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Study on homogeneity and repeatability of single-piece flow carburizing system

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ABSTRACT

Purpose: The purpose of this paper was to determine the homogeneity and replicability of carburized layers obtained by a continuous single-piece flow method.

Design/methodology/approach: A series of 100 gears was carburized under low pressure atmosphere using the single-piece flow method. The microstructures of the obtained carbon layers were investigated. Hardness penetration pattern and carbon concentration profiles were tested.

Findings: The findings have shown the validity/correctness of the microstructures of the carburized layers obtained by the single-piece flow method. It has been proved that the carbon layer in every gear is uniform, what confirms that each element is affected by the same process conditions and the gears in the whole series can be precisely reproduced.

Research limitations/implications: The short-pulse low-pressure carburizing technology needs further investigation to understand its all mechanisms fully.

Practical implications: The single-piece flow method provides the uniform and reproducible carburized layers with the precision magnitude exceeding the abilities of currently used thermo-chemical furnaces. When applying the method it is possible to obtain a uniform carburized case in every single gear from the whole series of elements subjected to the process. Optimized configuration of process parameters and carbon-carrying mixture allows to meet the high expectations of a modern and future industry, what is most crucial in exploiting carburized steel gears.

Originality/value: The applicability of the LPC single-piece flow method to a demanding mass production has been verified. The statistical validity of research results of the whole manufactured series of gears is being performed for the first time.

Keywords: Heat treatment, Thermo-chemical treatment, Case hardening, Vacuum carburizing, Single-piece flow

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MANUFACTURING AND PROCESSING

1. Introduction

Low-pressure carburizing (LPC) is a heat treatment process that is used for surface hardening. It was invented in late 1968, patented [1] and fully commercialized [2-10]. It is a complex process in which small amounts of carburizing gas are continuously pumped in and out of a furnace at a rate that allows the carbon on the surface of the steel to reach the austenite solubility limit [11-13]. During the saturation stage (boost stage), the steel surface is saturated by carbon from a low-pressure gas atmosphere and diffuses into the material. Subsequently, the gas supply is stopped, and only carbon diffusion occurs. Mass transfer during carburizing proceeds in three stages: carbon transport from the atmosphere to the steel surface, chemical reaction at the gas-steel interface, and carbon diffusion between the carbon-rich atmosphere and steel surface, which provides a driving force for the mass transfer phenomena and establishes a carbon concentration gradient at the surface of the carburized part [14]. Currently, the process has been elucidated quite well, both in terms of its kinetics [15-18], the effects of individual factors [19,20], surface phenomena [21] and the final properties of carburized material [22-27]. It was proven that LPC provides a more uniform carburized oxide-free case depth, cleaner parts and less part distortion [11,28,29]. In terms of mechanical properties carburizing process results in high hardness, wear-resistant surface and simultaneously the possibility of transferring great stress due to the load-bearing core in gears. The features are sufficient to successfully meet the needs of industries which use carburizing to improve the quality of steel gears [24,30,31].

Nowadays vacuum carburizing provides the best results for a particular application due to access to a wide range of vacuum equipment. It is the method of thermo-chemical modification of steel elements such as pinions, transmission gear elements or steering system elements [32] used in various industries from automotive, aerospace to small household machines constructions [33].

Although there are many benefits to these technology, there is one feature that remains unchanged. Even in modern vacuum furnace systems, parts are configured and processed in batches on special fixtures (Fig. 1) and undergo the whole case hardening process in such a configuration. The composition of the carburizing atmosphere is not uniform and changes as the atmosphere moves toward the centre of the batch, with the amount of carbon decreasing gradually, resulting in poorer carburization of the parts at the centre of the batch. The differences in the atmosphere composition (carbon potential) can be as great as 10%, and the case depth can change accordingly. The cooling rate during the quenching process also affects the case depth, with a faster quench increasing the case depth and a slower quench decreasing the case depth. Non-uniformities of the cooling medium flow rate through the batch can be as high as 50% and can also significantly impact the case depth by several more percentage points [34]. This means that each part in a batch is affected by the process conditions in a unique manner, based on its position within the batch. Each part is affected differently regarding the heating rate, composition of the process atmosphere, and intensity and direction of the cooling medium. There is no doubt that the parts in the outer layers of a batch are heated more quickly and to a different temperature (according to the temperature distribution within the batch), as the atmosphere around them is "richer," and they are quenched more intensely, compared to the parts toward the centre of the load. The result is that parts inside the batch have different physical and metallurgical properties than those on the outside of the batch, e.g., surface and core hardness, microstructure, and especially the effective case depth [35-38].

Fig. 1. Parts configured in batch, ready to process

Due to the compounding effect of these varying parameters inherent in batch processing, mostly the industry's quality expectations are very liberal. Tolerances can be as high as 50%, a direct consequence of batch processing and the currently accepted tolerances of the batch processing case hardening systems. For more demanding applications, the modern sophisticated vacuum furnaces are able to provide the accuracy of ±10% for effective case depth [39]. Nonetheless in order to achieve high precision the solution still requires an improvement [38].

The vast majority of weaknesses and limitations of the current case hardening processes are associated with its batch-related nature. Therefore, to eliminate these weaknesses and limitations, it would be ideal if batch processing was eliminated and replaced with a continuous, single-piece flow model. Precision and repeatability would be improved because each part would run individually and would be exposed to the exact same temperature and atmosphere. Single parts would be heated up more quickly and uniformly due to direct radiation and the beneficial effects this direct radiation has on the more consistent conduction of heat within the gear. Moreover, any temperature gradients within the chamber would be neutralized because each part goes through all the same positions.

The single-piece flow concept has been around for some time in theory and industry articles [40,41]. Various systems, more or less in line with the idea, have been developed, but no device for mass thermal treatment has been constructed that would fully embody the idea to date. Single-piece flow processing should mean that every single piece goes through the exact same positions and process conditions as every other piece. A system where parts are placed on trays, even in single layers, or when parts are processed individually in different process chambers, does not meet the criteria of a single-piece flow system.

Complete design solution was developed in 2016 [33]. A multi-chamber device for highly efficient, individualized and uniform heat treatment of machine parts using technologies of low-pressure carburization (LPC) and high-pressure gas quenching (HPGQ) meets all condition required by single-piece flow method. It seems to be proper solution for productions of important, high-performance elements with high geometrical and functional variety (gear wheels, rollers, synchronization rings, bearing rings, etc.) used in the mass industry (automotive, transmission and bearing industries).

The purpose of this paper was to study homogeneity and repeatability of carburized layers produced using single piece flow method.

2. Materials and experiments

A series of 100 gears with a diameter of 114.4 mm and a teeth mode M1 (Fig. 2) made of the steel EN 16MnCr5 grade was subjected to continuous single-piece flow low pressure carburizing process [34,35].

A vacuum furnace contained 3 process chambers dedicated to consecutively heating-up, carburizing and both diffusion and pre-cooling before quenching. Each of the chambers embraces 15 gear positions. During the process every gear, one by one, went through all 15 position and chambers. The first step involved heating-up elements to the temperature of 920°C. Subsequently in the second chamber, where remained the same temperature, elements were subjected to the carbon-carrying gas mixture under low pressure atmosphere. In the third chamber for 10 gears positions the temperature of 950°C was provided. It was reduced to 860°C for the last 5, hence the diffusion was allowed (Table 2). Eventually the gears were individually quenched in nitrogen and tempered in the temperature of 180°C.

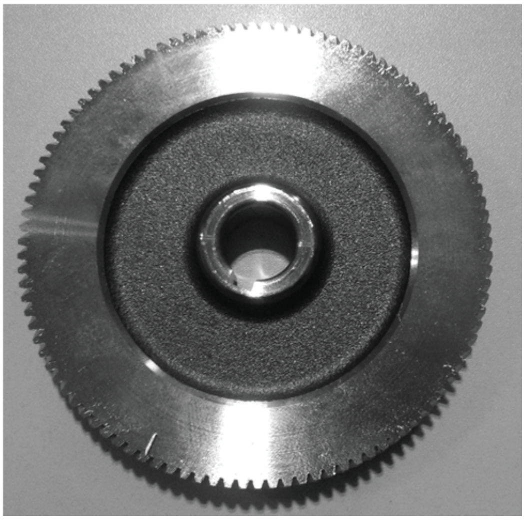

Fig. 2. Research element. Gear wheel. Material: EN 16MnCr5

Table 2.
Low-pressure carburizing (LPC) process parameters

Gear no.	Carburizing chamber temperature, °C	Diffusion chamber temperature, °C	Quenching temperature, °C
1-100	920	950	860

Out of the 100 gears in the series 10 details were randomly chosen for further investigation. The elements were subjected to metallographic tests, carbon concentration studies and hardness profile measurements.

Specimens' surface were abraded on SiC papers and then polished using diamondlike liquid. For specimens preparation the automatic polisher (Tegramin-30; Struers) was used. The microstructure observation was performed with optical microscope. The cross section of gear specimen in different locations was analysed in order to study the carburized case according to the Polish standard PN/H-04505 and work [44].

Hardness penetration pattern was tested on gear tooth flank using Vickers method. The automatic hardness tester was used (DuraScan Struers; Ecos Workflow). It allowed to obtain the accuracy of measurement at value approximately +/-30 HV (PN-EN ISO 6507-1:2007).

The carbon concentration profiles in the surface layer were examined by glow discharge optical emission spectrometry (GDS 850a; Leco) [42]. Three out of all gears were examined more profoundly; the material used to prepare specimens was taken/extracted from 4 different areas of gears to justify whether uniform carbon layer regards the whole gear. The carbon profiles in square specimens were determined by means of removing progressively thin outer layers of the samples approximately every 10 µm.

The place where predetermined hardness is achieved is usually interpreted as a border between carburized layer and the core of material. It is a perpendicular distance from the surface of the part to a point inside the part where defined hardness is measured (usually 550 HV1).

Sometimes, to determine the thickness of carburized layer, the effective case depth is measured.

3. Results

3.1. Microstructure

The microstructure of carburized case and core is shown in the Figures 3, 4 and 5. The microstructure of carburized layer includes tempered martensite within the range20-25% of retained austenite. There is no evident intergranular oxidation or decarburization near the surface.

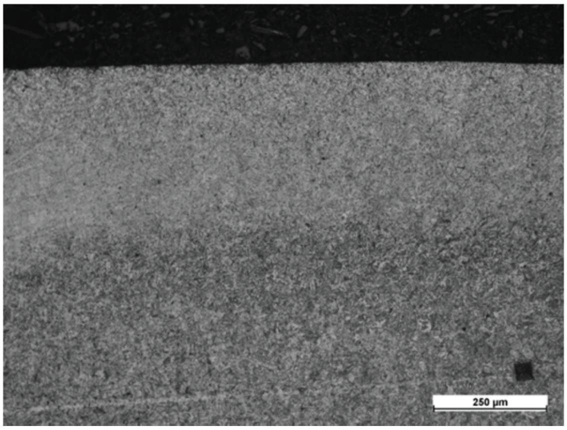

Fig. 3. The microstructure of flank. Material: EN 16MnCr5. State: after low-pressure carburizing (920-950 C), quenching (860 C), tempering (180 C). Microstructure: tempered martensite. Etching: 4% Nital

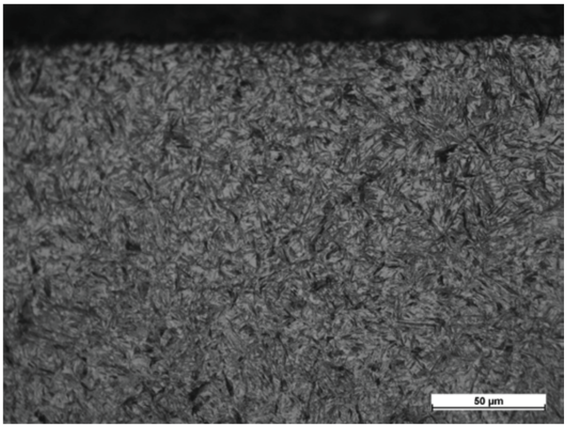

Fig. 4. The microstructure of flank. Material: EN 16MnCr5. State: after low-pressure carburizing (920-950 C), quenching (860 C), tempering (180 C). Microstructure: tempered martensite. Etching: 4% Nital

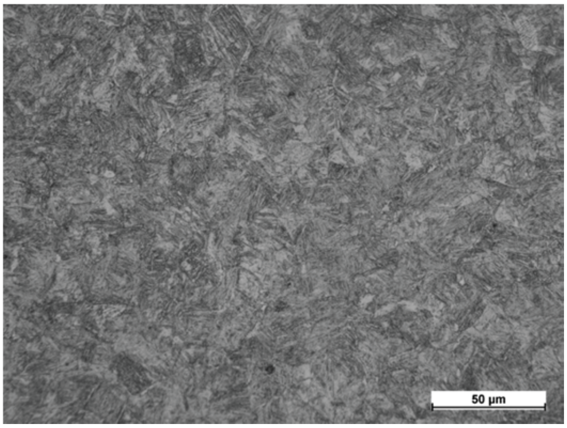

Fig. 5. The microstructure core. Material: EN 16MnCr5. State: after low-pressure carburizing (920-950 C), quenching (860 C), tempering (180 C). Microstructure: tempered martensite. Etching: 4% Nital

Core microstructure has been examined in the middle of the tooth on the root diameter (Fig. 5). A tempered martensite with bainite and some pearlite were identified. The microstructure does not include a blocky ferrite.

3.2. Carbon concentration

In the Figures 6 and 7 there are presented the results of carburization investigations on prepared specimens from examined gears. The measured effective case depths of tested gears were 0.368±0.010 mm.

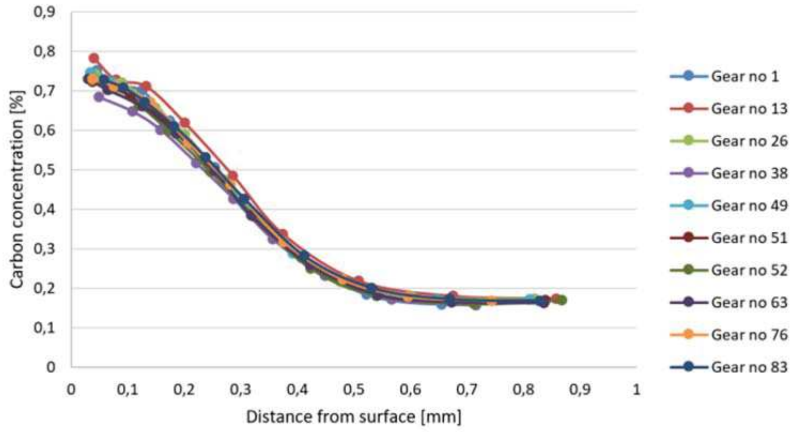

Fig. 6. The results of uniformity and homogeneity carburization investigations on geared wheels

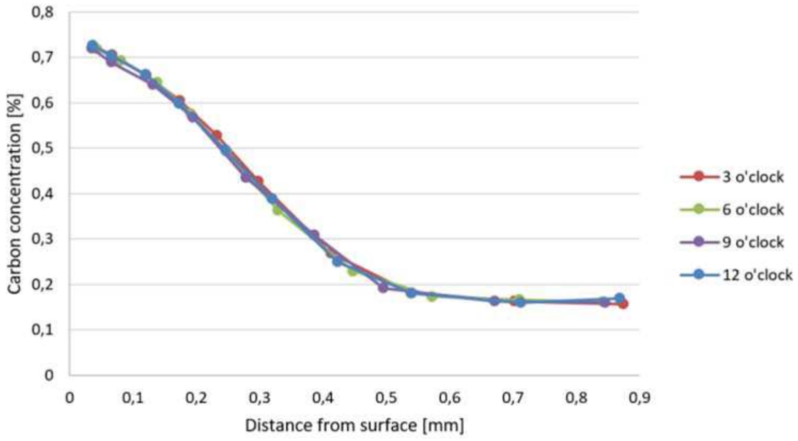

Fig. 7. The results of uniformity and homogeneity carburization investigations on a single geared wheel no. 52 in four different places (90 deg. angle)

3.3. Microhardness

The results of hardness measurement are shown in the graph Fig. 8 (flank). The effective case depth of tested gears in the root fillet (based on hardness measurement) was 0.37±0.01 mm.

3.4. Homogeneity and repeatability investigation

The evaluation of repeatability and homogeneity of diffusion layer were examined on the basis of studies on carbon concentration in carburized case. Student's t-distribution was applied to analyse all the calculations and obtained results.

The average value of ECD (effective case depth) was estimated to be 0.352±0.010 mm (mean ± standard deviation). Calculation was based on the trial with 10 elements tested with the criteria of carbon concentration 0.37%. On the grounds of the estimation the value of confidence coefficient was determined as P=95%, what allowed to set out the confidence interval for the average ECD in the whole series of 100 gears. The value of the average carburized effective case depth in the series appears to be in the range {0.345; 0.359} mm and a standard deviation σ is included in {0.007; 0.010} m.

The measurement results of carbon concentration in effective case depth for the gears tested only in one place are 0.351±0.009 mm, 0.350±0.008 mm, 0.341±0.007 mm. Confidence intervals for the average and standard deviation of the gears are (presuming 95% of confidence coefficient): $ECD_{51} \in \{0.337;\ 0.365\}$ mm z $\sigma_{51} \in \{0.005;\ 0.033\}$ mm, $ECD_{52} \in \{0.337;\ 0.363\}$ mm z $\sigma_{52} \in \{0.005;\ 0.031\}$ mm and $ECD_{63} \in \{0.330;\ 0.351\}$ mm z $\sigma_{63} \in \{0.004;\ 0.024\}$ mm.

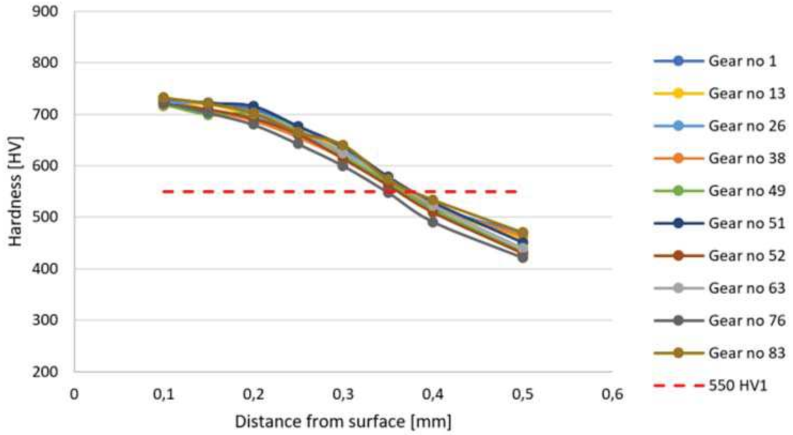

Fig. 8. Microhardness profiles measured in gear's flank line

The average hardness value was tested in the 10 chosen gears in the distance of 0.368 mm from the surface. It was estimated as 551±10 HV (mean ± standard deviation). On the grounds the confidence intervals and standard deviation for the whole series of 100 gears was evaluated (P=95%). The average hardness of depth in the series was determined to be in the range {544; 558} HV and the standard deviation σ was approximated as {6; 17} HV. The result can be interpreted as a confirmation of unusual uniform quenching in the quench chamber.

4. Discussion

The investigation of homogeneity and reproducibility of carburized case should be focused on two main parameters. As a matter of fact, the most critical one is case depth measured at the pitch line (because this area is the most susceptible to pitting). Another important area is root – because it is connected with bending fatigue life [43]. The mean ECD of tested gears in root fillet (from hardness measurements) was 0.316±0.016 mm. Uniform effective case depths have been achieved on flank; the mean ECD of tested gears is was 0.368 mm±0.010 mm. The case depths in root fillet are slightly thinner, which is a normal occurrence in this type of parts geometry.

The more carbon in the layer the higher hardness and fatigue strength (to a certain limit value). Surface carbon content in the carburized gears affects many metallurgical and fatigue characteristics that provide the gear quality. The proper amount of carbon in the carburized layer depends on steel composition, quench characteristics and other heat treatment parameters. Carbon level between 0.9-1.0 % at the surface of low alloy steels, allows to achieve optimum case properties (in relation to surface wear and fatigue strength) [43]. On the other hand, it can cause the excessive amount of retained austenite, hence the tendency to produce carbides can occur. The common practice is to carburize a gear to around 0.7%C in the surface. The carbon concentration in examined gears was around 0.73%.

Confidence intervals obtained for the singularly tested gears were slightly broader in comparison to the trial of 10 elements. The difference is caused by the smaller size of trial in the gears tested only in one place.

The amount of retained austenite was estimated during the metallographic inspection. The permitted amount of retained austenite depends on gear quality, but usually should not exceed 25% and does not precipitate hardness drop near the surface. The desired amount of retained austenite is considered from 15 to 20% due to the effect of pitting and wear resistance. [43].

5. Conclusions

The findings have shown the validity/correctness of microstructure of carburized layers obtained by the single-piece flow method. It has been proved that carbon layer in every gear is uniform, what confirms that each element is affected by the same process conditions and gears in the whole series can be precisely reproduced.

The single-piece flow method provides uniform and reproducible carburized layers with accuracy at about an order of magnitude exceeding the abilities of currently used thermo-chemical furnaces. By applying the LPC method it is possible to obtain uniform carburized case in every single gear from the whole series of elements subjected to the process. Appropriate configuration of process parameters and carbon-carrying mixture allows to meet high expectations of modern and future industry, what is crucial in exploiting carburized steel gears.

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