Induction hardening: Differences to a conventional heat treatment process and optimization of its parameters

Annika Vieweg¹, Gerald Ressel¹, Petri Prevedel¹, Peter Raninger¹, Michael Panzenböck², Stefan Marsoner¹ and Reinhold Ebner¹

¹ Materials Center Leoben Forschung GmbH, Roseggerstraße 12, A-8700 Leoben
² Department of Physical Metallurgy and Materials Testing, Montanuniversität Leoben, Franz Josef Straße 18, A-8700 Leoben

E-mail: annika.vieweg@mcl.at

Abstract. The possibility of obtaining similar mechanical properties with faster heating processes than the conventional ones has been of interest for several years. In the present study, investigations were performed in terms of the influences of such fast heat-treatments on the microstructure and mechanical properties of the material. This investigation compares an inductive with a conventional furnace heat treating process of a 50CrMo4 steel, however only the austenitizing treatment was changed and subsequent quenching and tempering was done in the same way. To this end experiments with a middle frequency generator, using different heating rates and austenitizing temperatures, were conducted and followed by oil quenching of the workpieces. The resulting structures were characterized regarding their microstructures and mechanical properties in order to gather a better understanding of the differences between the inductive and the conventional heat treating process. As a main result it was found, that the fast austenitized samples exhibited worse ductility than the conventional treated material.

1. Introduction

The field of induction hardening has become increasingly important in industrial heat treatment processes due to short production times, in line heat treatments and the fact, that they are ecologically more favorable than conventional furnace based heat treatments [1, 2]. Consequently, it is important to obtain mechanical properties, which are comparable to the ones from a longer process but with a much shorter production cycle. Nevertheless, differences in mechanical properties, especially toughness, have been noticed, when induction hardened material is compared to conventionally (oven-) hardened material [3, 4]. These differences may result from the different heating rates and dwell times at austenitizing temperature, as well as different cooling rates through spray quenching [5]. In conventional heat treatments the material is slowly heated to austenitizing temperature and kept within the furnace for a certain time. During the dwell time the austenite can develop a homogeneous composition with a low density of crystal defects. Conversely, induction heating uses high heating rates $\dot{T}$ (up to $\dot{T} = 100 \text{ K/s}$) and short - sometimes even no - dwell times. This may lead to chemical inhomogeneities and mechanical properties have been found to not hold up to the standards of conventionally treated material [3]. Furthermore, the effect, that the heat input within the surface, the so-called...
penetration depth, localizes 83% of the induced power, leads to faster heating of the surface of the workpiece, whereas the core temperature lags behind the surface temperature. This effect is highly dependent on the frequency and the magnetic, as well as the electric properties of the material.

In this study the influence of the austenitizing treatment on the microstructure and the mechanical properties is studied. Therefore, the inductive, fast heat treatment is compared to a longer conventional one. Following recommended literature [6], the challenge of incomplete homogenization was solved by choosing higher temperatures for the inductive heat treatment, to obtain an almost homogeneous structure even in a short period of time. The other characteristics of the heat treatment (e.g. quenching, tempering) were kept constant in order to be able to solely study influences of fast austenitizing treatments.

2. Experimental
The steel investigated in this study was a 50 CrMo4 steel with the chemical composition as listed in Table 1.

| C   | Si  | Mn  | Cr  | Mo  | P   | S   |
|-----|-----|-----|-----|-----|-----|-----|
| 0.49| 0.27| 0.71| 1.05| 0.18| 0.016| 0.010|

A well defined initial ferritic-pearlitic microstructure was adjusted using a heat treating process stated in the literature [7]. Cylindrical specimens with a diameter of 22 mm were austenitized at 850°C for 20 min, cooled down to 650°C, held for 1500 s and afterwards air-cooled to room temperature. Samples with this ferritic-pearlitic microstructure were put into the hot oven at 850°C, held at temperature for 20 min and quenched in oil in order to obtain a conventionally quenched structure. Quenched and tempered (QT) samples were obtained by subsequent tempering within the oven at 540°C for 40 min and afterwards air cooled.

For induction hardening a middle frequency generator (20 kHz, 30 kW) was used for the through heating of the workpieces of a diameter of 22 mm. The temperature evolution during heating was calibrated using a type S thermo-couple located in the center of the workpiece and which was positioned at the center of the induction coil. By applying different power values the samples were heated to 950°C and 1000°C for both temperatures within a processing time of 24 and 100 s. The heating power was around 15 kW for 50 K/s and 2 kW for the heating rate of 10 K/s. For the chosen power values a surface temperature evolution $T_S$ was measured 2 mm underneath the surface with a type S thermo-couple in order to get a rough estimate for the temperature profile over the cross-section. Temperatures at the surface exceeded the core temperature, depending on the heating rate. For 50 K/s the temperature 2 mm underneath the surface was 150°C higher than the core temperature, whereas the samples heated with 10 K/s received an overheating of 100°C. It can be assumed, that the temperature at the surface was somewhat higher.

The detailed parameter-set and the nomenclature of the samples is listed in Table 2. The so-called processing time is defined as the time for the whole austenitization treatment, including heating and dwell time, but without quenching and tempering time, which was the same for every process. The workpiece was statically held within the induction coil and dropped into an oil-bath at the end of the heating process. Subsequent tempering was done in the same manner as for the conventional QT-samples (oven 540°C for 40 min, air cooling).

Microstructural analysis was conducted at the part which was positioned at the center of the induction coil. Optical light microscopic (OLM) investigations were done on samples etched with 3% nital and prior austenite grain etching was achieved using a solution of picric acid.
Table 2. Parameter-set and nomenclature of the samples. Processing time solely corresponds to the time for the austenitizing treatment.

| Name | Processing time [s] | Austenitizing Temperature [°C] | Dwell time [s] | Heating rate \( \dot{T} [K/s] \) |
|------|---------------------|--------------------------------|----------------|-------------------------------|
| CONV. | 1800                | 850                            | 1200           | approx. 15                    |
| 10-1  | 100                 | 950                            | 0              | 10                            |
| 10-2  | 100                 | 1000                           | 0              | 10                            |
| 50-1  | 24                  | 950                            | 0              | 50                            |
| 50-2  | 24                  | 1000                           | 0              | 50                            |

Figure 1. OLM images of the conventional (CONV.) (a) and the 50-2 (b) state after quenching.

with benzenesulfonic acid as wetting agent. The mean grain size was evaluated using the line intercept method according to ASTM E 112-12. The near surface grain size was done around 500 µm below the surface.

Samples for mechanical testing were manufactured within the uniformly heated part of the workpiece, which was located in the center of the induction coil. Vickers hardness measurements were conducted at a Qness Q10A+. Mean hardness was evaluated for 8 points at half radius measured every 45° and an additional hardness profile was measured over the cross-section of the workpiece. Phase fraction analysis of retained austenite was carried out using X-ray diffraction (XRD) on a Xstress 3000 G2 diffractometer by Stresstech. Charpy impact energy was investigated at three samples for each condition at a Zwick RKP 450 at room temperature. Scanning electron microscopic (SEM) investigations were conducted using a Zeiss EVO MA25.

3. Results and Discussion

3.1. Differences of the as-quenched state

In a first step the microstructural characteristics at the center of the sample in the as-quenched condition were evaluated. OLM pictures, as presented in Figure 1, show the differences between the sample CONV. and 50-2. The conventional heat treated sample exhibits a fine microstructure. The inductively heated sample shows a significantly coarser microstructure, in which the martensitic laths can be observed very clearly. The higher temperature for the inductively heat treated sample (1000 °C) leads to a coarser microstructure, despite the short processing time. To evaluate dimensions of the microstructural characteristics, prior austenite grain sizes were analyzed.
Figure 2 depicts that the grain sizes of the samples are different for the different processing times and temperatures. The higher the austenitizing temperature the larger the austenite grain size, despite the shorter processing time. A difference in the austenite grain size can be observed between the surface and the core (open and closed symbols) of the workpiece. This occurs especially for high $T$, since the over heating for fast heating rates is more pronounced than for slower heating. A higher generator power is needed to achieve the mentioned heating rates and because of the skin effect a higher power density at the surface of the workpiece was obtained. The result is a fast or even an over-heated surface (up to $150^\circ$C), represented through larger prior austenite grains for higher $T$. This effect occurs as well for a higher austenitizing temperature and a longer processing time (10-2), also due to over-heating and longer holding times. This leads to a pronounced variation of the prior austenite grain size for the sample 10-2 over the cross-section. It can be stated, that, the slower the heating and the austenitizing temperature is, the more uniform the through heating of the workpiece and the smaller the difference between prior austenite grain sizes over the cross-section. It has to be noticed that even for short processing times and lower temperatures (Figure 2, 50-1 and 50-2) the austenite grain size is higher than for the conventional heat treatment, which might be due to increased overheating for the high heating rates.

In order to elucidate the influence of the processing on hardness, the mean hardness of the as-quenched state is depicted in Figure 3. The mean hardness is higher at lower processing times and maximum temperatures. Although the hardness increase is not even $10$HV10, this might be the result of the higher processing temperatures, which promote carbon solution within the matrix and thus enabling harder structures [8]. The amount of retained austenite (depicted through open symbols in Figure 3) is decreasing over the processing time. For the CONV. samples 7% retained austenite were measured, whereas the specimen 50-2 comprises 14%. The higher percentage of retained austenite at lower processing times leads to the conclusion, that higher amounts of carbon are dissolved in the matrix, which might also be a result of the high processing temperatures and the increasing over-heating phenomenon for the fast austenitized samples.

3.2. Differences of the tempered state

Figure 4 depicts the microstructures of the samples CONV and 10-2 after the tempering process. The fast austenitized sample (10-2) exhibits a coarser structure. Furthermore, the carbide distribution does show slight differences in the tempered samples. The conventional state shows few large globular carbides (indicated by the arrows in Figure 4a), which are expected to be undissolved carbides stemming from normalizing treatment. Apparently, not all carbides from the normalized structure did dissolve during the conventional austenitizing treatment. Therefore, it can be assumed, that the dwell time for the conventional process should be longer. The precipitating carbides, which form during tempering, occur finely dispersed, globular as well as in a plate-like shape (indicated by ellipsoids). Analyses of the plates in more detail reveals, that most of the plates show a tendency of becoming globular and the plate breaks apart.

Specimen 10-2 (Figure 4b) does not show larger globular carbides from the normalizing treatment, which can be attributed to the higher austenitizing temperature, which obviously causes full dissolution of all carbides. The precipitating carbides occur mostly in a plate-like shape and shows a tendency to precipitate strikingly at the former austenite grain boundaries (indicated by the arrow in Figure 4b) and at martensite lath boundaries. The inductive sample showed the effect of beginning spheroidization of the precipitating carbides in less distinct than the conventional sample. Precipitation of carbides at dislocations, at martensite laths and at prior austenite grain boundaries, as well as the plate-like shape has been observed in other studies [9]. The decomposition of retained austenite is also an important consequence during
Figure 2. Austenite grain size for the different the processing time. The open symbols represent the grain size at the surface of the workpiece, whereas closed symbols refer to the core. Circles correspond to austenitizing temperature of 950 °C, triangles to 1000 °C and the square refers to the conventional heat treatment at 850 °C within the oven.

Figure 3. Mean hardness, measured at half radius, and percentage of retained austenite of the as-quenched samples. Hardness is depicted by closed symbols and percentage of retained austenite by open symbols. Symbols are in accordance with Figure 2.

Figure 4. (a) SEM image of the conventionally heat treated material (CONV), arrows are pointing towards larger carbides, ovals are indicating plate-like carbide shapes; (b) SEM image of 10-2, arrow is pointing at carbides on a prior austenite grain, ovals are indicating plate-like carbides.

and after the tempering process. All samples comprise no retained austenite in the tempered state, therefore, it is clear that the retained austenite did decompose during tempering or during cooling after tempering. The kinetics of this decomposition were not analyzed, therefore it is not clear if the austenite decomposed only during heating or as well during the dwell time at tempering temperature of 540 °C.

All samples were tempered in the same manner and Figure 5 compares the hardness for the inductively and conventionally heat treated samples. Hardness profiles were measured along the diameter of the workpiece and shows no significant differences between core and surface. The hardness of the tempered samples is somewhat lower at longer processing times (approx.
15 HV10) and with lower austenitizing temperatures. Differences in hardness appear through the slightly different tempering behaviour depending on the prior austenitizing treatment. The different amounts of carbon dissolved within the matrix and retained austenite might be an explanation and might therefore be more pronounced with higher austenitizing temperatures and higher amounts of retained austenite (e.g. specimen 50-2).

The Charpy impact values (see Figure 7) follow a reversed trend compared to the hardness evolution, as they higher at longer processing times and lower austenitizing temperature. The conventionally heat treated sample obtains an impact value of 45 J, whereas the Charpy impact energy of the sample heated inductively to 1000°C within 24 s (50-2) drops down to 26 J. The inductively heated samples show a higher hardness than the conventionally heat treated one, which might be one reason for the lower Charpy impact energy. A decrease of a Charpy impact value of almost 20 J seems to be large for an increase in hardness of only 15 HV10, hence, it is assumed that other effects might influence the toughness of the inductive heated specimens.

In order to clarify this assumption, detailed analyses of the Charpy impact fracture surfaces have been carried out (Figure 7). They show increasing percentage of intergranular and some fractions of cleavage fracture for shorter processing time and higher austenitizing temperature. Sample 50-2 shows high amounts of intergranular failure, which corresponds to a low impact energy. At higher impact energies the fraction of intergranular and cleavage failure is lower, and seems to be non existent for the sample 10-1. The CONV. samples show as well solely ductile fracture surface (not depicted in the Figure). The increasing percentage of intergranular fracture leads to the conclusion, that the low impact values are caused by this type of microscopic fracture mechanism. The increasing intergranular fracture sites indicate, that certain prior austenite grain boundaries are weakened by the fast austenitizing treatment. As seen in Figure 4(b) the tempering carbides precipitation is favored at former austenite grain boundaries, hence their position and shape (plate-like) can be assumed as a weakening mechanism [10]. Furthermore, impurities (e.g. P, Sb) can not be excluded as a reason for intergranular failure. Segregation during austenitiziation and pile ups ahead of the tempering carbides during tempering has been reported, especially for P, in the literature [11, 12].

Nevertheless, it is not yet clear why intergranular failure occurs for the inductively heated samples and SEM investigations were not sufficient to analyze the fracture surfaces in regard to this problem. This is subject of further studies.

Figure 5. The mean hardness of the tempered samples at half radius for the different processing times. Symbols are in accordance with Figure 2.

Figure 6. Charpy impact energy in Joule for the different processing times. Symbols are in accordance with Figure 2 and the letters correspond to the nomenclature of fracture surfaces in Figure 7.
4. Summary
This study points out differences of microstructure and mechanical properties between a conventional and an inductive heat treatment of a 50CrMo4 steel.
An important difference between the inductively and conventionally heat treatment, is that during the inductive treatment temperature gradients occur over the cross-section, which is due to the skin effect. The gradient between surface and core is larger for higher heating rates, since the power intensities have to be increased. Temperature calibration at the core of the specimen lead to an overheated surface of the workpiece (up to 150°C for a heating rate of 50 K/s). The inductively heat treated samples were austenitized at higher temperatures (950°C and 1000°C) compared to the conventional one (850°C), which lead to increasing prior austenite grain sizes. Apparently, at higher temperatures a larger volume fraction of carbides dissolves during the heat treatment and the prior austenite grain size is increased. This agrees with the fact, that in the same specimens an increase in hardness and amount of retained austenite has been observed, which is a result of a higher carbon content in the matrix.
Subsequent tempering shows differences in carbide precipitation, due to different amounts of carbon dissolved as well as varying percentages of retained austenite. Further investigations might be helpful to analyse the kinetics of the tempering process in dependance on the prior austenitizing treatment, as well as detailed analysis of the precipitating carbides via e.g. TEM. A decrease in toughness for the inductively austenitized samples, represented by Charpy impact

Figure 7. SEM-images of the fracture surfaces of the samples 10-1(a), 10-2 (b), 50-1 (c) and 50-2 (d). Arrows are pointing to intergranular fraction sites.
energy, can be traced back to a combination of three phenomena: increase in hardness, increase in grain size and the change of the fracture behavior - from ductile to partly intergranular. The reason for the latter one requires further investigations, especially of the condition of the prior austenite grain boundaries regarding precipitations and impurities. Nevertheless, samples which were inductively heated with $T = 10 \text{ K/s}$ to both austenitizing temperatures show a good combination of hardness and Charpy impact energy. Despite the decrease of impact energy compared to the chosen conventional process, it would still be sufficiently high for the industrial specification of this steel (30 J). Furthermore, the samples show a sufficient hardness and the processing time is over 10 times shorter than for the conventional treatment. Heating rates as high as $T = 50 \text{ K/s}$ are difficult to control and lead to unsatisfactory toughness properties and are therefore not recommendable according to this study.

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6. Literature

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