別紙４－２（課程博士（和文））

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機械工学専攻	学籍番号	第169102号	指導教員	戸髙　義一 三浦　博己 伊﨑　昌伸
氏名	岡田　一晃			

論文内容の要旨　(博士)

博士学位論文名	浸炭と二次加熱・焼入れによる複合熱処理した肌焼鋼の機械的性質

(要旨　1,200字程度)

近年、環境保護の観点から自動車の電動化が進んでいる。それに伴い、駆動力を伝える歯車や軸受は衝撃特性や曲げ疲労，転動疲労・摩擦特性の力学特性向上が求められる。そのため、浸炭処理は共析組成から過共析組成へと炭素（C）濃度を高めた高濃度浸炭に移行しており、その応用技術として、真空浸炭と二次加熱・焼入れ（高周波焼入れ，雰囲気炉焼入れ）の複合熱処理を開発した。真空浸炭により粒界酸化の無い過共析C濃度の表層を形成でき、二次加熱温度や保持時間，焼入れ冷却速度の制御により異なるCの固溶，拡散状態や微細組織を精緻に設計できる。

高濃度浸炭の先行研究において、転動疲労や摩擦特性の向上は報告されているが、衝撃特性と曲げ疲労強度の両立が課題である。この課題解決のために、残留γ（オーステナイト）やθ（セメンタイト）の組織因子に着目した研究はあるが、残留γやθの量のみに着目しており、相互作用のあるその他の因子への影響にまで着目した研究は少なく、課題解決に至っていない。

以上の背景より、θや残留γの形態・分布，残留γの安定度，残留応力，α’（マルテンサイト）の形態など、それぞれが互いに影響し合う組織因子を上記の複合熱処理を用いて制御した肌焼鋼について、衝撃特性，曲げ疲労，摩擦特性を評価した。さらに、それらの特性を向上し得る熱処理条件と組織の設計指針を本論文において提案した。

それぞれの特性について評価した結果を踏まえて、次の設計指針を得た。

衝撃特性について、二次加熱は、レンズα’が形成しない上限温度と、Cの固溶，拡散が十分に生じる下限温度とし、雰囲気炉加熱の緩昇温と保持時間を設けることにより高靭化できる。亀裂発生抑制のためには、残留γ量は適度に多く、その安定化を図る。これは残留γの塑性変形による応力緩和を目的とする。また、焼戻し処理は、少量の残留γをα’へ相変態させ、圧縮残留応力の付与により亀裂発生を抑制する。亀裂伝播抵抗の向上のためには、θの形態は亀裂伝播方向に対して直角に配向させ、また、残留γ量は微少に抑えて圧縮残留応力を付与する設計とする。

曲げ疲労特性向上のための熱処理条件は衝撃特性の場合と同様であり、雰囲気炉を用いた二次加熱・焼入れによる基地部の固溶強化が疲労寿命の向上に有益である。高応力低サイクル疲労の高寿命化は、多量の残留γを疲労過程における加工誘起変態により圧縮残留応力へ変換できる設計が相応しい。一方、低応力高サイクル疲労の場合、加工誘起変態が生じず、その変換が容易ではないため、多量の残留γは負に作用する。従って、低・高サイクルの曲げ疲労特性が向上するように、予め、焼戻し処理を用いて適度に残留γを圧縮残留応力へ変換する設計とする。

摩擦特性について、微細組織化した表面をもつ転動材は低摩擦係数化した。その表面は、潤滑油の添加剤分子の吸着・反応を促進し、微小な摩耗粒子が転動面に介在することで平滑になり、温和な摩擦条件に遷移した。

上記の熱処理と組織の設計指針により、従来材と比べて、衝撃特性と曲げ疲労強度はそれぞれ20%向上し、また、摩擦係数は21%の低減に成功した。

別紙４－１（課程博士（英文））

Date of Submission (month day, year) : January 7^{th}, 2021

Department of Mechanical Engineering	Student ID Number	D169102	Supervisors	Yoshikazu Todaka Hiromi Miura Masanobu Izaki
Applicant's name	Kazuaki Okada			

Abstract (Doctor)

Title of Thesis	Mechanical Properties of Case Hardening Steels Subjected to Combined Heat Treatment with Excess Carburizing and Subsequent Heating and Quenching

Approx. 800 words

In recent years, automobiles have been electrified to preserve the earth environment. Accordingly, gears and bearings that transmit driving force must improve mechanical properties such as impact property, fatigue strength, and rolling fatigue strength / friction property. Hence, the carburizing treatment has shifted to excess carburizing in which the carbon (C) concentration is increased from the eutectoid composition to the hyper-eutectoid composition. As a heat treatment applying excess carburizing, we have developed the combined heat treatment with vacuum excess carburizing and subsequent heating and quenching (induction heating and quenching, atmosphere furnace heating and quenching). Vacuum carburizing process makes it possible to form the carburized surface layer with the hyper-eutectoid composition without internal oxidation. By controlling the subsequent heating temperature, holding time, and cooling rate during quenching, different C solid solution and diffusion state and fine microstructure can be precisely designed.

In previous studies, it has been reported that excess carburizing process improves rolling fatigue strength and friction property. However, since the C concentration is high, it is difficult to simultaneously improve the impact property and the bending fatigue strength. In order to improve these properties, many studies have focused on microstructure factors such as retained austenite and cementite. However, many studies focused only on the amount, and few studies focused on the effects of interacting factors, hence the issue has not been resolved.

From the above background, case hardening steels in which the following microstructure factors were controlled by using the above-mentioned combined heat treatment were prepared. The factors are not only the amount of cementite and austenite, but also the morphology and distribution of cementite and retained austenite, the stability of retained austenite, residual stress, prior austenite grain size, the morphology of martensite. In this study, we propose heat treatment conditions and microstructure design criteria to further improve the properties through evaluation of impact property, bending fatigue property, and friction property.

For the impact property, the heat treatment is designed at the upper limit temperature of austenitization that suppresses the formation of lenticular martensite and the lower limit temperature of austenitization that sufficiently achieves C solid solution and diffusion. In the subsequent heating and quenching process, C is solid solute and diffuse by providing the slow heating and the long holding time using the atmosphere

furnace, resulting in high impact property. In order to suppress the crack initiation, the amount of retained austenite is moderately large, and its stabilization is attempted. This is to relieve the impact energy by the plastic deformation of retained austenite. In tempering, a small amount of retained austenite is phase-transformed to martensite, and crack initiation is suppressed by applying compressive residual stress. To improve crack propagation resistance, cementite morphology is an undissolved state oriented perpendicular to the crack propagation direction. Cementite has an effect as a resistance to crack propagation, reducing the crack propagation driving force. As the amount of retained austenite decreases, compressive residual stress is applied and the crack propagation resistance increases.

For the bending fatigue property, the heat treatment design is same as the impact property, and it was confirmed that the solid solution strengthening of the matrix is beneficial for improving the fatigue life by subsequent heating and quenching using the atmosphere furnace. In order to improve the life of high stress and low cycle fatigue, the design that converts a large amount of retained austenite into compressive residual stress by generating deformation-induced martensite transformation is suitable. On the other hand, in the case of low stress and high cycle fatigue, deformation-induced martensite transformation does not occur, and a large amount of retained austenite acts negatively due to insufficient hardness. Therefore, in order to improve the bending fatigue property from low to high cycles, it is suitable to design in advance to appropriately convert retained austenite to compressive residual stress by tempering.

For friction property, rolling specimen that formed the surface with fine microstructure showed a low friction coefficient. The surface enhanced the adsorption and reaction of the lubricating oil additive, and the presence of the wear particles on the rolling contact surface gradually improved the surface roughness, resulting in a transition from severe to mild friction.

Based on the above heat treatment conditions and microstructure design criteria, the impact property and bending fatigue strength were improved by 20% each, and friction coefficient was reduced by 21% compared to the conventional one.