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AN OVERVIEW OF THE STATE OF THE ART OF THERMOCHEMICAL TREATMENT OF GEARS

BY

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Abstract. Gears are machine parts that generally transmit rotational motions from a power source to at least one executive element. During the transmission process, the gear’s teeth are subjected to high contact pressures and wear, while the gear’s body has to overcome high torsion stresses and eventual chocks. These localized and strongly differentiated loads require highly different properties for the teeth’ surface and the gear’s body. The common practice is to manufacture the gear, including the teeth, from hypoeutectoid alloy steel (typically below 0.2% C) and subject it to a complex thermochemical treatment. The gear is first carburized by exposing the teeth to a carbon-rich environment, such as methane. In this way, the outer layer would become strongly enriched in carbon (exceeding 0.77% C), which would generate cementite, thus significantly enhancing its hardness. The carburized gear is subsequently subjected to a complex heat treatment consisting of solution treatment and tempering. The former would enhance strength, due to the formation of martensite, and the latter would increase toughness and elasticity by transforming the quenching martensite into intermediate compounds such as bainite and troostite. In this way, the outer layer of the teeth would gain hardness by carburizing, thus providing enough resistance to contact pressure and wear. On the other hand, the gear’s body would gain strength and toughness to support high torsional stresses and shocks. After describing this industrial technology, the paper provides an overview of the state of the art of the thermochemical treatment of

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gears. The most common hypoeutectoid alloy steel grades, used for carburized gears manufacturing, were inventoried. Some experimental results obtained on the carburized, solution-treated and tempered 18CrNiMo7-6 steel were reviewed. Finally, a summary of the most frequently used parameters for carburizing, solution treatment and tempering was performed and some possible new research directions were outlined.

Keywords: Carburizing, solution treatment, tempering, carbides, steel.

1. Introduction

Some machine parts, such as camshafts, crankshafts, bearings, sprockets, and gears, are required to exhibit different properties along their functional cross-section. Their outer layer must be hard, showing resistance to abrasion, fatigue, and indentation. At the same time, their core has to be tough, able to slightly flex under load, absorb impact energy, and prevent brittle fracture. In other words, they require a hard outer layer and a tough, elastic core, a combination that provides both wear resistance and impact strength (Callister and Rethwisch, 2014).

To achieve such a combination of properties, the common processing routine of classical fabrication involves using a hypoeutectoid alloy steel (usually with a carbon content below 0.2% and an alpha-ferrite-pearlite structure) and subjecting it to a complex thermomechanical treatment consisting of carburizing, solution treatment, and tempering (Berns and Theisen, 2008).

Alpha ferrite is a solid solution of carbon dissolved in Fe_{α}-body-centred cubic, while pearlite is a two-phase lamellar microstructure [ordered mechanical mixture of alpha ferrite (87.5 wt%) and secondary cementite (12.5 wt%)]. The main technological stages are described in the following sections.

2. Carburizing

Carburizing involves subjecting the external surface of the thermochemically treated parts to a carbon-rich environment. Consequently, the outer layer of the hypoeutectoid steel, with a thickness up to 5 mm, becomes enriched in C, in such a way that it exceeds 0.77 % C at the surface, its character changing to hypereutectoid and its structure to perlite-cementite (Totten and Howes, 2006).

Cementite is a carbide-type intermetallic compound with the stoichiometric formula Fe_3C. In alloy steels, it may also contain manganese or some carbide-forming elements such as Cr and Mo. Under the form of secondary cementite, it precipitates from austenite (a solid solution of carbon dissolved in Fe_{γ} with a face-centred cubic, *fcc*, unit cell) below the critical point A_{cem} that corresponds to the solvus curve of austenite, during cooling. Secondary cementite is present in the structure of any type of plain carbon steel, either as a component of pearlite or in a free state, in hypereutectoid steels, where it is accompanied by pearlite. In hypoeutectoid steels, tertiary cementite can precipitate from alpha-ferrite (a solid solution of carbon dissolved in Fe_{α}) during cooling (Bhadeshia, 2020).

Cementite is metastable and the obtainment of large single-crystalline specimens, to be tested, is rather difficult. For this reason, its mechanical properties are typically ranged within certain limits such as 140-298 GPa for Young's Modulus and 1013–1340 HV for hardness (Uemoto and Ohtsuka, 2022).

The typical microstructures of some hypoeutectoid and hypereutectoid steels are exemplified in Fig. 1.

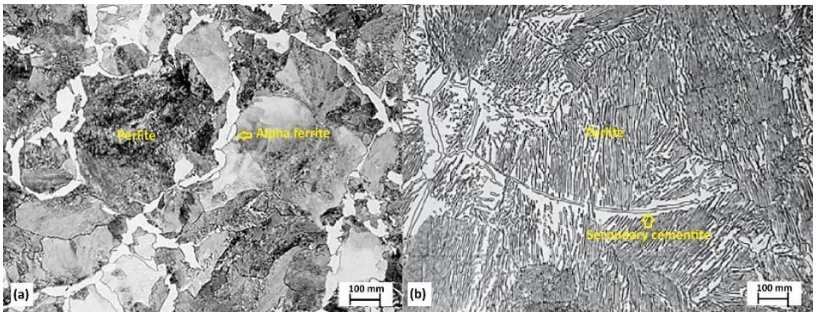

Fig. 1 – Typical microstructures of plain carbon steels: (a) hypoeutectoid; (b) hypereutectoid (Mackenzie, 2025).

After carburizing, the microstructure gradually changes from hypoeutectoid to hypereutectoid on the surface-modified layer.

Fig. 2 illustrates the microstructural particularities, observed by optical (OM) and scanning electron microscopy (SEM), of the surface-modified layer after the carburizing of a JIS SCM420 steel, with the chemical composition C-0.21, Si-1.12, Mn-0.81, P-0.020, S-0.017, Cr-0.32, Mo-0.17, mass % (Okada *et al*., 2020). It is noticeable that the hypereutectoid structure undergoes continuous changes from the surface to the total depth of the carburized layer.

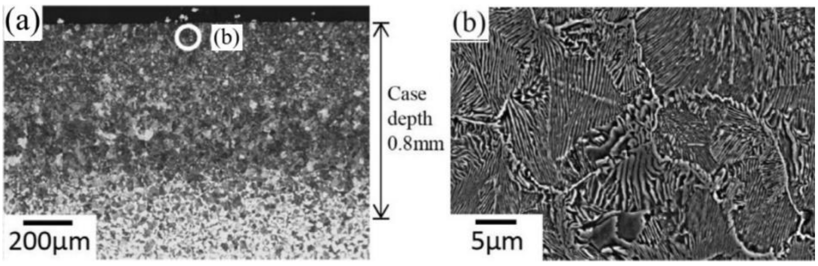

Fig. 2 – Microstructural aspects of a carburized JIS SCM420 steel: (a) optical micrograph near the specimen surface after vacuum carburizing; (b) high magnification SEM micrograph observed at the circle marked in (a), (Okada *et al*., 2020).

In the case of JIS SCM420 steel, carburizing was performed in vacuum, and was followed by gas cooling. Fig. 3 illustrates the chemical composition evolution from the core to the surface of the carburized part.

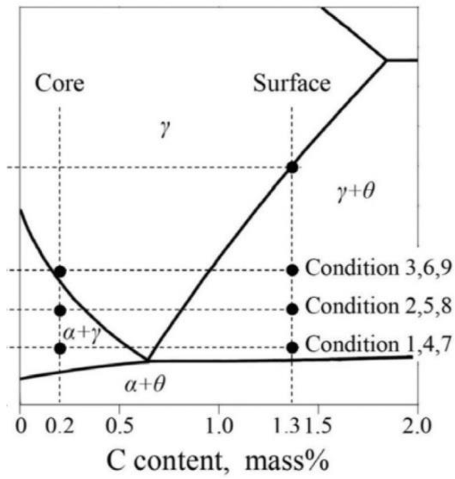

Fig. 3 – Phase diagram corresponding to different regions of carburized JIS SCM420 steel parts (Okada *et al*., 2020).

Since secondary cementite forms along the boundaries of austenite grains, it may generally form a network, which is harmful for the steel part's properties (Kantor and Vorkachev, 2017). In the carburizing practice, the C content is carefully controlled in such a way that spherical cementite forms, after a cyclic heat treatment (Miura, 1966).

The most common hypoeutectoid alloy steel grades used for carburized gears manufacturing are: 17CrNi16, 20MnCr12S, 17CrNiMo6, 20MoCrNi06, 34CrNiMo6, 34MoCrNi16, 42CrMo4, 34CrMo4, 20MnCr5, 18CrNiMo7-6 (Cheșa *et al*., 1989).

3. Solution treatment

In the case of 18CrNiMo7-6 steel grade, selected as a representative of carburizing alloy steels in the present review, carburizing was performed at 920°C, for different times in different carbon-rich environments: 1.2% C-potential atmosphere/ 17 h, 1.1%C/ 7 h and 0.9% C for 10 h sequentially (Zhao *et al*., 2018).

The carburized 18CrNiMo7-6 steel, with a surface-modified layer of 4.08 mm thickness, was reheated at 800°C for 2.5 h and quenched in oil. The material was tempered at 180°C for 10 h and the microstructure mainly consisted of martensite lath, as shown in Fig. 4.

In the case of common carburizing practice, the thermochenically treated part is maintained in a C-rich environment, above the critical point A_{cem} and, after its surface-modified layer was penetrated by C atoms, is solution treated by oil quenching. This heat treatment is meant to enable the transformation of austenite into martensite.

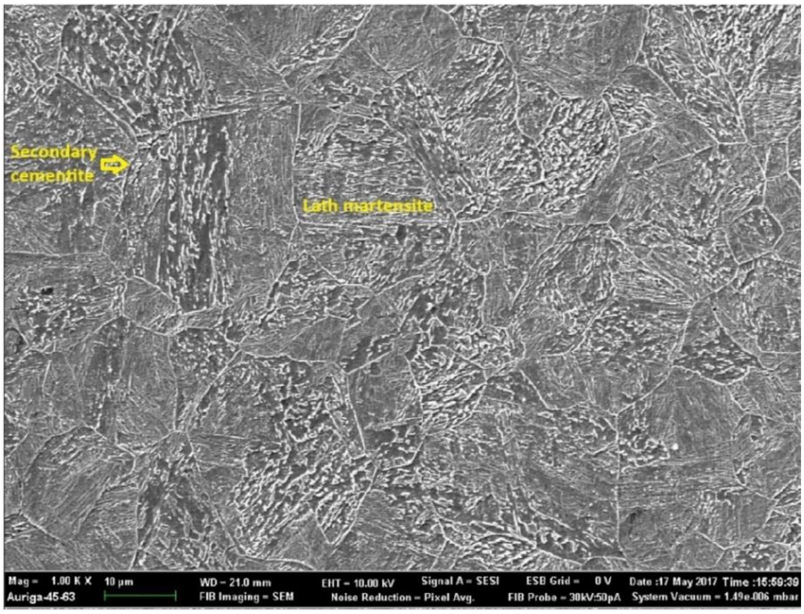

Fig. 4 – Typical micrograph of 18CrNiMo7-6 steel after carburizing (please see text for details), solution treatment (800ºC/2,5 h/ oil) and tempering (180ºC/10 h), (Zhao *et al*., 2018).

Comparing Figs.1(b), 2(b) and 4, it is noticeable that all figures display secondary cementite networks. The first two present pearlite colonies, while the latter contains rare arrays of lath martensite. Due to the low amount of C, which does not exceed 0.2%, no carbon saturation occurs and the number of martensite laths is rather limited (Bhadeshia, 2020). Nevertheless, lath martensite is metastable and retains a great amount of internal stresses which contribute to reducing its toughness. For this reason, a final heat treatment has to be applied to enhance elasticity by transforming the quenching martensite into intermediate compounds such as bainite and troostite.

4. Tempering

Fig. 5 displays some typical microstructures of martensite or of the pearlite-type compounds that may form during the tempering heat treatment which comprises the heating to different temperatures of a part with the structure mostly composed of quenching martensite, to reduce the internal stresses.

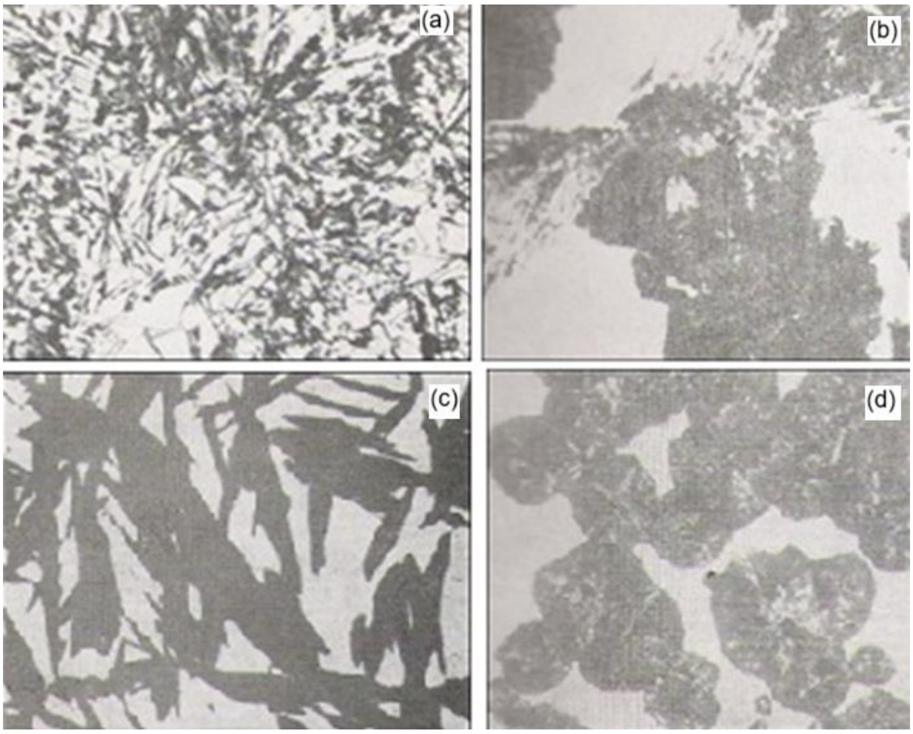

Fig. 5 – Typical tempering microstructures: (a) tempering martensite; (b) inferior bainite; (c) superior bainite; (d) troostite (Cheșa *et al*., 1989).

With increasing the tempering temperature, quenching martensite transforms to different resulting structures that may contain: (i) tempering martensite, Fig. 5(a); (ii) inferior bainite, Fig. 5(b); (iii) superior bainite, Fig. 5(c) or (iv) troostite, Fig. 5(d), (Cheșa *et al*., 1989).

A summary of the most frequently used parameters for carburizing, quenching and tempering is performed in the table below.

Table 1

Typical parameters for carburizing, solution treatment and tempering

	Thickness of cemented layer, mm	
	< 1 mm	*> 1 mm*
Heating temperature, °C	*900-930*	*900-930*
Holding time, h	*12*	*24-36*
Cementation media	CH_4	CH_4
Tempering temperature, °C	*200*	*550*

The global production of carburized parts includes various industries, such as:

- automotive, represented by gears, camshafts, crankshafts, and bearings that sustain the global car production, nearing 80 million units annually;
- aerospace, which demands high-quality carburized parts such as turbine blades, gears, and shafts;
- industrial manufacturing, in the case of heavy machinery, tools, and industrial equipment, from mining equipment to construction machinery and power generation components;
- oil and gas extraction that uses drill bits, pumps, and valves.

The Global Market demand for carburizing parts has grown both in the industrialized areas such as North America, Europe, and Asia-Pacific and in the emerging countries like China and India.

Carburizing Equipment and Services: Global demand for carburizing services has increased as more manufacturers outsource this process to specialized heat treatment service providers. Many of these companies are expanding their capacities due to the rise in demand for precision parts.

Exact global production figures are challenging to access, but some reports suggest the carburizing market is a multi-billion-dollar industry. Specific estimates might range anywhere from 5 to 10 million carburized parts per year, depending on the sector (Parrish, 1999).

5. Conclusions

Based on the documentary synthesis reviewed in the above sections, the following conclusions can be drawn:

- Due to their high hardness and great chemical stability, carbides can play an important role in the long-lasting functionality of carburized teeth.
- The main conditions required for carbides are: (i) not to exceed 15 μm in length, (ii) to be isolated (not to form a network) and (iii) having a spherical shape rather than elongated.

Subsequent research will be focused on the investigation of different variants of heat treatment able to produce evenly distributed small spherical carbides both inside and along grain boundaries.

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PREZENTARE GENERALĂ A STĂRII ACTUALE A TRATAMENTULUI TERMOMECANIC AL ROȚILOR DINȚATE

(Rezumat)

Roțile dințate sunt organe de mașini care transmit, în general, mișcări de rotație de la o sursă de putere la cel puțin un element executiv. În timpul procesului de transmitere, dinții roții dințate sunt supuși la presiuni de contact ridicate și la uzură, în timp de corpul roții, trebuie să învingă tensiuni de torsiune ridicate și eventual șocuri. Aceste sarcini localizate și puternic diferențiate necesită proprietăți foarte diferite pentru suprafața dinților și corpul roții dințate. Practica curentă este de a fabrica roata dințată, inclusiv dinții, din oțel hipoeutectoid (în general cu mai puțin de 0,2% C) și de a o supune unui tratament termochimic complex. Roata este mai întâi cementată într-un mediu bogat în carbon, cum ar fi metanul. În felul acesta, stratul exterior ar deveni puternic îmbogățit în carbon (depășind 0,77% C) ceea ce ar genera cementita, mărind astfel duritatea, în mod semnificativ. Roata dințată cementată este ulterior supusă unui tratament termic complex,

constând din călire de punere în soluție și revenire. Primul ar îmbunătăți rezistența datorită formării martensitei, iar cel de-al doilea ar mări tenacitatea și elasticitatea prin transformarea martensitei de călire în compuși intermediari, cum ar fi bainita și troostita. În felul acesta, stratul exterior al dinților ar câștiga duritate prin cementare, asigurând astfel suficientă rezistență la presiunea de contact și uzură. Pe de altă parte, corpul roții dințate ar câștiga rezistență și tenacitate pentru a rezista tensiunilor mari de torsiune și șocurilor. După descrierea tehnologiei industriale, lucrarea oferă o prezentare generală a stadiului actual al tratamentului termochimic al roților dințate. Au fost trecute în revistă cele mai utilizate mărci de oțeluri aliate hipoeutectoide utilizate pentru fabricația roților dințate cementate. Au fost menționate o serie de rezultate obținute pe oțelul 18CrNiMo7-6, cementat, călit prin punere în soluție și revenit. În final s-au prezentat parametrii uzuali de cementare, călite de punere în soluție și revenire și au fost subliniate unele direcții de cercetare noi posibile.