Consideration of residual stress and geometry during heat treatment to decrease shaft bending

Rémi Husson · Cyrille Baudouin · Régis Bigot · Edoardo Sura

Abstract In automotive industry, heat treatment of components is implicitly related to distortion. This phenomenon is particularly obvious in the case of gearbox parts because of their typical geometry and precise requirements. Even if distortion can be anticipated to an extent by experience, it remains complex to comprehend. Scientific literature and industrial experience show that the whole manufacturing process chain has an influence on final heat treatment distortions. This paper presents an approach to estimate the influence of some factors on 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 experiments on an industrial manufacturing process to understand the impact of residual stress due to machining on shaft bending and teeth distortion during heat treatment. Instead of being measured, residual stress is being neutralized. By comparing lots between each other, connections between gear teeth geometry and manufacturing steps before heat treatment are obtained. As a consequence, geometrical nonconformities roots can be determined more easily thanks to this diagnosis tool, and corrective actions can be applied. Secondly, the influence of product geometry on bending is experimentally considered. Moreover, metallurgical observations enable to explain the influence of workpieces geometry on shaft bending. Thanks to the obtained results, process and product recommendations to decrease shafts bending are proposed.

Keywords Heat-treatment · Shaft · Manufacturing · Distortion · Identification

R. Husson (✉) · E. Sura
Renault, Powertrain Process Engineering Division,
CTR A02 010, 67 rue des Bons Raisins,
92508 Rueil Malmaison, France
e-mail: remi.husson@gmail.com

E. Sura
e-mail: edoardo.sura@renault.com

R. Husson · C. Baudouin · R. Bigot
LCFC (EA 4495)-Arts et Métiers ParisTech,
4 rue Augustin Fresnel, 57078 Metz, France

C. Baudouin
e-mail: cyrille.baudouin@ensam.eu

R. Bigot
e-mail: regis.bigot@ensam.eu

1 Introduction

Heat treatment is widely used in automotive industry in order to improve mechanical properties of workpieces. Nevertheless, heat treatment has side effects such as geometrical variations on global and local scales [1]. Industrially, it means that these defects sometimes lead to increase scrap rates. In order to limit this problem, the goal of this study is to improve the understanding of distortion phenomena and so the quality of manufacturing.

Distortion is related to several causes. This study experimentally focuses on residual stress and geometry, which are two of these factors, and their influences on distortion after heat treatment are evaluated through experiments. In our case, major distortions during heat treatment are the bending of the shafts and teeth distortions. Therefore, these geometrical parameters are considered during this study. 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.

2 State of the art

Distortion during heat treatment is a consequence of the following three major phenomena:

- Spatial and temporal heterogeneities of temperature during heating and quenching leading to heterogeneous expansion [2]
- Timing of phase transformations, for example from austenite to martensite [2]
- Decrease of yield strength when temperature increases causing stress relief by plastic deformation [2]

A high number of process parameters influences distortion. They are evaluated to more than 200 [3]. Moreover, Fig. 1 shows that distortion during heat treatment is not only due to heat treatment but also to previous manufacturing steps. As a consequence, dealing with heat treatment distortion is complex and requires taking into account the entire manufacturing process. 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 [4]. Each manufacturing step contributes to the distortion potential, physically related to physical carriers. Carriers have dependencies on each other, as shown in Fig. 2 [5].

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 [6]. Then, during machining steps, turning and gear hobbing modify residual stress distribution and distortion [7]. As a consequence, residual stress can be considered in this study as a major factor of distortion [8]. Thus, among all carriers of distortion potential described in Fig. 1, this study first focuses on residual stress.

On the other hand, geometry also has a significant influence on distortion phenomena. For example, a heterogeneous geometry will generate a heterogeneous cooling and then distortions [9]. That is why this study secondly deals with the influence of geometry on distortion. The distortion is defined as the difference between geometry after a manufacturing step and geometry before this step. Geometry is measured all along the process by a coordinate-measuring machine.

As previously said, residual stress and geometry have dependencies on each other [5]. Indeed, when residual stress relieves, elastic and/or plastic deformation happen, modifying geometry of the workpiece. Microstructure also

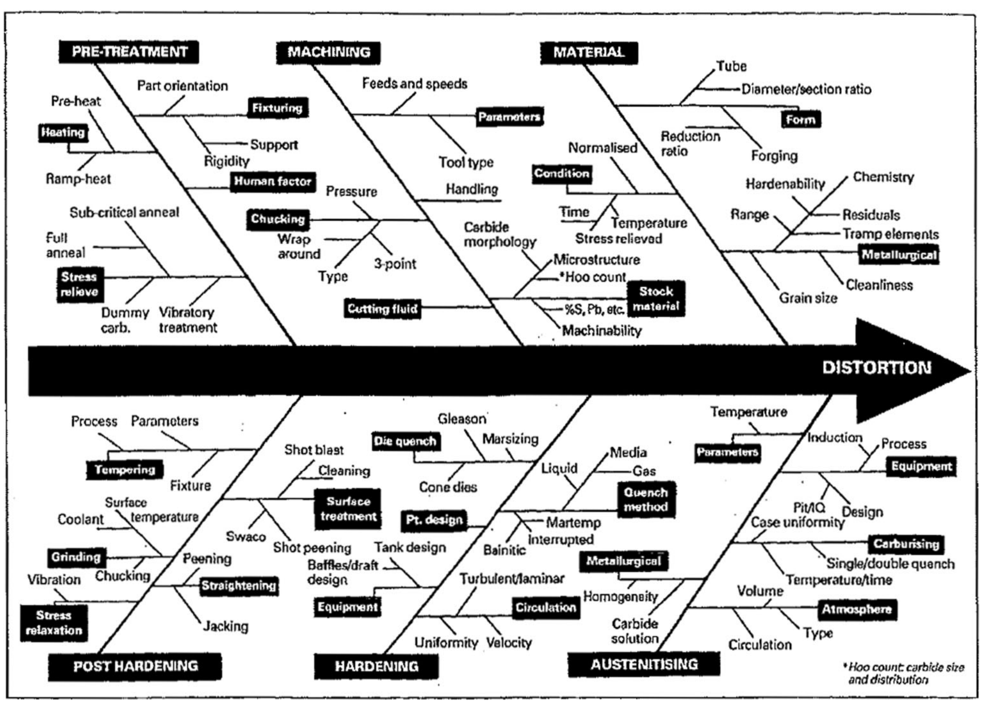

Fig. 1 Synthesis of major factors influencing distortion during heat treatment [2]

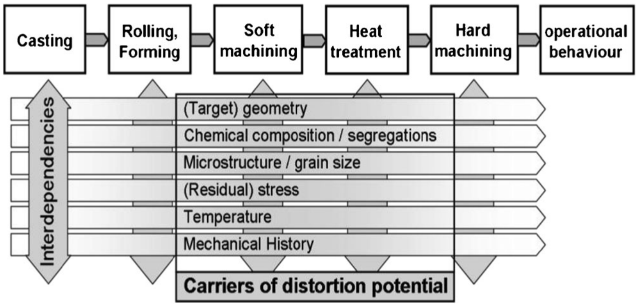

Fig. 2 Process chain and carriers of distortion potential of a typical component for the transmission industry before operational behavior [5]

appears as a factor influencing other carriers of distortion potential. In the case of our study, it has been observed that microstructure does not evolve during stress relief and manufacturing (except during heat treatment) and can be considered as steady [10]. As a consequence, residual stress and geometry will be both studied.

The global aim of this project is to improve the understanding of gearbox shafts and teeth distortion during heat treatment. Experiments are carried out with a secondary gearbox shaft of automotive industry represented in Fig. 3. Manufacturing steps are performed in industrial conditions in a Renault (French car manufacturer) plant. It has been observed that teeth distortion is a consequence of size and shape changes of the base-body [1]. As a consequence, by improving the understanding of shaft distortion and decreasing it, teeth distortion should be limited.

4 Experimental procedure

4.1 Experimental principle

In order to observe the influence of a carrier of potential distortion, this carrier is neutralized before heat treatment

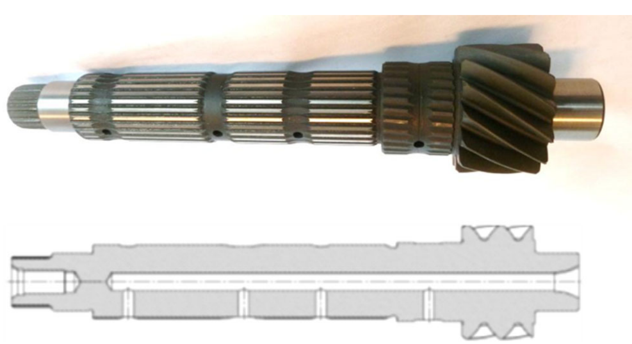

Fig. 3 Picture and cross-section view of the secondary automotive gearbox shaft used during industrial experiments. Axial and radial holes are drilled during machining to enable lubrication during operational behavior

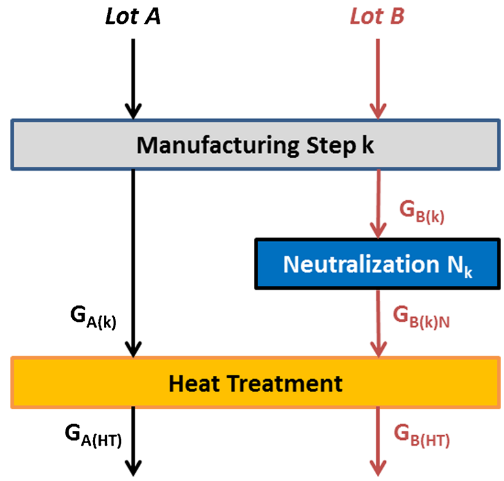

Fig. 4 Experimental principle: two different lots (A, B) are set up after manufacturing step k. Contrary to lot B, lot A is not neutralized. By comparing the geometry of lot A and lot B after heat treatment, the influence of the carrier of distortion potential is revealed

as presented in Fig. 4. After manufacturing step k, both lots A and B have the same geometry $G_{A(k)}$ and $G_{B(k)}$. Then, lot A goes directly to heat treatment and finally obtains geometry $G_{A(HT)}$ while lot B is being "neutralized." At last, lot B is heat treated. Its geometry after heat treatment is $G_{B(HT)}$. Finally, to observe the influence of the carrier of distortion on heat treatment distortion, a comparison is made between both geometries after heat treatment $G_{A(HT)}$ and $G_{B(HT)}$.

The hypothesis is made that during the residual stress neutralization, geometry remains consistent. Thanks to a comparison between $G_{B(k)N}$ and $G_{B(k)}$, this hypothesis is lately checked in Fig. 5. Indeed, stress relief does not modify shaft bending. Secondly, because machining steps are performed at ambient temperature, the carrier of distortion potential "temperature" is considered as steady during the experiments. Finally, raw parts have been selected into the same raw lot, therefore the carrier of distortion potential "material" is considered as consistent during experiments.

During the experiments, five lots are considered as follows:

- Lot A is not neutralized and all manufacturing steps are performed,
- Lot B is neutralized before heat treatment and all manufacturing steps are performed,
- Lot C is not neutralized and all manufacturing steps except radial drilling are performed,
- Lot D is not neutralized and all manufacturing steps except axial drilling are performed,
- Lot E is not neutralized and all manufacturing steps except rolling are performed.

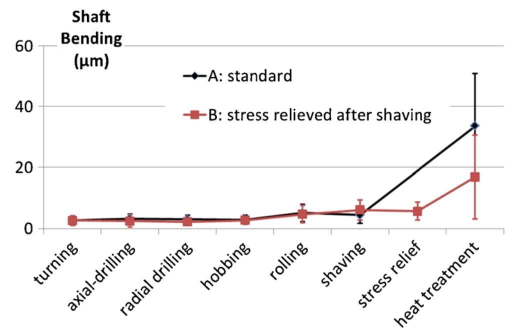

Fig. 5 Shaft Bending in ∝m for two lots A and B represented with standard deviation. Lot A and B follow the same manufacturing process with the exception: lot B is stress relieved after shaving

4.2 Application to residual stress

First, in order to observe the influence of residual stress after machining on heat treatment distortion, behaviors of two lots are experimentally compared. Evaluation of residual stress is a complex matter. Thus, instead of residual stress measurements, the before-mentioned method has been applied. After machining, gearbox shafts are separated in two different lots. Neutralization for lot B is applied through a 4-h 600 °C stress relief under a low-pressure atmosphere.

This stress relief has been chosen because it enables to decrease the levels of superficial residual stress from 300 MPa to less than 150 MPa in absolute value, which is less than 20 % of the rupture stress of the studied steel [8]. Thus, the residual stress level is hypothesized as not significant after the 4-h 600 °C stress relief. Finally, by comparing both geometries after heat treatment, the influence of residual stress due to the manufacturing process is revealed.

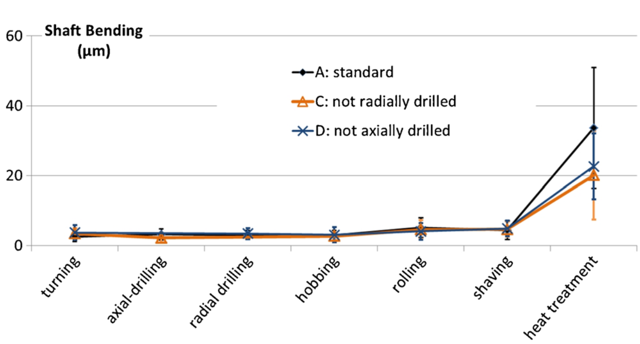

Fig. 6 Shaft bending in ∝m for three lots A, C, and D represented with standard deviation. Lot A, C, and D follow the same manufacturing process but lot C is not radially drilled and lot D is not axially drilled

4.3 Application to geometry

Once geometry is generated, it is complex to neutralize it. As a consequence, instead of adding a new step of "neutralization" as previously presented, the choice has been made to not apply a manufacturing step for one lot. In the case of the secondary shaft, experiments are made particularly on three machining operations: axial drilling, splines rolling, and radial drilling. The goal of cold-rolling is to generate splines along the shaft, as visible in Fig. 3.

Finally, by comparison between each lot and a "normal" lot, the influence of geometry on heat treatment distortion is observed.

5 Results on residual stress

By comparing shafts from lot A and B in Fig. 5, it can be seen that the amplitude of bending after heat treatment is lower for lot B that has been stress-relieved between shaving and heat treatment. Actually, shaft bending is almost the same all along the machining process for both lots and even during stress relief for lot B.

The biggest difference is observed after heat treatment where bending is about the double (34 ∝m) for lot A compared to lot B (17 ∝m). It is also visible that scattering also significantly increases during heat treatment, which confirms the instability of heat treatment in general.

As a consequence, stress relief appears as a manufacturing step which does not affect shaft bending directly but enables to decrease bending during heat treatment. Thus, applying a stress relief decreases the level of residual stress that has been stored into the material all along the process. Moreover, it does not lead to shaft bending but decreases the future bending due to heat treatment. In other words, shaft bending has an advantageous influence on the distortion potential regarding the carrier "residual stress."

Industrially, by applying a stress relief at the end of the machining process and just before heat treatment, shaft bending will be limited. Another way to take advantage of this result is to modify conditions of heat treatment in such a way that the beginning of heating becomes "softer": maintaining workpieces at about 600 °C during a few hours before increasing temperature for carbonitriding.

6 Results on geometry

6.1 Axial and radial drilling

In the case of geometry, a comparison is made between "normal" shafts (lot A), "radial drilling-less" shafts

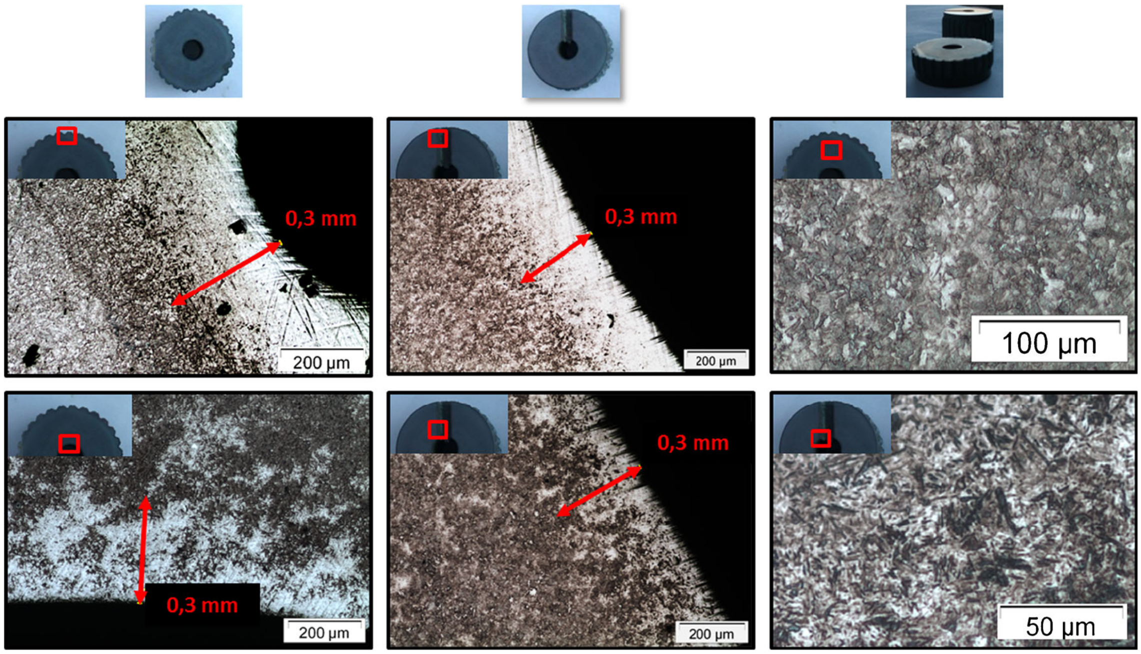

Fig. 7 Metallurgical observations after heat treatment of a lot *A* shaft. *On the left*, the first slice does not meet a radial lubrication hole. External (*above*) and internal (*below*) skins are observed. *In the middle*, along the axial hole, heat treatment affected surface varies in depth. *On the right*, the core of the workpiece contains bainite (*above*) and the skin (*below*) contains martensite

(lot C), and "axial drilling-less" shafts (lot D) in Fig. 6. As previously observed, shaft bending is low and steady all along the machining process for all the lots. The widest change of behavior is after heat treatment for scattering and most of all amplitudes. Shafts from lots C and D have a fewer bending (20 and 23 ∝m, respectively) compared to lot A (34 ∝m).

It can be explained by two possibilities as follows:

- Residual stress due to axial-drilling and/or to radial drilling has a damaging influence on the distribution of residual stress and so on the distortion potential of bending. It would explain why lot A shafts have a higher bending. Further experiments are required to confirm or not this explanation.
- By not applying axial or radial drilling, fluid circulation is not possible anymore on the inside of the shaft during carbonitriding and quenching. As a consequence, phase transformations will occur differently in amplitude and distributions. Geometry will be more homogeneous compared to lot A. It would explain decrease of shaft bending for lots C and D.

In order to confirm or not if the the fluid circulation during heat treatment affects bending, metallurgical observations have been made on two slices orthogonal to the shaft axis. By comparison of metallurgical structure in Fig. 7 between the core and the skin of the workpiece, several results appear as follows:

- A bainitic structure at the core (hardness $\simeq 370\ Hv$)
- A martensitic skin (hardness $\simeq 810\ Hv$)
- The same martensitic thickness as the skin is observed along lubrication holes but it is more diffuse

Consequently, the presence of martensite (hard microstructure) along the axial and radial lubrication holes leads to a local increase of volume and hardness. Both phenomena can unbalance the residual stress field into the

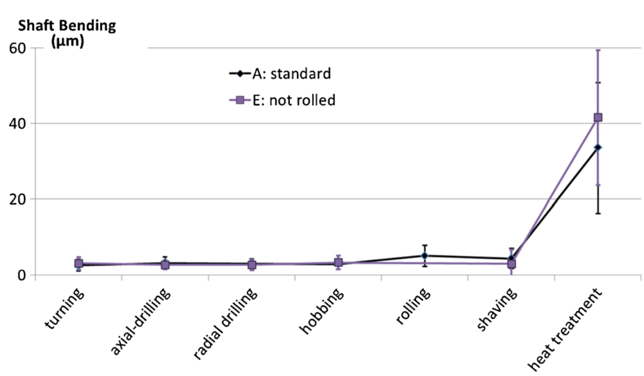

Fig. 8 Shaft bending in ∝m for two lots A and E represented with standard deviation. Lots A and E have the same manufacturing process but lot E is not rolled

workpiece and lead to bending distortion during heat treatment. Indeed, heat treatment distortion of nonsymmetrical components is higher [2]. Thus, a recommendation is to modify the orientation of the radial lubrication holes and to avoid alignment of radial lubrication holes.

6.2 Rolling

In this case, lot E shafts are more bended (42 ∝m) after heat treatment than lot A workpieces (34 ∝m), as visible in Fig. 8. Thus, geometry changes due to rolling tend to decrease indirectly heat treatment bending.

This result can be explained by two reasons as follows:

- Splines geometry increases the stiffness of the shaft, leading to lower shaft bending during heat treatment.
- Splines geometry increases external surface of the shaft. Consequently, carbon diffusion and heat transfer are greater due to the splines. Then, heat treatment is more efficient and leads to a deeper layer of martensite (hard metallurgical structure) and a higher stiffness of the shaft.

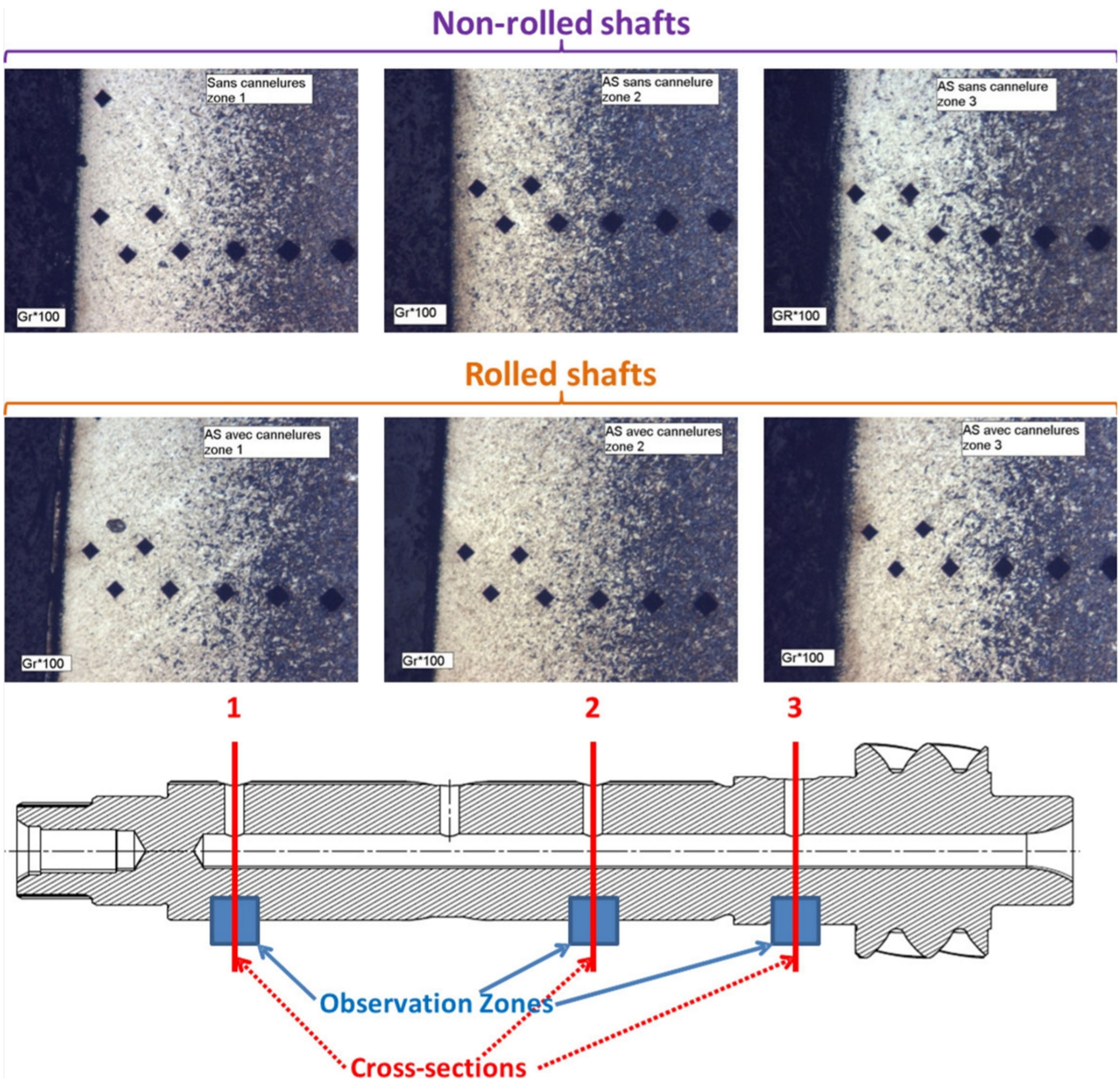

Fig. 9 Metallurgical observations (x100) after heat treatment in three cross-sections of a lot E non-rolled shaft (*above*) and of a lot A rolled shaft (*below*). The rolled shaft is more deeply affected by heat treatment

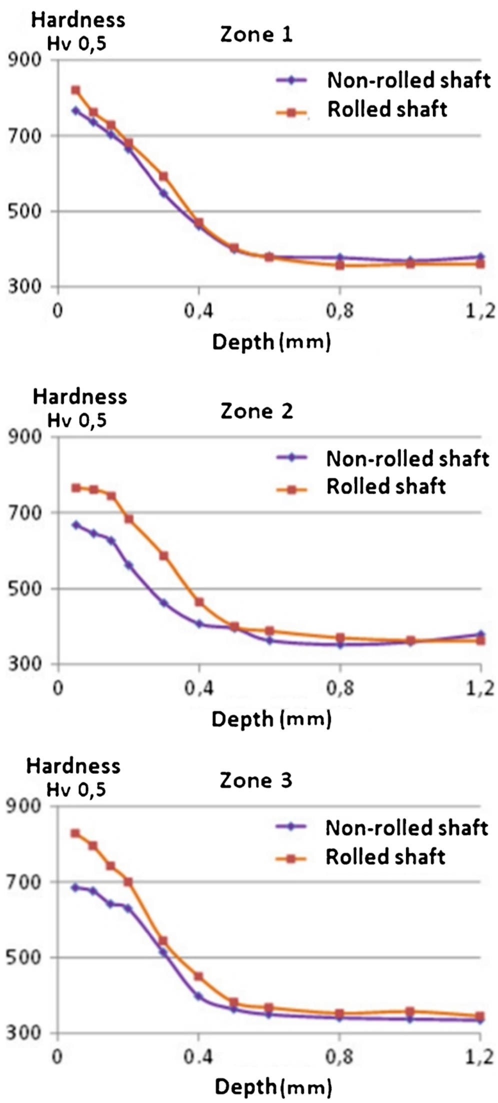

Fig. 10 Hardness $Hv0.5$ profiles for the three considered zones of observation confirm the difference of structure between both workpieces

To know more about the second phenomenon, a metallurgical observation is made on both a rolled and on a non-rolled shaft in Fig. 9. Heat treatment affects more deeply the rolled shaft than the non-rolled one. Hardness profiles confirms this differences of structure from 0 to 0.5 mm in Fig. 10. These results confirm the influence of splines (by the increase of heat transfer and the carbon diffusion) that has been previously described.

Heat treatment generates a harder skin surface for rolled shafts. Consequently, rolling increases the efficiency of heat treatment. Finally, the difference of microstructure can be an explanation to the distinct behaviors considering heat treatment bending.

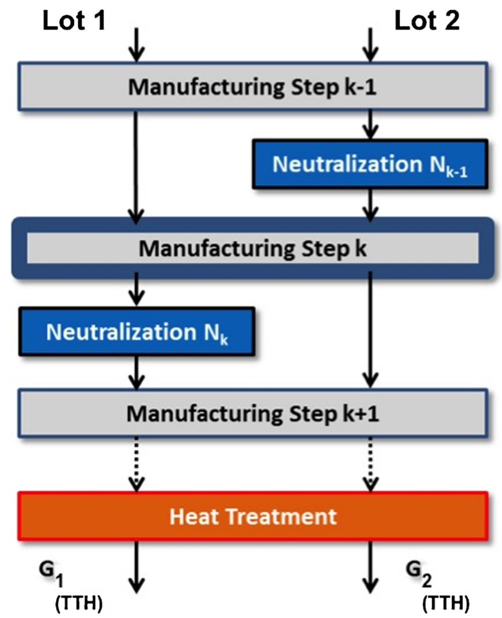

Fig. 11 Experimental principle, two different lots (*1, 2*) are neutralized before and after manufacturing step k. By comparing geometries of lots *1* and *2* after heat treatment, the influence of the carrier of distortion potential is revealed

7 Other example of evaluation of distortion potential

In order to have deeper results, further experiments were carried out. The same gearbox shaft is studied, but in this case a focus is made on the teeth. The objective is still to evaluate the distortion potential due to each manufacturing step. In order to do so, stress relief is applied to two lots. By considering the manufacturing step k as represented in Fig. 11, two lots are compared. In order to observe the influence of a carrier of potential distortion, this carrier is neutralized before and after step k. Lot 1 is neutralized after step k and lot 2 is neutralized before it. Other manufacturing steps are exactly the same for both lots. The only difference between both is the moment they have been neutralized. In the case of a geometrical deformation due to the neutralization, this variation can be checked thanks to measurements. Finally, by comparing geometry of lot 1 ($G_{1(TTH)}$) and lot 2 ($G_{2(TTH)}$) after heat treatment, the influence of the carrier of distortion potential attached to step k is revealed.

7.1 Experiments

This approach has been applied to an experimental manufacturing process, as presented in Fig. 12. The neutralization that has been chosen is the same as previously: a 4-h 600° stress relief (designated by "SR") [8]. Eight lots are considered: one lot without any stress relief and seven lots that are stress relieved once during their manufacturing history.

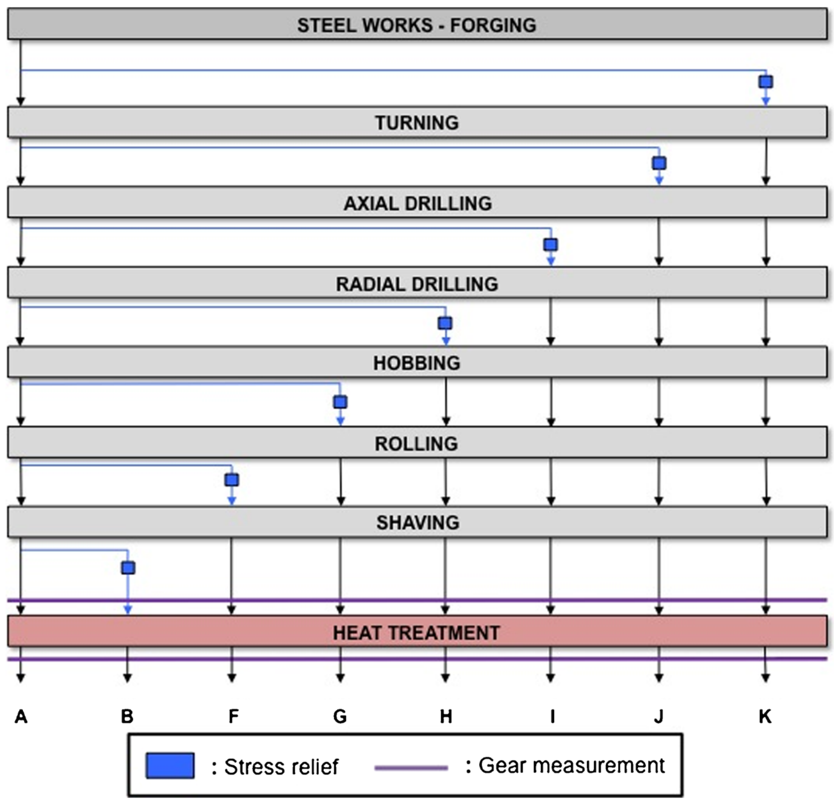

Fig. 12 Experimental manufacturing process and procedure. Each one of the seven lots B, F, G, H, I, J, K is stress relieved once during its history. By comparing the geometry of two lots, the influence of the carrier of distortion potential is revealed

Thus, 131 workpieces are manufactured under similar conditions in terms of time, tools, and machines. 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 ∝m for first scale of gears and 3 ∝m for second scale. Gear parameters are defined in [11]. Even if dispersion is quite high, it is possible to identify qualitative tendencies. Details about each result are not given here because of their complexity and confidentiality.

7.2 Results and discussion

The approach by neutralization and comparison can be applied to results and measurements. 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.

Table 1 Influence of each manufacturing step on the teeth distortion potential through the carrier "residual stress"

Step	Difference between lots	First level Gear teeth F_r, F_{pl}, F_{pr}	Second level Gear teeth $f H_{\alpha l}$	$f H_{\beta l}$	$f H_{\beta r}$
Turning	K - J	NS	NS	NS	NS
Axial Drilling	J - I	NS	NS	NS	NS
Radial Drilling	I - H	< 0	NS	NS	NS
Hobbing	H - G	NS	> 0	> 0	NS
Rolling	G - F	> 0	NS	NS	NS
Shaving	F - B	NS	> 0	< 0	< 0

The indicated value takes into account the norm but not its sign

NS refers to nonsignificant

At first geometrical level, only two manufacturing steps modify significantly the “residual stress” carrier of distortion: radial drilling and rolling. Radial drilling appears as favorable for first-level gear geometry. On the contrary, rolling modifies the residual stress distribution in such a way that it leads to an unfavorable 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.

These results are not necessary in conflict with results of Section 6 about the influence of rolling and radial drilling. In the case of Section 6, influence of a manufacturing step regarding the “geometry” carrier of distortion potential is considered. In the case of this section, influence of a manufacturing step regarding the “residual stress” carrier of distortion potential is considered. As a consequence, one influence can counterbalance another.

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 $f H_{\alpha l}$, 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 $f H_{\alpha l}$ and helix slope deviation of the left flank $f H_{\beta l}$ because classification between lots is similar.

8 Conclusion and perspectives

The proposed approach using a “neutralization” has been successfully applied to two carriers of distortion potential: residual stress and geometry. Thus, two main results have been obtained. First, shaft bending has been decreased by applying a 600 °C and 4-h stress relief before heat treatment. Secondly, by modifying the geometry of the components due to drilling and rolling, distortion during heat treatment has been changed. These geometrical influences have been explained by microstructure. As a consequence, the “shaft bending” distortion potential is highly dependent on geometry and residual stress. By improving the consistency of residual stress and geometry distribution within the process and particularly before heat treatment, shaft bending can be decreased significantly.

Moreover, by using another technique to evaluate the distortion potential, each gear geometrical parameter has been related to manufacturing steps. By neutralization and comparison, the “residual stress” carrier of distortion potential [4] has been revealed. Thus, when a nonconformity is detected after heat treatment for this experimental process, the synthesis table can be used as a diagnosis tool to correct machining parameters of the responsible manufacturing step.

Industrially, it means that residual stress as much as geometry should be taken into account during product and process design in order to limit bending distortion. Thanks to these results, time and cost savings will be earned during production. New production lines will be designed taking into account this feedback.

A further study on the shaft bending and correlation between various geometrical scales would provide more data about the complex phenomenon of heat treatment distortion. Secondly, stress relief highly decreases residual stress levels, therefore another perspective is to observe residual stress modifications and its consequences on fatigue strength of the components.

References

1. Kohlhoff T, Prinz C, Rentsch R, Surm H (2011) Influence of manufacturing parameters on gear distortion. Proc. of the 3rd international conference on distortion engineering 2011, Bremen, 14th to 16th September, pp 155–165
2. Cook WT (1999) A review of selected steel-related factors controlling distortion in heat-treatable steels. Heat Treat Met 26:27–36
3. Clausen B, Frerichs F, Kohlhoff T, Lübben T, Prinz C, Rentsch R, Sölter J, Surm H, Stöbener D, Klein D (2009) Identification of process parameters affecting distortion of disks for gear manufacture part I: casting, forming and machining. Materialwiss Werkst 40(5,6):354–360
4. Hoffmann F, Keßler O, Lübben T, Mayr P (2002) “Distortion Engineering” Verzugsbeherrschung in der Fertigung. HTM 57(3):213–217
5. Zoch HW (2009) Distortion engineering: vision or ready to application. Materialwiss Werkst 40(5,6):342–348
6. Cho JR, Kang WJ, Kim MG, Lee JH, Lee YS, Bae WB (2004) Distortions induced by heat treatment of automotive bevel gears. J Mater Process Technol 153:476–481
7. Kohlhoff T (2009) Analysis of the forces in different regions during hobbing and their effect on distortion. Materialwiss Werkst 40:390–395
8. Husson R, Dantan JY, Baudouin C, Silvani S, Scheer T, Bigot R (2012) Evaluation of process causes and influences of residual stress on gear distortion. Ann CIRP 61(1):551–554
9. Sugimoto T, Watanabe Y (2004) Evaluation of important factors affecting quench distortion of carburized hypoid gear with shaft by using computer simulation methods. Cailiao Rechuli Xuebao/Trans Mater Heat Treat 25(5):480–485
10. Husson R (2013) Contribution a l’identification des origines des deformations revelees au traitement thermique. Application a l’analyse d’une gamme de fabrication d’arbres a dentures de boites de vitesses. Arts et Metiers ParisTech, PhD thesis
11. Goch G (2003) Gear metrology. Ann CIRP 52(2):659–695