If the geometrical and stress balance between the two rolling racks and both tips is not respected, then residual stress can be heterogeneous. It may cause deformation during heat treatment.

| Step            | Difference between lots | First level Gear Teeth<br>$F_r, F_{pl}, F_{pr}$ | Second Level Gear Teeth |                 |                |                |
|-----------------|-------------------------|---|-------------------------|-----------------|----------------|----------------|
|                 |                         |   | $fH_{\alpha l}$         | $fH_{\alpha r}$ | $fH_{\beta l}$ | $fH_{\beta r}$ |
| Turning         | $L - K$                 | NS  | NS                      | NA              | NS             | NS             |
| Axial Drilling  | $K - H$                 | NS  | NS                      | NA              | NS             | NS             |
| Radial Drilling | $H - F$                 | $< 0$   | NS                      | NA              | NS             | NS             |
| Hobbing         | $F - E$                 | NS  | $> 0$                   | NA              | $> 0$          | NS             |
| Rolling         | $E - C$                 | $> 0$   | NS                      | NA              | NS             | NS             |
| Shaving         | $C - B$                 | NS  | $> 0$                   | NA              | $< 0$          | $< 0$          |

TABLE 1 – Influence of each manufacturing step on the teeth distortion potential through the carrier "residual stress". The indicated value takes into account the norm but not its sign. "NS" refers to non-significant and "NA" to not applicable.

In the case of the second geometrical level, only hobbing and shaving have an influence on profile and helix slope deviations. Hobbing and shaving are respectively rough machining and finish machining of the gear. Consequently, they are implicitly linked to the gear geometry. But their influences depend on gear parameter according to Table 1. For example in the case of profile slope deviation of the left flank  $fH_{\alpha l}$ , hobbing and shaving tend to increase the distortion potential because of the "residual stress" carrier. Results also show possible correlations between profile slope deviation of the left flank  $fH_{\alpha l}$  and helix slope deviation of the left flank  $fH_{\beta l}$  because classification between lots is similar.

### 3 Conclusions and Perspectives

Thanks to the presented study, each gear geometrical parameter can be related to manufacturing steps. By neutralization and comparison, the "residual stress" carrier of distortion potential has been revealed. As a consequence, when a non-conformity is detected after heat treatment for this experimental process, the synthesis table can be used as a diagnosis tool to correct machining parameters. Thanks to these results, time and cost savings will be earned during production. New production lines will be designed taking into account this feedback. Another further study on the shaft bending and correlation between various geometrical scales would provide more data about the complex phenomenon of heat treatment distortion.

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