Effect of Silicon, Chromium and Molybdenum on Resistance to Temper Softening of High Carbon Martensitic Steel*

Shinya TERAMOTO**, Manabu KUBOTA** and Jun TAKAHASHI**

The addition of alloy elements such as silicon, chromium and molybdenum is effective in the restraint of temper softening in martensitic steels. The martensitic steel containing such alloy elements is known to have excellent resistance to temper softening in low and high temperature tempering treatments. However, the effect of the compound addition and its mechanism have not yet been satisfactorily revealed. In this study, the effect of silicon, chromium, and molybdenum on resistance to the temper softening of a high carbon martensitic steel was investigated. As a result, it is revealed that the temper softening resistance quantity is maximum at the tempering temperature 773 K in the martensitic steel containing silicon, chromium, and molybdenum; this is because of the miniaturization of cementite and clustering of (Cr, Mo, Mn).C. Moreover, it is revealed to form this cluster at a tempering temperature lower than the temperature at which the alloy carbide usually precipitates (823-873 K).

Key Words: Resistance to temper softening, Cementite, Cluster, High carbon martensitic steel, Silicon, Chromium, Molybdenum

Fig. 1 (d) Resistance to softening by the addition of alloying elements tempering for 7.2 ks at each temperature; ΔHV = HV – HV Base.

Fig. 9 (a) 3D elemental maps of the area where cementite is precipitated in the SiCrMo steel tempered at 773 K for 7.2 ks.

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** Nippon Steel & Sumitomo Metal Corporation
Influence of Temperature on the Fatigue Strength of Disc Springs and Stacks of Disc Springs*

Andre SPIES**, Desislave VELEVA**, Jörg BEYER** and Matthias OECHSNER**

Disc springs and stacks of disc springs are frequently used in high force applications with limited space requirements. These assemblies are often subject to cyclic loads. For reliable dimensioning under cyclic loading, the knowledge of the structural durability and the fatigue limit of disc springs are of vital importance. Especially in the case of complex loading conditions (mechanical-thermal, mechanical-corrosive or mechanical-thermal-corrosive), where special corrosion- or heat-resistant disc spring materials are used, no systematic investigations have been carried out yet. In several research-projects at the Institute for Materials Technology at the Technische Universität Darmstadt, the temperature dependent properties of disc springs made of special materials were investigated. Particular interest was placed on how temperature influences the relaxation behavior, the lifetime and the fatigue limit properties. Besides high-grade steels containing chromium, like X22CrMoV12-1 (1.4923) or X7CrNiAl17-7 (1.4568), the nickel-based material NiCr19NbMo (2.4668) was examined.

**Key Words**: Disk spring, Fatigue limit, Structural durability, X22CrMoV12-1, X7CrNiAl17-7, NiCr19NbMo

Fig. 1 Schematic experimental setup of a disc spring testing device.  
Fig. 5 Load-deflection curve for an X22CrMoV12-1 disc spring.
Improvement of Torsional Fatigue Limit by Shot Peening for Spring Steel Containing a Crack-Like Surface Defect*

Koji TAKAHASHI**, Makiko NAKAGAWA**, Hitonobu KOIKE**, Hideki OKADA***

The effects of shot peening (SP) on the torsional fatigue limit of spring steel (SUP7) were investigated for specimens with Vickers hardness values of 460, 540, and 670 HV containing a semicircular surface slit. SP was conducted on smooth specimens and specimens containing a semicircular surface slit with a depth of 0.15 or 0.3 mm. Compressive residual stress was introduced to the specimens. Torsional fatigue tests were carried out under a stress ratio of $R = -1$. The torsional fatigue limits of the shot peened specimens with Vickers hardness values of 460, 540, and 670 HV increased by 8%–67%, 33%–143% and 36%–127%, respectively, in comparison with the non-shot peened specimens. The maximum depth of the slit that could be rendered harmless by SP was 0.15 mm for the 460 and 670 HV specimens. However, even a slit with a depth of less than 0.15 mm could not be rendered harmless by SP for the 540 HV specimen. Considering the improvement in the torsional fatigue limit and the size of the surface defect that could be rendered harmless, the 670 HV specimen is optimal for practical use.

Key Words: Torsion, Fatigue limit, Shot peening, Spring steel, Surface defect, Residual stress

ショットビーニングによるばね鋼のねじり疲労限度向上と表面欠陥の無害化

硬さが460HV、540HVおよび670HVで、半円スリットを有するばね鋼(SUP9A)のねじり疲労限度に及ぼすショットビーニング(SP)の影響を調査した。平滑材および硬さが0.15mmおよび0.3mmの半円スリットを有する各試験片に対してSPを施工した。試験片表面には圧縮残留応力を導入した。応力比$R = -1$でねじり疲労試験を実施した。SPを施工した試験片のねじり疲労限度は、硬さが460HV、540HVおよび670HVの場合に、未施工材に対して、それぞれ8%–67%，33%–143%および36%–127%向上した。SPにより無害化可能なスリットの深さは、460HVと670HVの試験片において、0.15mmであった。しかしながら、540HVの試験片においては、SPを行っても0.15mmのスリットを無害化することはできなかった。SP後のねじり疲労限度および無害化可能な表面欠陥寸法の観点から、実用上、硬さ670HVが最適であった。

Fig. 5 Residual stress distributions before and after torsional fatigue tests (670HV).

Fig. 6 Relationships between stress amplitude and depth of semi-circular slit (670HV).
Threshold Stress Intensity Factor of Crack Propagation of Delayed Fracture for Spring Steel and Design Method for Preventing Delayed Fracture*

Yurika GOTO**, Akira TANGE** and Eiji TSUJIMATSU***

In recent years, there has been a growing need for weight reduction of automotive suspension springs for the purpose of global environment protection, and with this, high-strength springs have been increasingly required. However, delayed fracture is induced when springs become highly-strengthened. Therefore development of design method considering delayed fracture and of prevention techniques is an urgent issue. In order to realize the design method for springs that prevents delayed fracture, this report provides the database of fracture mechanics parameters, i.e., threshold stress intensity factors of hydrogen embrittlement for spring steel (hereafter referred to as $K_{IHE}$). To be specific, the relationship between $K_{IHE}$ and hardness of SUP9A, SUP10, SUP11 and 51CrMoV4 steels, which are frequently used for leaf springs, was examined by the WOL testing. To confirm the usefulness of the relationship, the delayed fracture testing by four-point bending was conducted on test specimens with a semicircular notch. Moreover, effectiveness of shot peening to prevent delayed fracture, as a prevention technique, was also demonstrated, and the design method considering residual stress to prevent delayed fracture was studied as well. The acquired parameters for the prevention of delayed fracture can be applied not only to leaf spring steels, but also to spring steels in general.

Key Words: Leaf spring, Hydrogen embrittlement, Threshold stress intensity factor, Residual stress

近年、地球環境保全として、自動車用懸架ばねに対する軽量化ニーズが高まっており、ばねの高強度化がますます求められている。しかし、ばねの高強度化は遅れ破壊を誘発するもので、遅れ破壊を考慮した設計や防止方法の開発が緊急の課題となっている。そこで、ばねの遅れ破壊防止設計のために、破壊力学パラメータ、すなわちばね鋼の遅れ破壊き裂進展の下限界応力拡大係数（以後$K_{IHE}$とする）、のデータベースを提供することとした。具体的には、WOL試験により、板ばね鋼として多用されるSUP9A、SUP10、SUP11および51CrMoV4における$K_{IHE}$と硬さの関係を求めた。また、この有用性については、半円形状切欠を有する板状試験片を4点曲げ遅れ破壊試験することにより確認した。さらに、遅れ破壊防止技術として、ショットビーニングの効果が実証され、残留応力を考慮した遅れ破壊防止設計についても検討を行った。得られた遅れ破壊防止条件は、板ばね鋼のみならず、ばね鋼の遅れ破壊全般に使用可能である。

Fig. 1 Dimensions of WOL test specimen.  
Fig. 7 Relationship between $K_{IHE}$ and HRC.
Evaluating Compressive Residual Stress Depth Distribution by Eddy Current*  
Yoshiyasu MAKINO**  

Shot peening (SP) which makes fuel efficiency improvement by lightweight and high strengthening of product parts is used in aerospace industry and automobile industry. The compressive residual stress distribution introduced by SP contributes to fatigue strength improvement so much that it becomes important to measure compressive residual stress. The X-rays residual stress analysis is used for steel, but there is nothing but to destroy it for the check of the inner part of steel, so we need a nondestructive method to check. Therefore I aimed at an eddy current measurement method which can evaluate in principle the inner stress and tried to evaluate the compressive residual stress depth distribution introduced by SP. In this study, I have verified Eddy current measurement method evaluation of the distribution of the compressive residual stress accompanied by work-induced martensite transformation or only by the plastically deformed layer. As a result, eddy current measurement method is considered to be possible to evaluate the distribution of the compressive residual stress accompanied by work-induced martensite transformation or only by the plastically deformed layer.

**Key Words:** Eddy Current Measurement, Electromagnetic Characteristics, Shot Peening, Residual Stress, Non-destructive Inspection

渦電流測定法による圧縮残留応力分布の評価

航空宇宙産業や自動車産業において、部品の軽量化による燃費向上と高強度化を目的としたショットピーニング(SP)が用いられている。SPにより付与される圧縮残留応力分布が疲労強度向上に大きく寄与するため、圧縮残留応力を測定することは重要となっている。新材の応力測定にはX線回折法による手法が用いられているが、内部を検査するには破壊検査となるため、非破壊で検査する手法が求められている。そこで、原理的に内部応力を非破壊にて評価が可能な渦電流測定法に着目し、SPによる残留圧縮応力の深さ方向分布評価を試みた。本研究では、SPにより付与される加工誘起マルテンサイト変態を伴った圧縮残留応力分布や塑性変形層のみに起因する圧縮残留応力分布の評価法として渦電流測定法の検証を行った。その結果、渦電流測定法にて加工誘起マルテンサイト変態を伴う又は、塑性変形層のみの圧縮残留応力分布を評価することが可能であると考えられる。

![Schematic diagram of eddy current.](image1)

![Inductive reactance ratio of penetration depth (SSP).](image8)
The Difficulty to Calibrate an X-ray Diffractometer to Measure Residual Stresses. Is an absolute precise measurement possible?*

Eckehard MUELLER**

Many springs are shot peened and the quality of shot peening is essential for the fatigue life. Today the determination are often done via x-ray diffraction. The lattice distance is measured and out of this information the residual stress is determined (and not directly measured). For this kind of measurement an absolute gauge is not available. The only way is to calibrate it in some way. It is shown how precise measurements today are in relation to different x-ray diffractometers and a specimen must be designed to get something like a usable calibration sample.

Key Words: Residual stress measurement, Calibration, X-ray diffraction

X 線回折残留応力測定装置の較正における課題。
絶対精密測定は可能であるのか？

多くのばねはショットビーニング加工され、そのビーニング品質は疲労寿命にとって重要な要素である。今日、X線回折を用いた測定が多用されている。格子間距離を測定し、この情報から残余応力が決定される（すなわち、直接測定ではない）。この種の測定方法への絶対的な計測機器の使用は不可能である。唯一の方法は、何らかの方法で較正することである。今日、いかに精密に測定できるかは、数種類の異なるX線回折装置を使用し、供用される試験片は有用な較正サンプルが得られるように設計されなければならない。

Fig. 2 Calibration samples.

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** Bochum University of Applied Sciences
Evaluation of the Fatigue Process of Type 316 by Positron Annihilation Lifetime Spectroscopy*

Naoya UESUGI**, Kanehisa HATTORI**, Yoshihiko UEMATSU*** and Toshihumi KAKIUCHI**

Fatigue cracks, leading to catastrophic fracture of metal structure, generally initiate by the cyclic stress even under yield stress. At the first stage of this fatigue process, movement and increase of lattice defects (dislocations), namely microscopic sliding are taking place. The positron annihilation lifetime spectroscopy (PALS) has widely been used for probing open volume lattice defects in various materials. In this study, Type 316 stainless steel has been investigated. Using novel PALS system, it was able to trace the damages in fatigue process on the identical specimen. The results show that PALS is an effective tool for monitoring fatigue process.

Key Words: Positron annihilation lifetime spectroscopy, Rotating bending fatigue test, Non-destructively evaluation

Fig. 1 Behavior of a positron in a metal.  Fig. 8 The mean positron lifetime of No.350 specimen.

Fig. 1 Behavior of a positron in a metal.  Fig. 8 The mean positron lifetime of No.350 specimen.

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** Toyoeseiko Co., Ltd.

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Current Developments in the Experimental Durability Evaluation of Coated Coil Springs under Realistic Loading

Sebastian HOFFMANN**, Steffen RÖDLING**, Matthias DECKER**

Within a comprehensive test campaign different spring manufacturing technologies and surface protection systems were investigated comparatively regarding the fatigue lifetime. With the selected experimental procedure the relevant operating loads like deflection, abrasion, grit impact and corrosion were considered. As a result a significant reduction of the fatigue strength can be determined by means of mechanical damage of the spring surface and subsequent corrosion. The production technologies applied by the spring manufacturers cannot help to improve the fatigue lifetime. Only the application of a modified coating could prevent such a big lifetime reduction due to mechanical damage and corrosion. Merely on the basis of these measures the full potential of the spring technologies regarding lightweight design can be exploited completely.

Key Words: Suspension spring, Corrosion, Grit impact, Coating, Resonance tester

Fig. 2 IABG resonance spring testing machine.
Finite Element Simulation of Shot Peening on Helical Springs

Ulf Kletzin

The production of helical springs for engineering purposes involves a series of processes, as coiling, different tempering processes, presetting and in particular shot peening that change the functional and strength properties of springs. These changes are not completely known even today, which means that optimisation of spring production can take place only by expensive sample spring processes. Shot peening is a standard procedure for increasing the durability of dynamically loaded e.g. helical springs. The dependences of the residual stress profile from the parameters of the shot peening process are difficult to determine. The article will describe new developed special program tools for Finite Element (FE) simulation of shot peening on spring steel wire to calculate the residual stress profile, which is highly necessary for fatigue estimations. The interaction between the parameters such as particle dimensions, particle velocity as well as the materials of particles and spring and the expected residual stress profile will be discussed. The article describes a FE-simulation of the stepwise etching and measuring process of the residual stress profile and a discussion. Further, first 2-dimensional FE-calculations for the estimation of the influence of the shot roundness on both, residual stress profile and surface roughness will be demonstrated.

Key Words: Finite Element Analysis (FEA), Helical springs, Shot peening, Residual stress profile, Shot roundness

ヘリカルスプリングのショットビーニングに関する有限要素解析

ヘリカルスプリングの生産技術には、スプリングの機能性や機械的強度に影響を与えるコーリング、様々な熱処理工法、プリセッティングおよび特にショットビーニングなどの加工・処理工程が含まれている。今日においてさえ、これらの因果関係については十分に解明されているわけではないので、適正なスプリング生産を実現するには経費が掛かる試行錯誤的な生産を行う方法しかない。ショットビーニングはヘリカルスプリングなどに動的加力が掛けられた場合の寿命の増加を目的とした一般的な加工法である。残留応力分布をショットビーニングの加工条件から決定することは困難である。本論文は、鋼線にショットビーニングした時に、疲労寿命を推定するのに特に必要とされる残留応力分布を算出するための新しい先端的なプログラム手法について述べたものである。投射粒子のサイズと速度、被加工材と投射粒子の材質等の加工条件と残留応力分布との関係について検討を行った。本論文では、残留応力分布について、段階的に研磨しながら、有限要素解析と残留応力測定を繰り返し、解析結果と実測結果とを比較検討した。さらに、ショットの形状が残留応力分布と表面粗さに及ぼす影響について、二次元有限要素解析を用いて明らかにした。

Fig. 5 Experimental setup. Fig. 6 Residual stress distribution (SSP).
On the Effects of Heat Treatment on the Properties of Compression Springs*

Mark HAYES**

This project was instigated to answer numerous spring manufacturers’ questions about the effect of low temperature heat treatment on the load stability of compression springs. It was also written to clarify the temperatures at which effective heat treatment after cold coiling should be carried out because this is not explicitly written into standards, and end users of springs often specify non-optimised heat treatments for the spring they design and use. Carbon, SiCr and 302 stainless steel spring wires were made into compression springs of index 4, 8 and 12. They were heat treated at a range of temperatures to quantify the outside diameter change, and load tested to evaluate their elastic limit. Their stability after prestressing was also investigated, as was the effect of stress relief heat treatment after shot peening. The results indicate the need to revise some international spring design standards, and show a result that could easily be overlooked when designing a compression spring.

Key Words: Compression springs, Heat Treatment, Dimensional stability, Load stability

圧縮ばね特性に及ぼす熱処理効果

本プロジェクトは、圧縮ばね荷重安定性に及ぼす低温熱処理効果に関してばね製造者から寄せられる数多くの質問に答えるべく開始された。本論文はまた、冷間コイル後の効果的発熱処理温度条件を明らかにするものである。この温度条件は標準規格において明示されておらず、ばねのエンドユーザーが自分で設計し使用するばねに対し、かなりずしも最適ではない熱処理条件を指示することが多い。炭素鋼、シリコンクロム鋼、及び302ステンレス鋼線を用い、ばね指数4、8、12の圧縮ばねを製作し、試験に供された。これらのばねの外径寸法変化量を明らかにする為に温度条件を振って熱処理を行い、弾性限を評価する為に荷重試験を行った。また、プリストレス後の寸法・荷重安定性、及びショットピーニング後の応力緩和熱処理効果についても研究した。その結果、ばね設計国際規格の一部を改訂する必要性が浮上し、また圧縮ばねを設計する際に見落とされ易い知見が得られた。

Fig. 1 SiCr ground not Ground Fig. 2 C steel ground not Ground

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** Spring Expert
In-Process Quality-Control with Temperature Controlled
Spring-End-Grinding*

Uwe-Peter WEIGMANN** and Klaus WURSTER**

Most applications of compression springs require planar spring ends. Thus, plane grinding of the spring ends is performed. Exceeding critical spring temperature has to be avoided during process. Depending on wire material, size and spring geometry, high temperature during process changes microstructure of the springs. Then, brittleness of wire material increases and life time of the spring is reduced. Reaching critical spring temperature results in occurrence of annealing colours on the springs. State of the art is manual investigation of springs after grinding cycle. Spark out process removes annealing colours and springs with brittle microstructure may appear as good parts. To fulfill temperature requirements, a system has been developed that measures spring temperature during grinding process. It enables closed-loop control of downfeed for grinding at maximum output rate and best quality. Trend analysis of maximum temperature of different cycles allow conclusions regarding sharpness of wheels and necessity of dressing. The developed technology enables secure grinding at highest performance level. Number of rejects parts is reduced and such parts are detected before feeding to following process steps. It is no longer necessary to slow down the grinding feed to stay at a safety distance to critical spring temperature.

Key Words: Spring-end-grinding; Temperature controlled grinding; In-process-quality-control

端面研削中のコイルばねの温度制御による品質管理

殆どの圧縮コイルばねには平らな両端面が必要であり、端面研削が行われる。この時、ばねの温度が上がり過ぎないようにしなければならない。線の材質、線径、ばねの形状により、研削中のばねが高温になると、その金属組織に変化が生じて脆性が増し、ばねの寿命が短まる。この限界温度に達するとばねに焼きなまし色が発生する。その検出は研削工程後の目視検査により行われるのが最も手っ取り早い方法である。しかし、研削工程の最後に行われる仕上げ研削により、焼きなまし色は除去されてしまうので、脆性化したばねも不良品には見えない。そこで、研削時の温度を適正に保つために、研削中のばねの温度を計測するシステムが開発された。このシステムにより研削砥石の送りをフィードバック制御することにより高品質と最大生産効率を得ることが可能になった。また、種々の研削工程の最高温度傾向分析から砥石の切れ味とドレッシングの時期についての目安が得られた。この新開発の技術により、不良品を出さずに最も効率良く研削を行えるようになった。また、たとえ不良品が発生してもその数が減少し、ばね製造の次の工程に送る前にそれを検出できる。さらに、研削中のばねが限界温度に達しないような範囲に砥石の送り速度を減速する必要が無くなった。

Fig. 6 Infrared measurement system in air shower of spring-end grinding machine.

Fig. 8 Diagram of average temperature over cycle time in input desk of grinding machine.

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** WAFIOS AG
Developing a Complete Simulation Environment  
on the Example of Coil Springs*

Anders WINKLER**, Alan TAN*** and Kazuhiro MAEDA**

Modern simulation tools and technology allow engineers to conduct deep going investigations on the objects they are working on and to draw vital conclusions which greatly accelerate both progress and innovation, ultimately enhancing product experience. Current tools allow the analyst to conduct detailed assessments of individual parts in a simulated process chain. As such, a seemingly not apparent challenge lies in creating a framework where these assessments are linked in a logical fashion so that the focus is placed on the total engineering value output, rather than the connection between tools. Such a framework can be referred to as a simulation environment. A good simulation environment will provide the analyst with greater flexibility and more time to make the right engineering decisions. Coil springs are versatile machine elements that are well suited for virtual assessment; manufacturing, treatment, structural integrity and durability are parts of a simulation environment. These parts can be evaluated according to specifications and requirements, but also better understood and certainly optimized, with the right framework in place. In this work we have evaluated individual processes in a simulation process chain of coil springs with respect to real life applicability, and drawn up a map to chart the interactions between the processes. In addition we have tried to develop a generic way of creating simulation environments for coil springs, but one that is also applicable to other machine elements. This reference can hopefully be used to facilitate similar simulation tasks.

Key Words: Simulation Environment, Manufacturing, Structural Integrity, Durability, Virtual Assessment, Optimization, Engineering Value, Coil Springs

コイルばねを例とした統合シミュレーション環境の開発

最新のシミュレーションツールとテクノロジーは、エンジニアが取り組んでいる課題に対しより詳細な検討を行い、技術革新を進めるのに不可欠な結論を導き出すことを可能とし、結果として製品は十分吟味されたものとなる。既存のツールを用いて、アナリストは仮想工程内の個々のパーツに対し詳細な評価を行うことが可能である。それはそれとして、ツール間の連携により更に全工程を通じた総合的な検討結果を出力することに主眼を置き、ロジカルに組まれた評価であれば、フレームワークを構築することはさほど難しいことではない。そのようなフレームワークは、シミュレーション環境と称されることがある。優れたシミュレーション環境はその柔軟性により、ユーザーが正しいエンジニアリングの判断を行う為の多くの機会を提供してくれる。コイルばねは、仮想評価に非常に適した用途の広い機械要素であり、成形工程、処理工程、構造の完全性、耐用性評価がシミュレーション環境の個々のパーツである。これらのパーツは仮想及び要件項目に従い評価されるのみならず、正しいフレームワークを用いるならば個々のパーツについての適切な判断と最適化がなされる。本開発において著者らは、コイルばねの実寿命適用可能性に関するシミュレーション環境の実用化に向け、仮想工程全体における個々の工数を評価し、工程間の相互作用を示すマップを構築した。さらに、コイルばねのみならず他の機械要素にも適用が可能な、シミュレーション環境作成の一般的な方法の開発を試みた。本報は、このようなシミュレーション業務の促進に活用されよう。
Reverse Engineering Based Trunk Lid Torsion Bar Design Method*

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This study reports the development of a new automotive trunk lid torsion bar (TLTB) design method to determine a free shape that meets a target closed shape with a specified torque. A TLTB is utilized to help elevate and hold open the trunk lid. A TLTB supplier obtains bend points and torque at a closed trunk position as specification from a car maker. The free TLTB shape is conventionally determined by rotating the given bend points around a hinge axis to satisfy the specified torque. In most cases, a deformed TLTB shape in the closed position designed in the conventional method is different from the specified shape given by a car maker (target). Hence, this sometimes causes interference issues with surrounding components. Therefore an FEA based reverse engineering method is developed. The free TLTB shape is designed as follows: Using the results from the conventional method, the difference between FEA closed shape and target closed shape is determined. A new free shape is automatically created by adding/subtracting the difference to/from the initial free shape with some modification for torque. This process is repeated until the difference becomes less than an acceptable tolerance. Validity of the method is proven in this paper.

Key Words: Trunk lid torsion bar, Reverse engineering, FEA design, Validity of the Method

リバースエンジニアリングによる
トランクリッドトーションバーの設計法

本研究は、乗用車用トランクリッドトーションバー（TLTB）の自由形状を、トランククローズ時の仕様トルクと目標変形形状を満たすように決定するための新設計手法を提案するものである。トランクリッドトーションバーは、乗用車用トランクリッドの開閉をサポートするデバイスである。通常、仕様としてトランクがクローズ時のある点（目標変形形状）及びトルクが顧客から与えられ、その曲げ点を仕様トルクが満たされるように、ある軸周りに回転して無荷重時の形状（フリートーン）を設計する。しかし、従来法で変形後に与えられた目標形状に収まらず、周辺部品との干渉が起こる可能性が高い。この問題を解決するため、本論文では有限要素法（FEA）を使用したリバースエンジニアリングによる設計法を開発した。従来法で設計したフリー形状を初期形状として利用し、FEAで求めたそのクローズ形状と目標形状との差をベースに、トルクを修正しつつフリー形状を更新する。このループを、差分が公差内に入るまで繰り返す。本手法により設計の自動化が可能となり、本論文ではこの手法の有効性を確認した。

Fig. 2 Target closed shape and deformed shape by conventional methods.

Fig. 4 Difference vector concept.

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Optimum Design Approaches for Disk Springs

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Disk springs, also known as Belleville Springs, offer large energy storage capacity with minimal small deflection and are commonly used in applications where the operating space is limited, such as automobile transmissions. These springs can be designed to provide various load-deflection characteristics including linear, progressive or regressive. The addition of slits increases further design flexibility, although it can also make optimum design more difficult due to the greater degree of design freedom compared to conventional design. The authors have developed an optimum design approach for disk springs that combines Almen Laszlo model (basic formula of disk spring) with the genetic algorithm (GA). This approach can be used by less experienced designers to generate disk spring designs in a relatively short time frame. The authors have also studied the effect of slit configuration on load-deflection characteristics and stress concentration using Finite Element Method to estimate the validity range of the optimum design approach.

Key Words: Disk springs, Optimization, Genetic Algorithm, Finite Element Analysis

皿ばねの最適設計手法

皿ばね (ベルビルスプリング) は、最小限のたわみで効率的にエネルギーを蓄えられることから、作動空間が狭い自動車用トランスミッションなどに多く使用されている。その荷重-たわみ特性は直線、ブロギュレッシブ、及び逆ブロギュレッシブなど様々な設定する事が可能である。さらにスリットの追加により設計自由度は増すが、一方で最適解を一意に決定することを困難ならしめる。そこで本研究では、皿ばねの基本式であるアルメン・ラスロの式と、最適化手法の一つである遺伝子学的アルゴリズム (GA) を組み合わせ、皿ばねの最適設計を試みた。この方法により経験の浅い設計者でも比較的短時間で皿ばね設計を達成できる。著者たちは、スリットが荷重-たわみ特性及び応力集中に及ぼす影響を、有限要素法 (FEM) を用いて研究した。

Fig. 2  Deflection of disk spring with slits.  
Fig. 7  Evolution of fitness.

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The Optimal Design of a Side Load Helical Spring for MacPherson Vehicle Suspension System*

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In this paper the parametric modeling method for FE analysis and optimal design of a side load helical spring is presented. Using APDL of ANSYS software, the parametric modeling, FE analysis and optimization of the side load helical spring are realized. The visual interface which includes conveying the user inputs to ANSYS software and conducting post-process is programmed by Visual Basic. Beam element is used in FE analysis of the helical spring to improve simulation precision and save computation time. Both side and vertical stiffness of the spring were taken as objective function. The optimal parameters of the side load helical spring have been obtained.

**Key Words:** Side load helical spring, Finite element analysis, Optimal design, Secondary development, ANSYS parametric design language (APDL)

マクファーソンサスペンションのための
横力を有するコイルばねの最適設計

本紙では、FE解析と横力を受けるコイルばねの最適設計のためのパラメトリックモデリング手法を提示する。ANSYSソフトウェアのAPDLを用いて、前記コイルばねについてのパラメトリックモデリング、FE解析および最適化が実現される。ユーザーからの入力をANSYSソフトウェアへ伝達する視覚的インターフェースと、後処理の実行はVisual Basicによってプログラムされる。シミュレーション精度改善と計算時間の節約のために、コイルばねのFE解析に梁要素が用いられる。目的関数としては、横方向および縦方向の両方のばね剛性を選択した。横力を受けるコイルばねの最適パラメーターが得られた。

Fig. 2 Sample of figure.  
Fig. 6 Sample of figure.