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Influence of steel austenitization to part quality in continuous austempering

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Abstract. In the automotive industry, the heat treatment of strip steel safety components is a crucial and highly responsible process in terms of quality. The growing demand for passenger car safety makes heat treatment highly important in qualified engineering. This study is focused on the part austenitization in the industrial furnace. The study includes testing with a laboratory furnace and an industrial test on a continuous austempering line. The purpose of this work is to find the basis for selecting optimal furnace parameters for the heat treatment line furnace without affecting the final quality of treated parts. For this study, the safety belt tongue, as the main product of the involved company, was chosen. Seatbelt tongues are fineblanked from steel grade C60E, which is preferred for austempering, to gain the desired lower bainitic structure. The results of the study show that the austenitization of the parts depends on the furnace temperature, heating time, layer thickness and the geometry of parts. All these variables affect the final quality of the tongue.

Key words: continuous austempering, austenitization, heating diagram, automotive industry.

1. INTRODUCTION

Austempering process is the isothermal transformation of a ferrous alloy at a temperature below that of the pearlite formation and above that of the martensite formation [1]. The structure obtained by the austempering process is bainite [2]. The final result of the process is mainly affected by the steel austenitization in the heating furnace and proper cooling in the molten salt tank, which are both related to the material chemical composition [1,3]. Optimal processing parameters are essential to produce parts with good quality and cost effectively. Currently, the selection of austempering line process parameters is based on the experience or industrial testing. Performing an industrial experiment to optimize process parameters is time-consuming, risky and expensive. Hereby the understanding of affecting variables such as the part geometry, material thickness, grade, desired hardness and character of heating provides a suitable basis for selecting the optimal heat treatment parameters. The selection of the appropriate austenitization temperature is related to material chemical composition according to the Fe-Fe_3C phase diagram [4]. The duration of the austenitization process depends on the austenitization temperature, soaking time, steel composition and initial structure of the material [4,5]. Thus as far as machinery is concerned, the austenitization of the parts depends also on the installed heating power of the furnace [4]. Varying the rate of heating effects the rate of phase transformation and dissolution of the alloying constituents [4,6].

The limitation for choosing the austenitization furnace temperature is twofold. Firstly, the austenite grain growth, obtained due to high temperature and long soaking time, has to be avoided as there is a risk for material brittleness. Secondly, higher temperature reduces the life expectancy of furnace components, especially heating elements. The maximum working temperature 930 °C of the furnace is limited with the used construction materials. Hence, if an optimal temperature regime for austenitization is chosen, it also reduces the general processing cost, including energy consumption and maintenance cost.

Austenitization of steel is determined by carbon diffusion in austenite. The austenitization rate depends on the material chemical composition, initial microstructure (distribution of individual phases), grain size, heating rate and temperature [4]. During the heating of steel with spherodized cementite in ferrite matrix, the austenite phase nucleates at the ferrite-cementite boundary. Furthermore, austenite consumes cementite and then grows into ferrite with diffusion controlled growth [4]. With pearlitic microstructure, austenite formation occurs in two stages. The first stage is the pearlite dissolution and the second stage is the ferrite to austenite transformation, which finishes at Ac_3. Both processes occur by nucleation and growth [5]. After the completion of austenite formation, continued heating leads to grain growth of austenite. The growth rate of austenite is believed to be controlled by either volume diffusion of carbon or by boundary diffusion of substitutional alloying elements [5]. For the selection of proper austenitization parameters it is essential that the homogeneous austenite has formed without residual carbides in the hardened microstructure. The aim of the study is to define optimal austenitization parameters for continuous austempering line furnace.

2. EXPERIMENTAL

2.1. Used part and material

The seatbelt tongues, made of soft annealed steel C60E (Table 1), were chosen for testing as the main product processed on the heat treatment line. The type of the tongue was selected according to its particular design (Fig. 1), as it

Table 1. Chemical composition (wt%) of the used steel

C	Si	Mn	Al	Cr
0.60	0.27	0.62	0.007	0.22

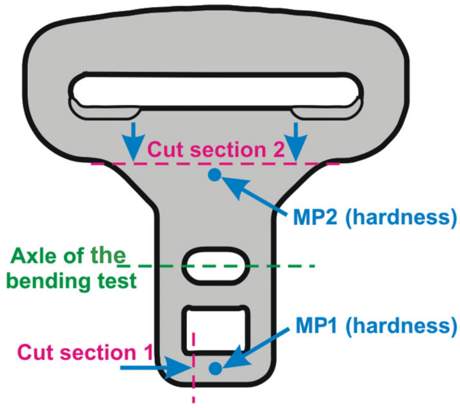

Fig. 1. Scheme of hardness measurements, sections of the cut for the micrograph and location of the tongue bending axle.

has a wider area in the middle section, which in time has shown sensitivity to hardness variation compared with other tongues. The material grade C60E is a standard grade used on seatbelt tongues for the austempering process. The required hardness of the tongue after hardening is 46–50 HRC and the rupture strength must be greater or equal to 23 kN. The industrial process flow for the seatbelt tongue is the following: fine blanking from the 3 mm strip steel, degreasing, heat treatment, centrifugal mass finishing, Ni-Cr plating and plastic injection moulding.

2.2. Laboratory austempering

To understand the austenite formation during continuous heat treatment, a testing in a laboratory batch furnace was performed. It is not practical to perform the test on the industrial heat treatment line due to the amount of parts involved, especially in borderline conditions. The test was carried out at different austenitization temperatures and times to see the connection between the furnace set-point temperature and heating time and the tongue properties. The austenite formation at different temperatures and times can be observed from the microstructure. The temperature curves of the heated tongues in the furnace were also measured and recorded.

A set of tongues was treated at austenitization temperatures 740, 780, 820, 860 and 900 °C and at different heating times: 2, 4, 6, 10, 15 and 25 min. The temperatures of phase transformations was calculated considering the chemical composition of the steel [1]:

$$\mathrm{Ac}_1 = 723 - 20.7\mathrm{Mn} - 16.9\mathrm{Ni} + 29.1\mathrm{Si} - 16.9\mathrm{Cr} \quad \text{(standard deviation } \pm 11.5\,^\circ\mathrm{C}), \tag{1}$$

$$\mathrm{Ac}_3 = 910 - 203\sqrt{C} - 15.2\mathrm{Ni} + 44.7\mathrm{Si} + 104\mathrm{V} + 31.5\mathrm{Mo} \quad \text{(standard deviation } \pm 16.7\,^\circ\mathrm{C}). \tag{2}$$

After austenitization the specimens were quenched in the molten nitrite-nitrate salt, which was kept at constant temperature 320 °C. For the first 30 s, the tongues were set in motion in the salt to reproduce salt circulation as in the actual process. As the laboratory salt bath does not have agitation, the temperature was chosen lower (320 °C) to compensate the cooling speed of the salt and to achieve hardness in the same range as in the industrial process.

While processing the tongue, the hardness has to be nearly uniform all over the range of the tongue body to ensure functional quality of the final product. Thus the hardness achieved after quenching is the direct feedback of tongue austenitization and the variation between the achievable hardness indicates insufficient austenitization. The hardness of treated tongues was measured according to Fig. 1 at points MP1 and MP2 at the thickest and widest cross-section.

2.3. Industrial test

The test was conducted with the same type seatbelt tongue made of material grade C60E. The aim of the testing was to evaluate the possibility to run the industrial heat-treatment line with higher production feed rate. The involved austempering line consists of the loading unit, steel austenization furnace, quench tank with molten nitrite-nitrate salt and two-step water treatment. As the process is continuous in each stage, there are conveyor belts that transport the parts to the next treatment step. Additionally, the protective endothermic atmosphere is used in the austenitization furnace to prevent oxidation of the part surface. Two different feed rates were chosen: the regularly used 370 kg/h, and the maximum 440 kg/h, which the loading unit is capable for. The size of the test batch was sufficient to run the work on the line for at least two hours to obtain stable equilibrium condition in the austenitization furnace. The main parameters of the furnace are shown in Table 2 and the furnace heating time and other relevant parameters in Table 3. The main processing parameters of the heat treatment line were kept constant, only the production feed rate was changed. As the furnace belt speed was constant, the layer of loaded parts on belt in case of 440 kg/h was consequently higher. During the testing with both feed rates, the heating graph of parts in the furnace was recorded to get feedback about the austenitization process. For that purpose, a long thermocouple was driven into the furnace between the parts and the corresponding temperature curve was measured. After

Table 2. Furnace zone temperatures, °C

Zone	Z-I	Z-II	Z-III	Z-IV	Z-V
Temperature	850	860	880	880	880

Table 3. Austempering line parameters

Parameter	Feed rate, kg/h	
	370	440
Furnace time, min	24	24
Salt temp, °C	330	335
Submerge time, min	9	9
Agitation intensity*, %	65	65
C-potential, %	0.33	0.33

* Agitation intensity – the percentage of salt pump power. That circulates salt to improve parts cooling.

Table 4. Hardness, rupture force and bending test results of tested tongues

	Hardness, HRC				Rupture force, kN		Bending, °	
	MP1		MP2					
Series*	I	II	I	II	I	II	I	II
Average	48.8 495 HV	48.0 484 HV	47.4 476 HV	46.9 470 HV	28.5	27.8	45	45
Standard dev.	0.3	0.4	0.6	0.5	0.3	0.3	–	–

* Series: I – 370 kg/h; II – 440 kg/h.

hardening, the tongue’s quality was evaluated by hardness (Table 4). The rupture strength and bending test were conducted after Ni-Cr plating, as electroplating introduces hydrogen into the material, causing the risk for brittleness (Table 4).

2.4. Quality control of the parts

Quality of hardened parts was verified with hardness measurement in Rockwell C-scale and the microstructure analysis was also conducted. Hardness of the austempered tongues was measured with Indentec 4150LK Rockwell hardness testing device. Tongue hardness was measured at two different measuring points MP1 and MP2 (Fig. 1) to detect potential hardness variation between the narrow and wide area of the tongue. The rupture strength test was executed on a quasi-static tensile testing machine Housefield H100K with the suitable fixture indicated in Fig. 2a with the testing speed 100 mm/min. Rupture strength results are indicated in Table 4. For hardness and rupture force, the set of 125 tongues were used as the feedback from process capability.

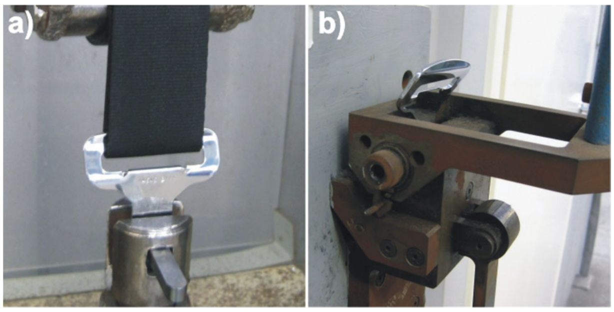

Fig. 2. Appliances for the rupture test (a) and bending test (b).

As steel with bainitic microstructure (hardness 48 HRC) is already sensitive to hydrogen embrittlement from Ni-Cr plating [7], the bending tests of the tongues were performed to evaluate the brittleness. The bending test appliance is shown in Fig. 2b and the axle for bending tongue is indicated in Fig. 1. The bending test was performed with 25 samples and the results are indicated in Table 4.

For microstructure studies, the specimens were cut according to Fig. 1. The sections were hot mounted in plastic, grinded and polished. Final polishing was done by using the 0.05 μm Buehler Masterpolish suspension. To reveal the microstructure, the nital etchant (nitric acid, 3 wt%) was used [8]. Microstructure was examined using light optical microscope Axiovert 25 and scanning electron microscope EVO MA-15 (Carl Zeiss).

3. RESULTS AND DISCUSSION

3.1. Laboratory austempering

A set of 4 tongues were heated in the batch furnace and then quenched into molten salt to imitate the industrial heat treatment. The hardness results are graphically presented in Fig. 3, where the hardness increase in MP1 and MP2 is the feedback of tongue austenitization. It is obvious that in the wider section MP2 the hardness increases more slowly than in the thinner section MP1. As the wider cross-section has more material to heat up, the austenitization takes accordingly more time [4]. From Fig. 3 it follows that the higher the set temperature the less time is needed for achieving the uniform hardness of the tongue. It is visible in Fig. 3 that starting temperature 820 °C is already suitable for hardening the material C60E.

The heating diagram of performed heat treatments (Fig. 3) was composed to follow the temperature change and to link it with austenite formation. As it is known that the wider section is more critical from the side of austenite formation, the heating curve was measured at MP 2. For composing the heating diagram (Fig. 4) of the tongue, the thermocouple was inserted in a small flat-wise drilled hole in the centre of the tongue wide section, at MP 2. According to the graph,

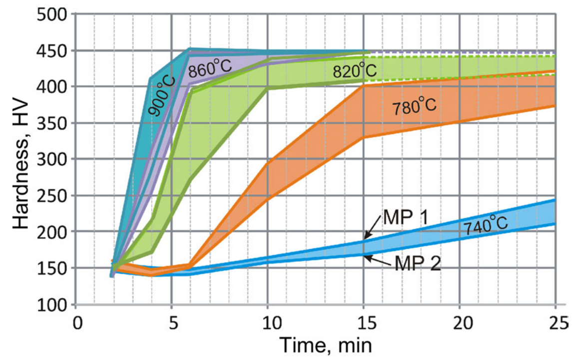

Fig. 3. Hardness – austenitization time graph including section effect (hardness on the graph is converted from HRA and HRC measuring results to the scale of HV).

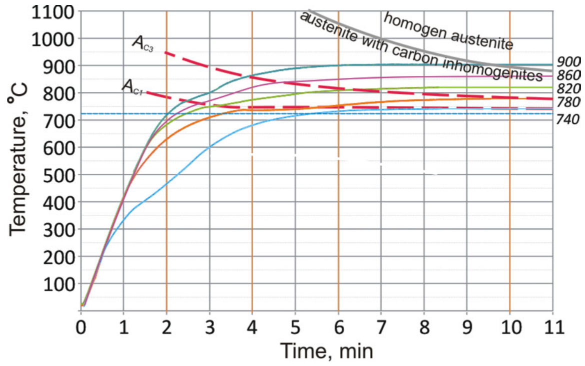

Fig. 4. Heating diagram of the tongue middle section (MP2).

the phase transformation curves Ac_1 and Ac_3 on the temperature curves can also approximately recognized. For that, the estimated curves of Ac_1 and Ac_3 temperatures are drawn on the graph. It can be seen that the higher the furnace set-point temperature is, the quicker is the austenite formation start temperature Ac_1 surpassed. According to the hardness results, it is understandable that the degree of overheating from the Ac_3 temperature is a relevant factor for the speed of austenite formation. The higher the austenitisizing temperature of the furnace, the shorter is the soaking time for developing homogeneous austenite. The lower the furnace set-point temperature is, the more carefully the soaking time has to be chosen. Soaking time is important to give time for carbon and alloying elements to diffuse in the austenite to get the desired homogeneous austenite for quenching.

The micrographs of differently heat-treated tongues were recorded and are shown in Fig. 5. In Fig. 5 it is possible to follow the drive of austenite formation at temperatures 740, 820 and 900°C with different heating times in the furnace. Comparing these results with Fig. 4, it can be concluded that the Ac_1

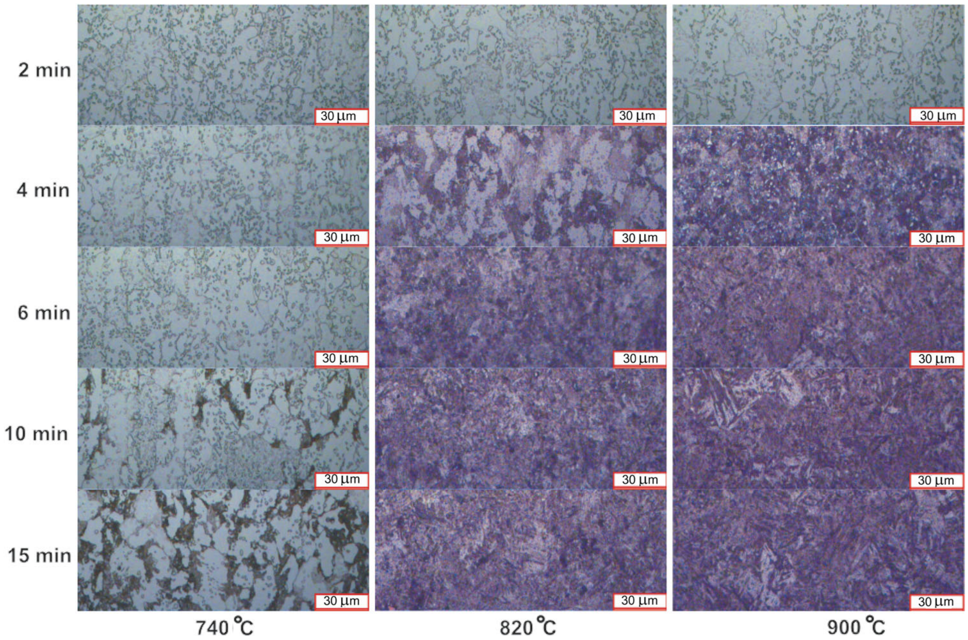

Fig. 5. Formation of microstructures (magnification 500X).

temperature line was surpassed as follows: 740 °C – 4.5 min, 820 °C – 2 min and 900 °C – 2 min. It can be seen from the microstructure that in case of 740 °C austenite has started to form on the 10th min. With 820 °C and 900 °C the austenite formation has already taken place after the 2nd min. The homogeneous austenite, without carbides, in case of 820 °C is achieved on the 15th min and at 900 °C on the 10th min in the furnace.

3.2. Industrial test

Industrial test of tongues, using two different production feed rates on the austempering line, were performed to study austenitization in the actual production process. With different feed rates, the temperature change of tongues in the furnace was measured by means of a long thermocouple to observe austenitization. The measured temperature profile of the empty furnace and the two heating curves of parts with different feed rates are shown in Fig. 6. The increase of the temperature on the heating curve of 370 kg/h is more rapid. In the case of 370 kg/h the parts achieve Ac_1 temperature about 2 min earlier than in the case of 440 kg/h, which gives more time for austenitization. It is realized that in case of the feed rate of 440 kg/h the temperature of the tongues at the end of the furnace is slightly lower than in case of 370 kg/h. If the furnace feed rate is raised, more parts will be loaded on the belt and the layer thickness increases. Since the heating elements in furnace are located above the belt, the higher thickness of the

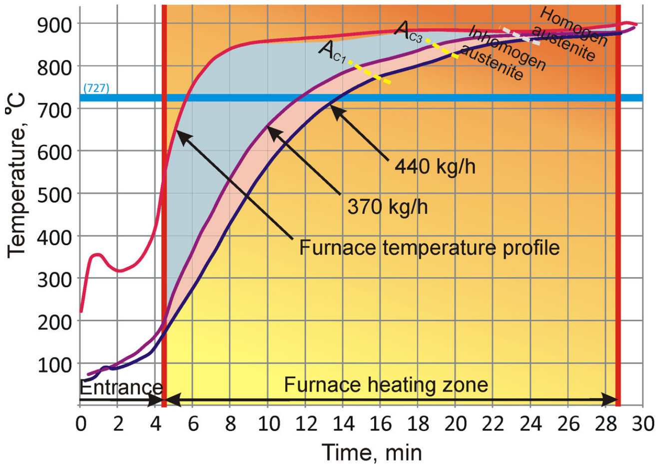

Fig. 6. Heating diagrams of the tongues in the industrial furnace.

load increases the time for the heat flux to reach the bottom parts. It means that the heating curve, which is measured in the bottom parts, characterizes the heating cycle in the furnace [9].

The furnace heating diagram of parts (Fig. 6) can be conditionally divided likewise to Fig. 4 and with different temperature rise the Ac_1, Ac_3 and homogeneous austenite temperature lines will also shift. It is understood that with the feed rate 370 kg/h, the austenite formation starts at a higher temperature as the heating rate of parts is more rapid.

With the industrial test the seatbelt tongue quality criteria were measured to see potential variation in results between different feed rates. The results are presented in Table 4. According to the outcome the results are stable, a slight difference was detected between hardness and rupture force values (Table 4). This can be explained by the difference between used quench salt temperatures (Table 3). As the final hardness of parts is related to salt temperature, the difference in salt temperature of 5 °C result in higher hardness and consequently in higher rupture force results in case of 370 kg/h.

The measured hardness and rupture strength results were stable with both production feed rates. The higher deviation of hardness at MP2 is caused by the wider cross-section as it was explained above. Brittleness evaluation, using bending test, does not show the influence of hydrogen embrittlement. To analyse the quality of parts austenitization in the furnace, the metallographic sections of tongues were taken according to Fig. 1. The metallographic sections were chosen due to the different cross-sections of the part, herein the 1st section is the smallest and the 2nd section is the widest. SEM images of the specimen's microstructures are shown in Fig. 7.

It can be seen in the SEM microstructure images that there are no residual cementite particles observed in the microstructures as an indication of inhomo-

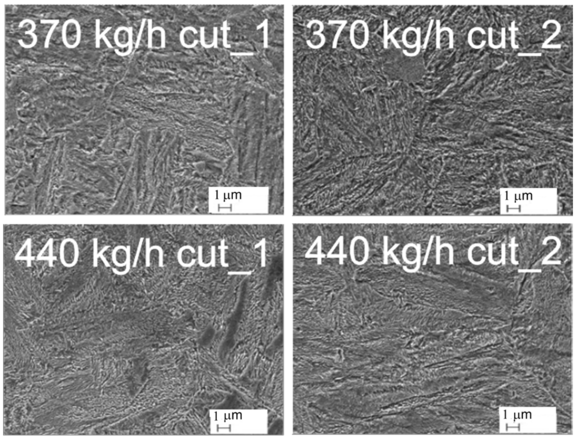

Fig. 7. SEM images of steel microstructures for different production rates.

geneous austenitization. This implies that the austenitization process in the heating furnace has been sufficient and homogeneous with both feed rates. There is a slight difference in the size of bainite sheaves in case of the lower feed rate of 370 kg/h. It can be explained by better heating capacity and with slight coarsening of the austenite grain size [2]. As the austenite formation has been complete with both production feed rates, it shows that furnace temperatures can be optimized.

4. CONCLUSIONS

By the selection of austenitization parameters for an industrial furnace, the following inputs must be considered: material chemical composition, furnace temperature, feed rate, layer thickness and heating time. The laboratory test indicated that the wider and narrow sections of the part will austenitisize unequally in time. The main conclusions are as follows.

1. The geometrical aspect such as wider cross-section of the safety belt tongue requires higher temperature or longer soaking time to achieve uniform hardness.
2. If the austenitization temperature or time has been insufficient, the undissolved carbides will remain in the microstructure.
3. The greater the overheating step from Ac_3 transformation line is, the less importance has the soaking time for homogeneous austenite formation.
4. It is relevant to decide on the austenitization time and temperature in the furnace with the heating diagram, which is measured at the bottom of the loaded layer.
5. The austenite formation is complete with both tested feed rates, which shows the possibility of further optimization of the industrial austenitization furnace temperatures.

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Austenitiseerimise mõju detaili kvaliteedile pidevtermotöötlusel

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Detaili austenitiseerimise hindamiseks tööstuslikus isotermkarastuse protsessis viidi läbi laboratoorne ja tööstuslik katsetus. Laboratoorsest katsetusest ilmnes, et austenitiseerimine detailis toimub erineval kiirusel tulenevalt detaili geomeetriast. Kuumutusahju temperatuuri valik määrab austenitiseerimise kiiruse, seejuures mida kõrgem on temperatuur, seda väiksem osatähtsus on seisutusajal homogeense austeniidi saavutamiseks. Mittehomogeense austeniidi korral jäävad karastusstruktuuri karbiidid, mille alusel saab austenitiseerimist protsessijärgselt hinnata. Austenitiseerimise hindamiseks tööstuslikus ahjus on praktiliseks meetodiks ahju suunatavate detailide kuumenemiskõvera mõõtmine alumises kihis. Tööstuslik katsetus erinevatel liini tootlikkustel näitas võimalust austenitiseerimise režiimide edasiseks optimeerimiseks.