Quenching and Distortion

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This paper will first give a brief overview of the fundamentals of distortion formation. The mechanisms will be explained, the Distortion Potential with its carriers and the method of Distortion Engineering will be presented. Furthermore, some distortion-related aspects of quenching technology are discussed. Finally, selected examples are presented which illustrate the relationships between distortion and the quenching process. The examples were selected from all three levels of Distortion Engineering.

Keywords: *quenching, distortion, basics, examples*

1. Introduction

It is well known throughout the world that dimensional and shape changes in components, which in many cases only become visible after heat treatment, lead to very high costs due to reworking or scrap. However, it is also known that not only the heat treatment is responsible for these dimensional and shape changes. Rather, the causes can be found in each individual process of the production chain, including the design. In this lecture only the quenching process and its influence on distortion shall be taken into account. In addition, reference should be made to some publications that have dealt with other processes and other sources of distortion and present excellent overviews [1-4]. Further material on the fundamentals of distortion and the influence of quenching on dimensional and shape changes can be found, for example, in [5].

2. Basics of distortion generation

2.1 Mechanisms

Dimensional and shape changes can be caused by volume changes or deformations [6]. Volume changes result in principle from density and mass changes. The density is influenced by phase transformations and precipitation processes, which in turn are determined by the chemical composition and the temperature-time path that has been followed. Furthermore, stresses can have an influence on the transformation behaviour. Mass changes occur in every thermochemical treatment because additional atoms are introduced into the area near the surface.

Deformations contributing to distortion can be divided into plastic and elastic deformations. The elastic deformations relevant for the dimensional and shape changes are due to heat treatment, occur during the heat treatment itself, and are caused by the residual stresses of the component. Stresses are necessary to generate plastic deformations. These can have several causes. On the one hand, they can be thermal and transformation stresses, as they occur in many heat treatment processes due to thermal or thermal and chemical gradients. On the other hand, load stresses can lead to dimensional and shape changes as they occur in quenching fixtures or by the own weight of components. Residual stresses originating from the processes before heat treatment have the same effect as the above-mentioned residual stresses after heat treatment. The difference is that during heat treatment the temperatures are inevitably higher than in use. Accordingly, this can result in significantly greater dimensional and shape changes.

However, the stresses can only result in dimensional and shape changes if they lead to plastic deformations. This can happen by exceeding the yield limit, by creep processes, or by transformation plasticity. The first mechanism requires a minimum stress that is greater than the local yield limit. This value depends, among other things, on temperature. At low temperatures, comparatively large stresses can be elastically tolerated. As the temperature rises, however, this resistance to plastic deformation decreases more and more down to only a few tens of MPa at usual holding temperatures. In addition, at these temperatures only a slight strain hardening occurs, so that small exceedances of the yield limit can lead to large plastic deformations. Creep does not require a minimum stress. It is observed especially at elevated temperatures and is a time-dependent effect. Transformation induced plasticity also does not require a minimum stress for plastic deformation. The transformation-plastic strain increment is proportional to the stress deviator and always occurs when a transformation process and a non-hydrostatic stress occur simultaneously.

2.2 Distortion potential

The considerations presented so far have been of a general nature and are essentially independent of manufacturing processes. In the following, the variables that are decisive for the formation of distortion are introduced [7].

When looking at a crown wheel, it is immediately clear that there is significantly less mass in the area of the toothing than in the lower part. In addition, the toothing results in a significantly larger surface area than the base body of the crown wheel. From these facts, it immediately follows that the toothing area cools significantly faster during a quenching process. The resulting thermal strains are also distributed asymmetrically (top/bottom) and lead to stresses that cause the crown wheel to tilt. The reason for this shape change is the asymmetry of the mass distribution of the crown wheel. The geometry must therefore be considered as a factor influencing the potential for distortion.

If components with highly symmetrical mass distribution (e.g. balls) exhibit asymmetrical size changes, then it must be assumed that something is or was also asymmetrically distributed inside. Systematic analyses have shown that, according to current knowledge, this is the case for the distributions of the following quantities:

- all relevant alloying elements,
- microstructure including grain size,
- stress, residual stress
- mechanical history, and
- temperature

If the distributions of these quantities exhibit asymmetries or inhomogeneities, deformations may occur due to the mechanisms described above during heat treatment. If a component contains such asymmetries, it contains a potential for distortion formation that is released during heat treatment and causes the measurable changes in size and shape. This potential is called the "distortion potential" of a component and the six quantities mentioned above are the distortion potential carriers.

From the point of view of process chain simulation, these carriers – with the exception of geometry – are the distributions of the state variables at the end of a process within the manufacturing chain and must be specified as initial conditions for the simulation of the next process. However, for understanding origin of distortion, the interactions of the state variables during the processes have to be analysed.

In conclusion, it must be stated that distortion is not only a heat treatment problem. Changes in the carriers of the distortion potential can occur at any step of the manufacturing chain. Therefore, distortion is a system property and the control of distortion in manufacturing processes must follow a system-oriented approach. Here, the relevant system is the entire manufacturing chain!

2.3 Distortion Engineering

To deal with distortion problems, a three-level strategy called “Distortion Engineering” was developed [7]. Always taking into account the entire process chain, this methodology consists of three levels of investigations. On level one, the parameters and variables influencing distortion in every manufacturing step must be identified and analyzed. In general, a large number of parameters may be important. Therefore, Design of Experiment (DoE) techniques should be applied which allows the experimental investigation of larger numbers of parameters by a limited number of samples, enabling the identification of cross-influencing parameters as well as interdependencies.

After identifying the major influencing parameters, level two focuses on understanding the distortion generation by using the concept of distortion potential and its carriers. Modeling and simulation are helpful, in many cases necessary tools to fully understand the interactions of the mechanisms ruling the distortion generation. Understanding these interactions in many cases already allow for reduction of distortion.

On level three, Distortion Engineering aims to compensate distortion. On the one hand, this approach uses the conventional method to increase the homogeneity, respectively the symmetry, of the carriers of the distortion potential. On the other hand, well-directed insertions of additional inhomogeneity/asymmetries in one or more of the distributions of the carriers can be used to compensate the resulting size and shape changes of the unavoidable asymmetries. For example, an inhomogeneous quenching process can be used to compensate shape changes from the previous manufacturing process. In principle a compensation is possible for single components. With this regard, in-process measurement and control techniques can be very important [8].

3. Some distortion-related aspects of quenching

Quenching involves a great risk of producing dimensional and shape changes. This is due to the fact that the critical cooling rate of the respective material must be exceeded in order to produce the required hardness values. Depending on the quenching medium, the dimensions, and the material of the component, this requirement can lead to large temperature gradients which in turn generate thermal stresses. This is the basis for deformations and distortion. A second aspect is in general the minimization of costs. Conventionally this will be achieved by building huge batches of as many parts as possible. Typically, such a batch consists of many layers depending on the dimensions of the heating chamber. The result is that the inhomogeneity of cooling rates in the complete batch volume is much larger than for a single layer or even a single component. This again can be a basis for distortion and large scattering of the dimensional and size changes.

3.1 Evaporating quenchants

The main problem of quenching processes in evaporating quenchants such as oils or water is the rewetting process as consequence of the Leidenfrost phenomenon. In the first phase of quenching, heat transfer is reduced by the formation of an insulating layer of vapor and the resulting heat transfer coefficient and the corresponding cooling rate is comparable small. The heat transfer mechanism during this phase is called film boiling. The vapor film normally does not collapse suddenly. Instead so-called “rewetting fronts” move on the surfaces of the component. Such a front is the boundary between areas of the component exposed to vapor with low heat transfer and fluid with drastically increased heat transfer. Therefore, at the rewetting front large temperature gradients perpendicular to the front occur and huge thermal stresses result. The distortion potential of rewetting processes is small if their symmetry and the symmetry of the components are identical. But if the agitation produces non-symmetrical flow fields around the component a modified rewetting process will result and huge shape changes can be the consequence [5].

3.2 Non-evaporating quenchants - gases

Quenching processes in non-evaporating media (gas, liquid salt, and liquid metals) are based on convective heat transfer. Therefore, no rewetting processes can occur. Especially in the case of gas quenching, the quenching process is controllable by a lot of parameters as kind of gas, pressure, gas velocity, batch structure, flow guidance, nozzle systems, filling time of the furnace, and gas back cooling. Further differences are the smaller heat transfer coefficients (HTC) and the considerably smaller density of the quenching gases (mainly nitrogen and helium).

Since the mid-1990s, various gas quenching methods have been developed. In the following these are given in approximately chronological order:

- High pressure gas quenching with many layers without and with separate quenching chamber
- Single part quenching in tailored gas nozzle field at atmospheric pressure
- High pressure gas quenching with one layer and separate quenching chamber
- Single part quenching with high pressure and tailored gas nozzle field

On the one hand, these developments were intended to increase the HTC. On the other hand, however, the reduction of distortion was the declared goal.

4. Examples illustrating the relationships between distortion and quenching

4.1 Level 1 - parameter and variables

The first example shows the influence of the quenching medium, batch structure, and dimensions on the distortion of discs with a hole. The distortion measurements were done by coordinate measuring machine in radial and axial directions. Figure 1 shows the size and shape changes schematically.

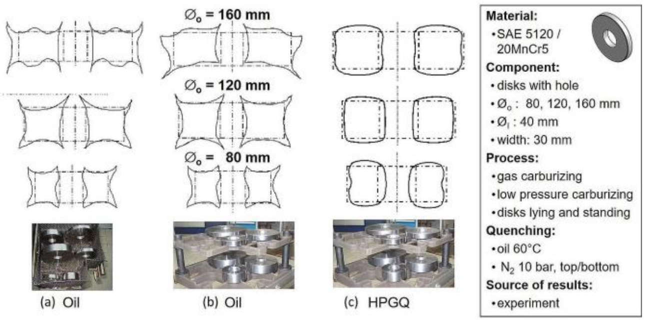

Figure 1: Distortion behaviour of disks with a hole with different outer diameter, quenching media and batching. Oil quenching with hanging disks (a), oil quenching with lying disks (b), HPGQ with lying disks (c) [10]

A comparison of oil quenching with high pressure gas quenching (HPGQ) shows the formation of edge effects as the main difference. HPGQ modifies the original geometry in the direction of spherical shape. Thus, according to Wyss [9], there has been a temporal separation between large thermal strains and phase transformation. Apart from these edge effects, these disks do not exhibit any other shape changes. Although the HPGQ leads to asymmetric cooling in the lying disks due to the inflow from the top to the bottom, there is no tilting of the disks regardless of the dimensions. The lower quenching intensity of the HPGQ obviously does not generate a sufficiently large temperature gradient and thus a sufficient bending moment.

Independent from batch structure oil quenching results in a distinct thread spool shape. According to Wyss, phase transformations and high thermal strains must have occurred simultaneously in this quenching condition.

A comparison of the batching during oil quenching, shows that at the maximum outer diameter, in addition to the edge effects, tilting also occurs with the lying disks. This tilting occurs with thinner disks (15 mm), which are not shown here, already at an outer diameter of 120 mm.

4.2 Level 2 - carriers of distortion potential and distortion mechanisms.

To understand the tilting of the lying disks during oil quenching, one disk was instrumented with thermocouples (positions see Figure 2a). From the cooling curves, it was evident that cooling was fastest at the outer diameter at the bottom. In principle, this result can be explained by a wetting front running from the bottom to the top on the outer surface, a behavior that generally occurs with shafts. A second wetting front running from the outside to the inside on the underside would explain the slower cooling at the bottom-inside. However, since no corresponding observations were available, it was assumed that this wetting front does not exist. The HTC was derived from measurements on cylinders. The wetting front on the outside was roughly modeled using a location-dependent Leidenfrost temperature. For the simulation, existing material data were used. The results are given in Figure 2d. Calculated and measured cooling curves are not perfectly identical, but very similar. The final distortion (Figure 2c and 2e) is not exactly the same, but shows a similar tilt angle and the same tilt direction. Therefore the tilting of the discs can principally be explained by rewetting behaviour.

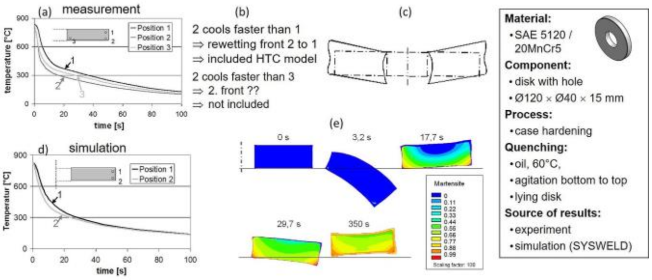

Figure 2: measured cooling curves (a), conclusions for the modelling of HTC (b), measured distortion (c), simulated cooling (d) and simulated distorted disc with martensite distribution after different quenching times (e) [10]

4.3 Level 3 - actions for compensation of distortion

A reduced weight and/or minimized volume of gearboxes is more and more focused in industrial activities. Reducing the dimensions of gears can lead to serious distortion problems due to reduced stiffness and asymmetric mass distribution. To analyze this problem, gear base bodies with reduced thickness of web and gear rim were investigated. Figure 3 shows some selected results. It can clearly be seen that with reduced dimensions of web thickness and gear rim thickness, there is a very high sensitivity of the gear rim distortion for the orientation and position of the web. In addition, this distortion is clearly amplified by the quenching intensity: the changes in radius are significantly higher for oil quenching (Figure 3).

With these results, the question arose as to whether there are suitable combinations of the dimensions of the gear rim thickness and web thickness as well as the web position that lead to tolerable distortions of the gear rim. This question was answered with the help of heat treatment simulation and by the method Design of Experiments DOE. In Figure 3c the used procedure is given. Figure 3d shows iso lines as function of web thickness and web position for a gear rim thickness of 5 mm in combination with oil quenching and the size class personal car. This diagram shows, for example, combinations of web thickness and web positions that lead to tilt angles of 0°.

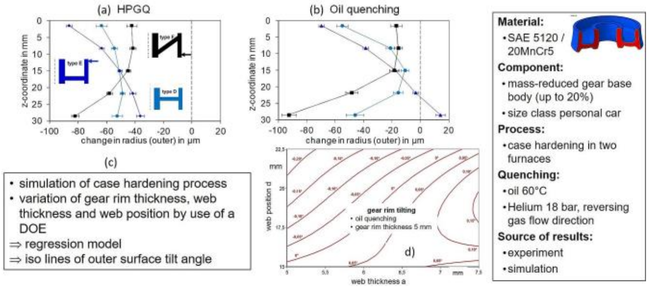

Figure 3: changes of outer radius versus position in axial direction for HPGQ (a) and oil quenching (b), procedure (c), numerically established iso lines for gear rim tilting in [°] as function of web thickness and web position (d) [11]

5. Conclusions

- The quenching process generally holds great potential for generating distortion
- There are approaches to keep the dimensional and shape changes within limits despite this great potential

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