The Effect of Temperature in Induction Surface Hardening on the Distortion of Gear

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Abstract. One way to extend the lifetime of gear is minimizing the distortion during the manufacturing process. One of the most important processes in gear manufacturing is induction surface hardening. Induction hardening causes a geometric distortion in gears. This study aimed to analyze the distortion of the gear after induction surface hardening. The material of gear that used in this research is S45C, and it was designed with the a module (m) of 1.75, and 29 teeth (z). In the experiment, the gear was heat-treated using induction hardening at variations of temperatures of 820, 880, and 920 °C with holding time was 35, 45, and 55 s, respectively. Then the gear quenched in water at room temperature. The microstructure analysis was conducted to explore the phase change in gear teeth. Hardness test was also performed on the gear using Rockwell test, and finally, the gear dimension was evaluated. The results showed that the hardness of gear at the teeth surface was 64.9 HRC at the case depth of 5 mm is proper to be used. The microstructure of gear at the surface is martensitic, and the deeper area is pearlite. Gear distortion of all teeth with average thickness was reduced and the highest value was 1.593% at the austenite temperature of 820 °C. While the highest reduction was produced at the temperature of 920 °C and generated the highest shrinkage. The induction surface hardening of the gear was not high, and the highest distortion was found in the outside diameter.

Keywords: Distortion, gear, surface hardening, S45C.

1. Introduction

Gearing is perhaps one of the most critical components of any machinery. Their satisfactory performance depends on the durability of their tooth surface. Pitting and spalling are amongst the common surface fatigue failures for gear teeth. The variability of the gear ratio on the teeth wear is conditioned by the variability of the angular velocity; this is the additional factor of the excitation of vibrations in gearing, especially when there is a considerable distortion of the outline of teeth because of their wear [1]. Normal wear is usually understood as a process of gradual change in size by friction, and characterized by the removal of particles of tooth material from the contact surface. Based on the quality of manufacture, the geometric characteristics and the operational conditions, the gears as machines work classified in the boundary lubrication regime [2]. High-precision gears are finished by honing or grinding machine after hardening. The finishing process after hardening is used to achieve higher quality grades on pitch deviation, profile deviation, and lead deviation. One of the
most important processes in gear manufacturing is induction surface hardening. Heat treatment causes a geometric distortion in gears. Minimizing distortion and enhancing compressive residual stress are the important focuses for fabricating high-quality gears [3]. The distortions can be caused by combined effects of various phenomena. The variations in the predicted distortions are typically started in the order of 2 microns. Such amount may be neglected, but in industry, only a tolerance of 10 microns is allowed [4]. The bending tendency after heat treatment to hypoid gear and pinion gear respectively indicates that the axial displacement experiences an expansion [5]. Induction hardening is a fast and environmentally friendly process to treat the surface of highly loaded steel parts such as cams, shafts, splines, and gears [6]. This study focused on changes in the dimensions of certain parts of the gears based on some reasons and consequences associated with distortions that arise during the induction surface hardening. The experiment and gear distortion analysis would be discussed in this study.

2. Experimental Method
The study began with the preparation of materials included the three spur gears (self-manufactured) as shown in Figure 1.

![Spur gear types. (a) gear (A) at the temperature induction of 820 °C, (b) gear (B) at the temperature induction of 880 °C, (c) gear (C) at the temperature induction of 920 °C](image)

The modules of the gear were similar, and the gear modules were \( m = 1.75 \) and \( z = 29 \). The geometrical parameters of gears are shown in Table 1.

| Item               | Gear A at temperature of 820 °C | Gear B at temperature of 880 °C | Gear C at temperature of 920 °C |
|--------------------|---------------------------------|---------------------------------|---------------------------------|
| Number of Teeth    | 29                              | 29                              | 29                              |
| Module             | 1.75                            | 1.75                            | 1.75                            |
| Pitch diameter (mm)| 52.551                          | 52.552                          | 52.529                          |
| Face width (mm)    | 8                               | 8                               | 8                               |
| Bore diameter (mm) | 20                              | 20                              | 20                              |
| Tooth Depth (mm)   | 3.852                           | 3.828                           | 3.836                           |
| Pressure Angle (°) | 20                              | 20                              | 20                              |
| Outside diameter (mm)| 56.363                      | 56.377                          | 56.397                          |
| Tooth Thickness (mm)| 2.730                         | 2.731                           | 2.737                           |

The gears were made from S45C medium carbon steel. Dimensional measurement, microstructure analysis, hardness Rockwell test and chemical composition analysis were conducted before the induction surface hardening of gears. Furthermore, the gears for induction surface hardening were set for different parameters of temperature. Gear A was set at a temperature of 820 °C, with a frequency...
of 48 kHz and holding time of 35 s. Gear B was set at a temperature of 880 °C, with a frequency of 49 kHz and holding time of 45 s, and then gear C was set at a temperature of 920 °C with a frequency of 50 kHz and holding time of 55 s. The gears were rotating at 70 Rpm when they were heated by induction hardening. The process of induction hardening is shown in Figure 2.

![Figure 2. Induction surface hardening gears](image)

After the heating process, the gear was quenched immediately with water at room temperature. The following step was the second measurement of the gears to identify the dimensional change, hardness Rockwell test, macro test, and microstructure analysis results. Such identification aimed to compare the number of changes in the gear characteristics and the number of changes in dimension of the gears before and after the induction surface hardening. The distortion occurred on the gears was measured based on the tooth thickness and their outside diameter as shown in Figure 3. The tooth-by-tooth measurement was performed to all gears.

![Figure 3. Measurement locations on the spur gear. (a) outside diameter, and (b) tooth thickness](image)

Where $D_0$ is the outside diameter and $t$ is the tooth thickness. The tooth thickness and outside diameter were measured by Coordinate Measurement Machine (CMM) with the type of Bright STRATO 707, Japan; travel: $X = 605$, $Y = 605$, and $Z = 705$. The data from Coordinate Measurement Machine would be transferred to Autodesk Inventor to get the value of the dimensional measurement. The Microstructure analysis was performed by OLYMPUS BX41M optical microscope.
The hardness test of Rockwell C (HRC) is based on the standard of ASTME18-11 with the hardening penetration position as shown in Figure 4. All points of penetration rate and indenter diameter results showed average values.

![Figure 4 Indenter position by Rockwell testers.](image)

### 3. Results and Discussion

The chemical composition analysis showed that the gear was medium carbon steels. The Cr and Mo on the gears had lower chemical composition results as shown in Table 2.

| Alloy  | Fe  | C   | Si  | Mn  | P   | Cr  | Ni  | Mo  | Cu  | Al  | V   | W   |
|--------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| S45C   | 98.15 | 0.41 | 0.18 | 0.63 | 0.10 | 0.32 | 0.01 | 0.01 | 0.03 | 0.01 | 0.10 |

#### 3.1 Microstructure and macro analysis

| Tested Gear | Macro analysis | Microstructure analysis | Types of phase | Case depth (mm) |
|-------------|----------------|-------------------------|----------------|-----------------|
| Gear (A) at the temperature of 820 °C | | Full martensitic | 7 mm |
| Gear (B) at the temperature of 880 °C | | martensitic + perlite | 9 mm |
| Gear (C) at the temperature of 920 °C | | martensitic + perlite | 13 mm |

Table 3 shows the difference in the depth of hardening at various temperatures for each gear after induction surface hardening. The tested gears were varied at the temperatures of 820 °C, 880 °C, 920 °C and the holding time were 35, 45, and 55 seconds, respectively. Then the hardness values of the case depth were respectively 7, 9, and 13 mm. The results of the hardening process was a hardened
profile of all gear teeth, which was due to the limited means of induction hardening (led to insufficient capacity of frequency), and an influence of the types of coils used i.e. circular winding coil surrounding the tooth profile that allowed all teeth to be subjected to heat during the heating process. Such coil type was used in this research because of its popular pattern of induction hardening, especially for small-sized gears and sprockets. However, the heating process should be done very carefully because the hardening process to all teeth can cause cracks (Rudnev et al. 2003). From the three gears used in the experiment, it could be concluded that a higher temperature and a longer heating time resulted in a thicker layer and therefore a greater level of hardness. It happened because the higher temperature and the longer heating time result in the propagation of the austenite phase heating. After the rapid cooling process, the austenite phase was then transformed into martensitic phase.

3.2 Hardness
The hardness distribution in gear A, gear B and C are shown in Figure 5. In gear A (820 °C, 35 seconds at the frequency of 48 kHz), the hardness values measured from the outer diameter to the root diameter were 64.9, 62.5, 62.0, 61.8, and 61.8 HRC. While in gear B (880 °C, 45 seconds at the frequency of 49 kHz), the hardness values measured from the outer diameter of teeth to the root diameter were 65.0, 64.4, 63.7, 62.0, and 61.5 HRC. In gear C (920 °C, 55 seconds at the frequency of 50 kHz), the hardness values measured from the outer diameter of teeth to the root diameter were 65.9, 65.8, 65.6, 63.1, and 62.2 HRC.

| Hardness Case Depth (mm) | The hardness of Gear A at the Temp. (820 °C) HRC | The hardness of Gear B at the Temp. (880 °C) HRC | The hardness of Gear C at the Temp. (920 °C) HRC |
|-------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------------------|
| 2                       | 64.9                                          | 65.0                                          | 65.9                                          |
| 5                       | 62.5                                          | 64.4                                          | 65.8                                          |
| 8                       | 62.0                                          | 63.7                                          | 65.6                                          |
| 11                      | 61.8                                          | 62.0                                          | 63.1                                          |
| 14                      | 61.8                                          | 61.5                                          | 62.2                                          |

Figure 5. The hardness distribution of the Specimen gears after induction surface hardening for the end from the outer diameter of teeth to the root diameter.

It happened because the higher temperature and the longer heating time can even result in the propagation of heating in the austenite phase. After the rapid cooling process, the austenite phase was
transformed into a martensitic phase which was very hard and brittle. It caused the hardness value of the gear to increase, and the comparison of these results meet the acceptable standards of AGMA.

3.3 Distortion arose at the Tooth Thickness
Figure 6 shows the results of gear distortion of all teeth, such as in the form of average values of the tooth thickness to be reduced or expanded. The highest value of reduction was 1.593%, and the maximum value of expansion was 1.396% at an austenite temperature of 820 °C as shown in Figure 6 (a). While the distortion was reduced at the temperature of 880 °C, and the highest percentage or reduction was 4.129% as shown in Figure 6 (b). Subsequently, the reduction was reduced and expanded at the temperature of 920 °C. The highest value of reduction was 7.187%, and the highest value of expansion was 2.404% as shown in Figure 6 (c).

![Figure 6](image)

(a) (b) (c)

Figure 6. Dimensional changes in tooth thickness of the three gears; (a) gear A (b) gear B, and (c) gear C.

3.4 Distortion at the outside diameter
Figure 7 shows the results of gear distortion in the form of the average values of the reduced or expanded diameter of all teeth outside diameter. The highest value of the shrinkage was 0.228%, and the maximum value of the expansion was 0.021% at the austenite temperature of 820 °C such as shown in Figure 7 (a). There were shrinkage and an expansion of distortion at the temperature of 880 °C. The highest value of shrinkage was 0.147%. Moreover, the highest value of expansion was 0.059% as shown in Figure 7 (b). Then, at the temperature of 920 °C shrinkage and an expansion of distortion were also found. The highest value of shrinkage was 0.099%, and the maximum value of expansion was 0.284% as shown in Figure 7 (c).
4. Conclusion
Based on the data obtained from the results and the previous discussion of gears after induction surface hardening, the following summary can be drawn as follows. Induction surface hardening of gear has martensitic type and pearlite phase. The highest hardness value of induction surface was achieved at a case depth of 2-5 mm from the upper tooth profile. A higher austenitic temperature would increase the gear hardness, and more the type of martensitic would be formed. The highest type of gear distortion was a drastic shrinkage of the teeth. Distortion of induction hardening gear was found to be very high with a value of 7.187% at the temperature of 920 °C. The highest value of distortion would precisely influence inappropriate tooth contact. The highest shrinkage of the tooth thickness and outside diameter would affect the contact angle and tooth clearance because the size of gear tolerance was not standardized [7].

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