Effectiveness of cutout pattern and position on distortion of driven sprocket during heat treatment process

Abstract Distortion during a hardening process increases the production costs significantly. The problem is even worse with the presence of weight reduction cutouts of various shapes and sizes in the sprocket. The study of cutout patterns and positions is necessary for optimal design in which a minimum weight with a tolerable teeth bottom runout can be achieved. In this paper, cutouts having a different pattern, size and position have been studied. The study reveals the effect of the cutouts on the distortion of the sprocket during a heat treatment process. The finite element method, incorporating an elastic-plastic constitutive model, the phase transformation and temperature-dependent material properties, is used. The conclusions drawn from this study can guide in the selection of cutout patterns and positions during sprocket design.

Keywords Distortion · Finite element method · Heat treatment · Phase transformation · Plastic deformation · Teeth bottom runout

Introduction

Induction hardening has been widely used in manufacturing to increase the surface hardness [1]. This method involves rapid heating of a component to a certain temperature at which austenite is formed. The component is subsequently quenched to transform the austenite into martensite, resulting in an increase in surface hardness. However, due to the large temperature gradient, local plastic deformation and phase transformation, severe distortion may occur during the heat treatment process [2], which may considerably increase the cost of operations and have a significant effect on the performance of the components. It is well known that the heat treatment is a very complicated process. A thorough understanding of the mechanism of distortion during heat treatment, and the development of a methodology for optimal design, are challenging issues. Since experimental study is expensive, time consuming and is unable to identify the effect of each individual parameter in the distortion, computer simulation becomes a powerful tool in studying this problem. In general, thermal and structural analyses are carried out in a coupled way. Thermal analysis is performed first, followed by stress and deformation analyses, in which the temperature distribution from thermal analysis is used as an input data. The temperature distribution can be obtained by means of a coupled magnetic and thermal analysis for induction heating [3,4]. Thermal stresses are produced due to large temperature gradients, and are influenced substantially by the evolution of microstructure, while phase transformations are accompanied by volume variation and transformation plasticity. Therefore, the stress/strain field and the phase transformation behaviour affect each other. When the local stress exceeds the yield strength, a non-uniform plastic flow occurs. This causes the residual stress and distortion at the end of the heat treatment. The total effect of these mechanisms induces continuously changing material properties during the heat treatment process. Therefore, the temperature gradient, the plastic deformation and the phase transformation are the most critical factors controlling the deformation of heat-treated components [5,6,7,8,9,10,11].

In this paper, the study of the heat treatment of a sprocket system has been performed using a commercial finite element code, ABAQUS. The entire heat treatment processes, including induction heating and oil quenching, for sprockets made by S45C mid-carbon steel have been systematically analysed. It is known that the factors affecting the distortion during heat treatment of the sprocket can be categorised into three types: geometry of the component; material properties; and heat treatment history. It has been observed from experiments that the heat treatment of the sprocket, especially for those designs with large cutouts, often induces serious distortion problem. As the weight reduction of sprockets is done by implementation of large cutouts, it is important to understand the distortion mechanism related to cutout geometry.
In this paper, efforts are mainly focused on analysing the effect on the distortion by altering the pattern, size and position of cutouts on a sprocket.

**Heat treatment model**

Modelling and simulation of heat treatment are difficult due to the complexities associated with a real heat treatment process and the high non-linearity of the problem. An efficient thermal analysis requires the characteristics of the heating and quenching media and component, which include the material properties, the complexity of surface features, the agitation of the quenching media, and so on. In the present work, due to the absence of such details and reliable information for thermal analysis, the temperature distributions of a sprocket after the heating and quenching stages were obtained from an experiment. Subsequently, a non-linear stress analysis with initial temperature condition and thermal load was accomplished through ABAQUS. In the heat treatment model, temperature gradient, plastic deformation and phase transformation have been considered.

**Phase transformation**

This occurs due to a significant change of temperature during the heat treatment process. It is known that the austenite start temperature $A_s$ is about 723$^\circ$C for steel [12], which means that when the temperature at any point of the component exceeds $A_s$ during the heating stage, the material of this point becomes austenite. On the other hand, the martensite start temperature $M_s$ is about 300$^\circ$C when the component is quenched in oil. Once the temperature is lower than $M_s$, austenite starts to transform into martensite.

In sprocket heat treatment, surface hardening is done for teeth, so the induction heating time is very short, such that the higher temperature is created only in the vicinity of the teeth. Accordingly, the phase transformation occurs only near teeth. In this study, the region, where phase transformation occurs is defined as zone one (Fig. 1), in which the temperature exceeds $A_s$ and the material is converted into austenite during heating. Because the temperature of oil is about 40$^\circ$C, which is lower than $M_f$ (martensite finish temperature), all the austenite formed during heating is thus transformed into martensite during quenching. As a result, the material properties of zone one in both the heating and quenching stages are different. The remaining part of a sprocket is called zone two (Fig. 1), in which the phase transformation does not occur. Therefore, in zone two, the material properties are not changed in the heating and quenching stages. The curve between zones one and two is defined as the phase transformation curve (Fig. 1) in which the temperature is 723$^\circ$C after heating.

**Elastic-plastic constitutive relation and material properties**

During heat treatment, local plasticity caused by temperature gradient or phase transformation, or a combination of both, would cause distortion. Therefore, the elastic-plastic constitutive relation has to be applied in the material model. The von Mises yield criterion and the isotropic hardening have been employed in the model. In the present work, the uniaxial tensile stress and strain relation is taken as

$$\varepsilon = \begin{cases} \frac{\sigma}{E} & \sigma \leq \sigma_y \\ \left(\frac{\sigma}{\sigma_y}\right)\left(\sigma/E\right)^{1/N} & \sigma > \sigma_y \end{cases}$$

where $\sigma_y$ is the yield stress, $E$ is the Young's modulus and $N$ is the strain-hardening exponent. In the analysis, all the material properties have been considered as temperature dependent [2,12,13,14,15], except for the strain-hardening exponent $N$. The strain-hardening exponent is 0.1 in the simulation. It should be noticed that the yield strength is strongly dependent not only on the temperature, but also the specific phase present. The yield strength of martensite decreases rapidly with increasing temperature and a pronounced change in slope at the martensite start temperature exists. However, the decrease is less pronounced in the austenitic phase [2,12].

**Heatting and quenching stages**

In induction heating, the sprocket is heated for about 2–3 seconds from room temperature of 25$^\circ$C, which is input as an initial condition, to a certain temperature. The temperature distribution after heating, obtained from an experiment, is used as a temperature load. For instance, Fig. 2 shows the temperature profile of a sprocket obtained by experiment. The thermal accumulation occurs in the area above the cutout, and thus the phase transformation curve is formed not as a prefect circle but as a lobed...