Materials for Springs

Y. Yamada (chief Ed.)

Materials for Springs

Translated from the Japanese original edition published by JSSE

Organized by JSSE translation committee

With 336 Figures

Springer

JSSE Japan Society of Spring Engineers

Dr. Eng. Yoshiro Yamada
Dr., Professional eng. Japan in Metallurgy
Yamada Research & Consultant Office
Lecturer, Setsunan Univ.
Japan

Mr. Toshio Kuwabara
General Affairs Director
Japan Society
of Spring Engineers (JSSE)
MH-KIYA Building 3F
12, KANDA-MIKURACHO
CHIYODA-KU, TOKYO
101-0038 JAPAN

Library of Congress Control Number: 2007933493

ISBN 978-3-540-73811-4 Springer Berlin Heidelberg New York

Springer is a part of Springer Science+Business Media
springer.com

Typesetting: by the authors and Integra using a springer LaTeXmacro package
Cover design: deblik, Berlin

Printed on acid-free paper SPIN: 11731405 89/Integra 5 4 3 2 1 0

Foreword

The Japan society of Spring Engineers, formerly called the Japan Society of Spring Research, was established in 1947. Thereafter, the society has endeavored to edit and publish many books on spring technologies. Among these publications, there have been such books as "Bane" in Japanese or "Springs" in English published in 1959, revised in 1964 and 1982, and "Spring Design" published in 1963, revised in 1982. Since then, various advanced materials and improved process technology have been developed. Reflecting the rapid development of PC hardware and software, we published "FEM for springs", in 1997 for advanced spring design analyses. The book was later translated into English and published from the Springer publishing company in 2003.

As for spring materials, "Spring Materials and their characteristics (in Japanese)" was published in 2000.

The book "Materials for Springs" is the English version of this book with some additional information currently available in the latest Japanese material industry.

I am confident that this book will provide a lot of advanced technical information on spring materials to engineers, researchers and students in worldwide spring industry.

April 2007

Kosuke Nagaya
Chairman, The Japan Society of Spring Engineers
Professor, Dr., Gunma University, Japan

Preface to Japanese Edition

Since the publication of the last edition of the book entitled “Springs” (written in Japanese) in 1982, extensive progresses have been made in all areas of spring materials technology. Publishing a new book on spring materials and the related technologies and adding information obtained in the twenty years after the last edition seem to be appropriate.

This book is basically intended for engineers related to spring materials and technologies who graduated from metallurgical or mechanical engineering course in technical high school, or in other higher engineering schools, as well as those who are related to purchases or sales of spring materials.

In the first chapter, the fundamental selection processes of spring materials and concomitant working processes including the information sources on materials database are given, followed by the basic mechanisms and theories of spring failures such as fatigue fracture, creep/stress relaxation and stress corrosion cracking of metallic materials.

In the second chapter, ferrous and non-ferrous metallic materials are the main topics. In the third and fourth chapters, polymer materials, FRP (Fiber Reinforced Plastics), ceramics and C/C composite materials are the main subject respectively. In each chapter from the second to the fourth chapter, material grades belonging to each material category, their characteristics, production processes, and special cares to be taken of when actually using the materials for springs, are given. Spring design technologies are little included in this volume however, because they are separately dealt with in the fourth volume (in Japanese) in this publication series.

In the fifth chapter, lists of Japanese spring material manufacturers and their material grades being produced, relative prices of some spring materials compared to standard materials in Japan, comparisons of spring materials in the Japanese Industrial Standards with some other foreign standards, etc, are summarized. It is to be remarked that the information on the relative prices of some spring materials in this chapter is not always applicable in any cases, since the price depends on various factors such as quantity of one time purchase, delivery condition, etc.

I express my feeling of great thanks to Mr. Yoshihide Nagai, a former director of the Japan Society of Spring Research and Mr. Kazuya Nakagawa, Nikkan Kogyo Shimbun Company, for their help for editing this book.

January 2000

Yoshiro Yamada, Dr.
Leader of the publication Working Group

Preface to the English Version

In editing this English version, efforts were made to update the contents in the original Japanese edition such as Japanese Industrial Standard (JIS) specifications and some other information that was felt better to up-date. For full particulars of any national or international standard, the up-to-date edition should always be consulted.

Since new information on delayed fracture of spring steels has been obtained, topics on delayed fracture and notch susceptibility of high strength steels in corrosive environments have been newly added at the end of the Chapter 1.

It is hoped that readers of this English version will gain knowledge from this book in which the most advanced spring and spring material technologies are contained.

Special thanks are due to Mr. Kanji Inoue, Senior Manager of NHK Spring Co. Ltd. for proof reading most part of the English translation manuscript and to Ms. Shimiko Shimamura, President of Plain Corporation for her efforts for preparing galley proofs. Acknowledgement is also given to Mr. Toshio Kuwabara, Director of the JSSE, for correspondence with the Springer Verlag Company for publishing this English edition and proof reading of Chapter 3, to Mr. Hiroshi Koyama for his important efforts to promote the activity throughout this project, and to all the engineers and researchers who participated in the English translation of this original Japanese book.

April 2007

Yoshiro Yamada, Dr., Professional eng. Japan in Metallurgy
Leader of the English Translation Committee in JSSE

Author Index

Japanese Edition Authors (Organization belonged when published.)

Tadasu Abumiya (Kobe Steel Ltd., Chap. 2.5)
Hiroaki Hayashi (Suzuki Metal Industry Co. Ltd., Chap. 2.1.3 (2), (4), and 2.3)
Hiroshi Horikawa (Furukawa Techno Materials Co. Ltd., Chap. 2.6)
Tomohito Iikubo (Daido Steel Co. Ltd., Chap. 2.2)
Hideaki Iwata (Tokai Rubber Industries Ltd., Chap. 3.2)
Kenji Kanazawa (Chuo University, Chap. 1.2.3)
Yutaka Maeda (MRC Techno Research Inc., Chap. 3.3)
Teruyuki Murai & Akio Ikenaga (Sumitomo Electric Industries, Ltd., Chap. 2.1.3 (1))
Takao Nakagawa (Across Corporation, Chap. 4.2)
Toshimasa Ochiai (NGK Industries, Chap 2.4.1, 2.4.2, 2.4.4, and 2.4.5)
Ken Okabe (Harada Metal Industries, Chap. 2.4.3)
Yasuhiro Oki & Nobuhiko Ibaraki (Kobe Steel Ltd., Chap. 2.1.1 (3) and (10) i)
Masao Sakamoto (National Research Institute for Materials Sciences, Chap. 1.2.2 (3) and (4))
Shigemi Satoh (NHK Spring Co. Ltd., Chap. 4.1)
Yatsuka Takata (Aichi Steel Corporation, Chap. 2.1.1 and 2.1.2)
Yoshinori Tanimoto (Nippon Seisen Co. Ltd., Chap. 2.1.3 (3))
Akio Tsuzuki (Togo Seisakusho Corporation, Chap. 5)
Katsuyuki Uchibori (Mitsubishi Steel Mfg. Co. Ltd., Chap 2.1.2 (11))
Isao Ueda (Horikiri Industries, Chap. 2.1.2 (10) ii)
Kyosuke Uemura (DuPont Kabushiki Kaisha, Chap. 3.1)
Yoshiro Yamada (Suncall Corporation, Chap 1.1, 1.2.1, 1.2.2 (1), (2), 2.1.3 (1) viii)

English Translation Committee:

Yoshiro Yamada, Committee Chief, Setsunan University
Hiroshi Koyama, Committee sub-Chief, Japan Society of Spring Engineers
Kanji Inoue, Translation Supervisor, NHK Spring Co. Ltd.
Toshio Kuwabara, Coordinator, Japan Society of Spring Engineers

Abraham Mehari, Aichi Steel Corporation
Nobuhiko Ibaraki, Kobe Steel Ltd.
Teruyuki Murai, Sumitomo Electric Industries Ltd.
Kenichi Shimizu, Sumitomo (SEI) Steel Wire Corp.
Fumiaki Nozoe, Sumitomo (SEI) Steel Wire Corp.
Akihiko Nishikawa, NHK Spring Co. Ltd.
Tomohito Iikubo, Daido Steel Co. Ltd.
Suguru Nomura, NHK Spring Co. Ltd.

Contents

1

A Guide to Spring Material Selection

1.1 Introduction

Spring material and its quality can be normally taken into consideration or highlighted in such cases as; (i) a spring installed in mechanical products, failed either by fracture or by significant deformation in use, (ii) a mechanical product newly designed or improved, where a new design of a spring is required, in this case, the spring with higher quality can be required, and (iii) a cost reduction requested for the spring having been used without any difference of the quality.

The case (i) can be divided into the following two cases:

(A) Quality requirements set up in the initial quality design stage, were not achieved in the actual products.

(B) Although the quality requirements set up at the design stage were satisfied in use, the springs were used in severer conditions than initially expected or some important quality requirement failed to be included in the initial quality requirements in the design stage.

When a spring has failed due to (A) or (B), an investigation for finding the failure cause is carried out, and the quality of the material used and the manufacturing process history are required to be studied. In the case of (ii) or (iii) described above, making the grade of material, dimensions for similar applications and the spring working processes clear, the search of substitute material grades can be started. Considering the availability, quality level, price, and the matching with working processes (conventional or new process), the most suitable material can be chosen.

As described above, the most suitable selection of spring material and its working processes can be said to play a very important role in quality and cost.

1.2 Functions and Qualities Required for Springs and the Spring Material Selection

1.2.1 Basic Items to be considered in Spring Material Selection

In the spring material selection and the working process designing, the following points shall be taken into consideration.

(1) Selected material and manufacturing process are such that the quality of finished springs satisfies customer's quality requirements.
(2) Availability of selected material.
(3) Economical feasibility of material and spring working processes (cost).
(4) The manufacturing processes, where the material quality should not be deteriorated.
(5) recycling.
(6) No pollution, safety, and regulations observance through spring manufacturing to disposal or recycling.

Springs play at least one of the following five basic roles or functions [1]:

(1) When unloaded, springs return to the original position or to the original shape.
(2) Absorption or utilization of vibration.
(3) Relaxation or absorption of impact force.
(4) Storage and/or release of energy.
(5) Measurement of force.

An unloaded spring often does not recover to its original shape, and this kind of shape change is called a permanent set of a spring. If a permanent set takes place in a spring, it may exert some deleterious effect on the measurement of force (5), or possibly on the functions (2) to (4) described above. In whatever basic spring functions are required for springs, springs loaded under repeated or varying stresses can sometimes fracture due to fatigue. In general, permanent set and fatigue fracture can be said to be the most important quality factors of springs to be paid attention to. In addition to these, failure of springs due to wear and/or corrosion is to be taken into consideration according to the application or the environments in use. Table 1.1 shows typical failures of springs, which occur in use.

Depending upon the load pattern of springs in use, quality requirements for the spring material vary. In Table 1.2 [2], relations between types of spring load pattern and the essential quality required for spring material are summarized. The quality requirements for spring materials change with such conditions as temperature or environments where the springs are used.

In Table 1.3, quality and performance characteristics of springs are listed.

As workability of spring materials, forming ability during spring forming, heat treatment performance (for example, hardenability of spring steel) to

Table 1.1. Principal types of spring failures

Fracture	Fracture with repeated stresses • Fatigue with no corrosion • Corrosion fatigue • Fatigue from fretting corrosion or wear Fracture with impact stress • Brittle fracture (Low temperature brittle fracture) • Ductile fracture Fracture with static stress • Stress corrosion cracking • Delayed fracture (Hydrogen embrittlement fracture)
Deformation (Permanent set)	• Yielding, plastic deformation (due to over stressing) • Static creep • Dynamic creep • Stress relaxation
Decrease of cross-sectional dimensions	• Wear • Fretting • General corrosion • Local corrosion • Errosion

Table 1.2. Types of load [2]

Types of load		Figures to be acquainted	Properties required for material
Static load	A constant and invariable load (permitted insignificant variation of load)	Load and deflection	High elastic limit
Repeated load	Constant loads repeatedly applied	Mean load Load amplitude Deflection Number of cycles	High fatigue strength
Impact load	A load applied abruptly at high speed	Impact force Deflection Number of cycles	High elastic limit High impact value
Load for measuring load	Accurate load being ensured for a wide range of deflection, like a spring balance	Spring constant Maximum load	High elastic limit High dimensional accuracy

obtain targeted quality, and the workability during material production processes, can be taken into consideration, since these workability characteristics are also very important in spring material selection.

Table 1.3. Quality and characteristic properties of spring materials

Physical properties
Crystal structure
Transformation temperature
Melting temperature
Density
Electrical conductivity
Electrical conductivity at 20°C (% IACS)
Electrical resistivity
Dielectric coefficient
Magnetic permeability
Magnetic saturation flux density
Coercive force
Magnetic hysteresis
Magnetic striction
Specific heat
Thermal conductivity
Linear thermal expansion coefficient

Microstructure
Metallurgical structure
Crystal grain diameter
Second phase particles
Chemical composition
Non-metallic inclusion
Surface decarburization
Internal oxidation

Mechanical properties
Elastic modulus (Young's modulus E)
Shear modulus G
Poisson's ratio
Elastic limit (tension, compression, torsion, bend)
Yield strength (ibid)
Proof stress (ibid)
Spring deflection limit
Residual stress
Tensile strength
Torsion strength
Hardness
Viscosity Viscoelasticity
Fatigue characteristics
*Fatigue strength
*Fatigue limit
*Fatigue strength at a particular life
*Fatigue life
*S-N curve (diagram)
*Fatigue limit diagram
*Crack growth rate
*Lower limit threshold stress intensity factor range
Fracture energy (Toughness)
*Charpy impact value
*Fracture bending stress
*Fracture toughness

Environmental resistance
Corrosion
Oxidization
Delayed fracture
Hydrogen embrittlement
Stress corrosion cracking
Stress cracking resistance
Atmospheric corrosion
Corrosion fatigue
Wear
Fretting corrosion
Erosion

Workability at spring manufacturing processes
Material and spring workability
*Drawability
*Rolling ability
*Machinability
*Grindability
*Bendability
*Torsion characteristics (wire)
*Surface lubrication
*Drawability (sheet)
*Punching ability
*Heat treatment ability
*Hardenability
*Isothermal transformation characteristics
*Continuous cooling transformation characteristics
*Temper softening characteristics
*Decarburization characteristics
*Temperature-time-austenitization characteristics
*Low temperature annealing characteristics
*Age hardenability (precipitation characteristics)

Shape characteristics
*Cross section
*dimensions and its accuracy
*Flatness
*Camber
*Wire cast
*Twist
*Bend
*Notch shape
*Surface flaw

Recycling ability

Safety

1.2.2 Spring Material Selection Method

Procedures of Spring Material Selection

In Sect. 1.2.1, basic factors to be considered in selecting spring material were described. In this section, more precise material selection procedures and special remarks can be discussed.

(1) The condition where the spring is used, such as volume, dimension, temperature and environmental atmosphere should be made clear.
(2) The quality requirements (load, deflection, fatigue life, etc.) should be made clear.
(3) The material grade, section size, elastic modulus, design stress, spring shape and its dimensions should be determined. Since in conventional usages, kinds of material used are normally known, see Table 1.4, it can be possible to make the material selection based on these kinds of information. It seems to be desired that the conditions where various kinds of springs are used, and the corresponding materials characteristics such as material grade, hardness, production process and dimensions, are collected and compiled as case-bases [4], and they can be utilized when necessary and can be updated.
(4) The testing methods and evaluation standards shall be determined in preparing material specifications.
(5) According to Japanese Industrial Standards (JIS) B 2704-2000 Helical compression and extension springs – Requirements for design, B 2709-2000 Helical torsion springs – Requirements for design, allowable stresses can be recommended for these kinds of springs used under static load with different wire diameters. In these specifications, fatigue life estimation methods based on the fatigue strength diagram between the maximum stress and minimum stress, are also described for reference. However, when higher quality springs than JIS specifications are required, spring materials other than JIS specification and spring manufacturing technologies such as shot-peening, should be studied.
(6) According to the JIS B 2704-2000 and B2709-2000 specifications, it can be recommendable to use figures listed in Table 1.5 as for elastic modulus or Young's modulus, E, and modulus of rigidity, G, for springs produced with various material grades and used at room temperature. It is noted, however, that cold rolled sheet material directionally varies elastic modulus. The extent of anisotropy caused by cold work changes with the degree of cold work and material chemical compositions.
(7) Material selection has to be made according to the temperature in use. Piano wire and hard drawn wire are the most popular material grades and their procurement is comparatively easy. Steel rope made of hard drawn wire can be used under dynamic stress even at 233 K (minus 40°C) without any problems. This means that piano wire springs and hard drawn wire springs can be used at such low temperatures.

Table 1.4. Types of springs, their applications and examples of material used

Type	Applications	Material grade (JIS)
Multi leaf spring	Suspension for automobile and railway train	SUP 3, SUP 6, SUP 9A, SUP 11A
Helical spring	Suspension for automobile and railway train	SUP 6, SUP 7, SUP 9, SUP 12
	Suspension for railway train and large spring for machine for general use	SUP 9A, SUP 10, SUP 11A, SUP 13
	Small spring for machine in general use	SW, SWP
	Machines in general use and automotive suspension	SWO, SWOSM, AWOSC-B
	Engine valve spring	SWO-V, SWOCV-V, SWOSC-V, SWP-V
	Mechanical spring with corrosion resistance	SUS-WP
Torsion bar	Torsion bar for automobile	SUP 9, S45C
	Stabilizer bar for automobile	SUP 9, S48C, SUP 11, STKM 15A equivalent
	Automobiles, Railway trains, OA appliances, Torsion bars with arm	SWP-A, SWP-B, SWO-V, SWOSC-V, SUS304WPB
Sheet spring (including Belleville, washers)	Industrial machine, Automobile, Electrical appliance	SK 4, SK 5, S45C-S70C, SUP 10
	Computer related equipment requiring corrosion resistance	SUS301CSP, SUS304CSP
	Engine part requiring heat resistance	SUS631CSP
	Electrical contact for switches etc.	C5210, C1700
Spiral spring	Industrial and construction machine, Electrical appliances etc.	SK4, SK5
	Automobile, Industrial machine, Electrical appliance etc.	SWRH62-82, SUP12 (Flat wire), SK4, SK5, SUS301CSP, SUS631CSP
Spring washer	Prevention of bolts and nuts unfastening	SWRH, SW, SWP, SXXCM, SKXM, C5191P-H, C5212P-H
Mesh spring	Exhaust gas catalyzer, Airbag	SUS304, SUS316, SUS310S, Inconel 601
Retaining ring	Eccentric C-clip, Concentric C-clip, Circlip etc.	SWRH, SWX, SWPX, SXXCM, SKXM

Table 1.5. Young's moduli and moduli of rigidity for spring material

Material	Modulus of rigidity, G GPa	Young's modulus E, GPa
Spring steel	78.5	206
Hard drawn wire Piano wire Oil tempered wire	78.5	206
Stainless steel wires for springs SUS302, SUS304, SUS304N1, SUS316	68.5	186
Stainless steel wire SUS631J1	73.5	196
Brass wire	39.0	98
Nickel-silver wire	39.0	108
Phosphorus bronze wire	42.0	98
Copper beryllium wire	44.0	127

For springs used from room temperature to 423 K (150°C), piano wire and hard drawn wire can be normally used under the dynamic stress conditions and the statically stressed conditions respectively. If fatigue fractures and/or creep problem(s) cannot be overcome by piano wire or hard drawn wire, oil tempered wire can be considered.

Stainless steel is sometimes used at more elevated temperature than oil tempered wire, because creep resistance of the stainless steel is generally superior to that of the oil tempered wire. For spring used at higher temperature than stainless steel springs, iron-base superalloy A286 (JIS SUH660), Nickel-base superalloy or ceramics (silicon nitride) are mainly used. Figure 1.1 is a result of a survey inquiring the relation between spring material grades and their temperatures being used [5]. Open circle marks, ◯, in the Fig 1.1 indicate temperatures of springs in use. Figure 1.2 is a copy from a book entitled 'Spring Materials Selector' [6], indicating maximum temperature of use for various materials. These two figures can be usable as a reference when choosing the candidate material, although the selection of final material is difficult since the material's maximum temperature of use varies depending on stress condition of the spring.

(8) Since there are such cases as the endurance of a spring is deteriorated because of hazardous environment the spring is exposed to, the material selection to meet with the environment in use or a measure insulating the spring from the environment can be required. Table 1.6 shows the suitability of material to various media or environments [6]. This refers

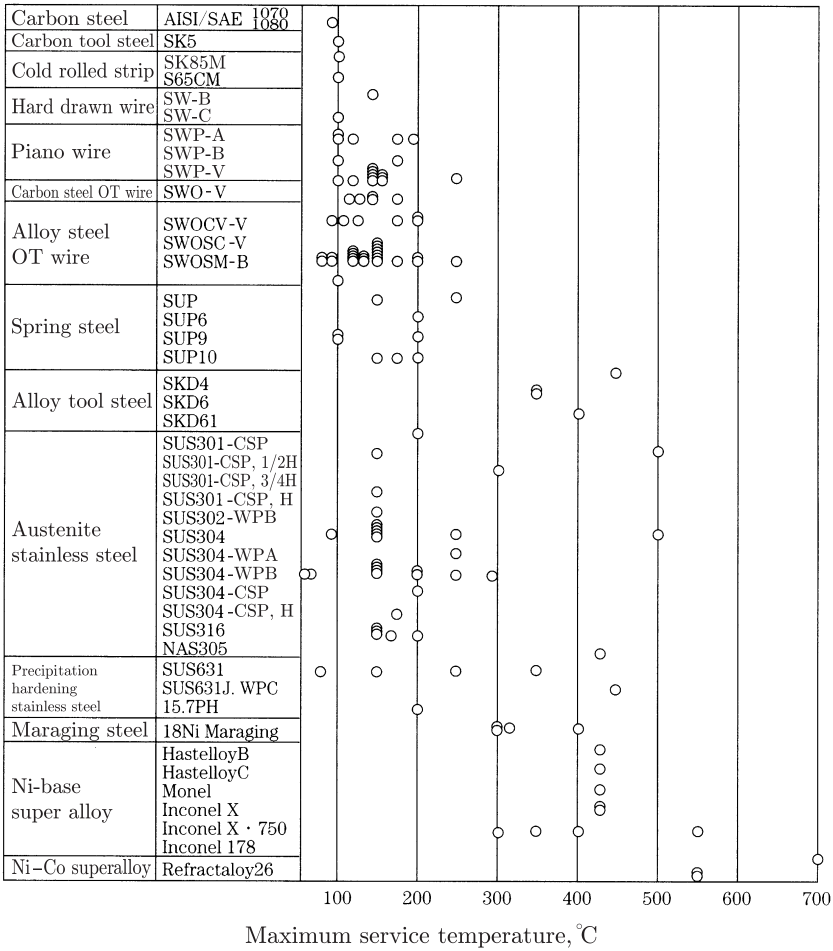

Fig. 1.1. Maximum service temperature of alloys [5]

to the original book "Spring Materials Selector, 2nd Edition" published by SRAMA (now, Institute of Spring Technology). This table should be regarded as a quick initial consideration, since small changes in temperature, concentration or impurities in the corrosive media can change behaviors remarkably.

(9) It can be normally said that the fatigue strength of metallic springs show the relationship proportionate to its hardness or tensile strength at least up to a certain level. As for steel springs, springs with too high hardness can often cause fatigue fracture in use, due to the notch sensitivity to small defect. Likewise, cracking troubles in spring cold-forming processes tend to occur more often as the spring material strength is in-

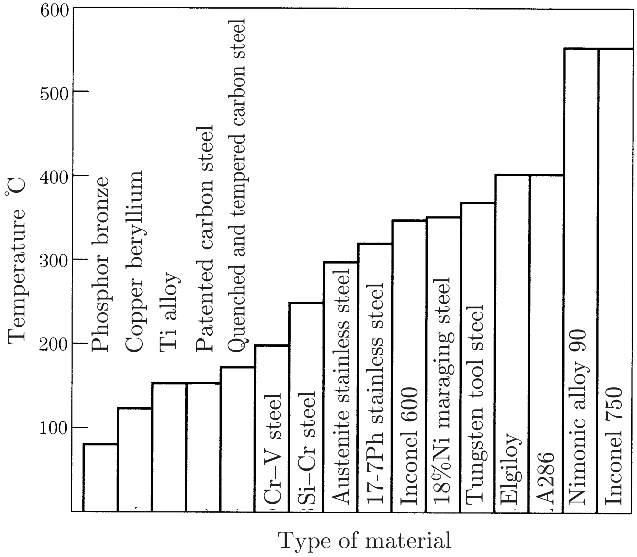

Fig. 1.2. Maximum temperature of use for various materials [6]

creased. Too high hardness also often can cause the fracture by hydrogen embrittlement or stress corrosion cracking, especially in steel springs. For example, in case of the steel spring manufactured by quenching and tempering, it should be cautious that temper at too low temperature may make the spring very susceptible to cause the delayed fracture under static load or the brittle fracture by impact.

Generally, piano wire and hard drawn wire have less susceptibility to hydrogen embrittlement than oil tempered wire and quenched-and-tempered steel. However, piano wire and hard drawn wire with excessively higher strength than specified can be susceptible to delamination (cracking along wire axis). Therefore, such high strength wire should not be used. Since austenitic stainless steel is susceptible to stress corrosion cracking in chloride containing environment, it is recommendable for austenitic stainless steel springs not to be used in such an environment. As for polymers, amorphous polymers such as polycarbonate, polystyrene, ABS, acrylic resins etc., tend to suffer from environmental stress cracking due to the exposure to ester compounds. In addition, the embrittlement due to ultra-violet light is to be prevented in polymer springs, as another example.

(10) Springs with comparatively large cross-section are normally made of spring steels through the process of hot-forming (or hot-working), followed by quenching and tempering. The spring steel grade actually used should be the one that has enough hardenability. This means that the material shall be hardened to the center of the cross-section and its

Table 1.6. Selection of spring material under chemical products [6]

✓ = almost applicable
– = need to study
× = not applicable

chemicals	Density %	Temperature °C	Monel 400	Inconel 600	Inconel 625	Incoloy 825	Stainless 302	Stainless 316	Brass	Titan alloy
Acetaldehyde	99	40	✓	✓	✓	✓	✓	✓	–	×
Acetic Acid	0–99	30	–	–	✓	✓	✓	✓	×	✓
Acetic Anhydride	100	30	–	–	✓	✓	✓	✓	×	✓
Aceton	0–100	100	✓	✓	✓	✓	✓	✓	✓	✓
Acetylene	100	150	–	–	✓	✓	✓	✓	–	–
Acrolein	100	100	–	–	–	–	–	–	–	–
Air	100	–	✓	✓	✓	✓	✓	✓	✓	✓
Alcohol-Allyl	100	30	✓	✓	✓	✓	✓	✓	✓	✓
Ethyl	100	30	✓	✓	✓	✓	✓	✓	✓	✓
Mehyl	100	30	✓	✓	✓	✓	✓	✓	✓	✓
Allyl Chloride	100	30	✓	–	✓	✓	–	–	–	–
Aluminium Chloride	0–30	30	–	–	✓	–	–	–	×	✓
Aluminium Sulphate (Alum.)	100	30	–	×	✓	✓	×	✓	×	✓
Ammonia Liquid	0–100	30	×	–	✓	✓	–	–	×	–
Ammonium Bicarbonate	0–100	100	–	–	–	–	–	–	–	✓
Ammonium Carbonate	0–20	30	–	–	–	–	–	–	–	✓
Ammonium Chloride (dry)	0–20	20	–	–	✓	✓	–	✓	×	✓
	100	100	–	–	✓	–	–	✓	×	✓
Ammonium Hydroxide	0–30	70	×	–	✓	✓	✓	✓	×	✓
Ammonium Nitrate	0–40	80	–	–	✓	✓	✓	✓	×	✓
Ammonium Phosphate	5	100	–	–	✓	✓	✓	✓	×	✓
Ammonium Sulphate	0–40	100	–	–	✓	✓	✓	✓	×	✓
Amyl Acetate	100	30	✓	✓	✓	✓	–	–	–	–
Amyl Chloride	100	30	–	–	✓	–	–	–	–	–
Aniline	100	30	×	–	✓	✓	–	–	–	–
Barium Chloride	0–40	100	–	–	✓	–	–	–	–	✓
Barium Hydroxide	100	1040	–	–	✓	✓	–	–	–	✓
	0–50	100	–	–	✓	✓	–	–	–	✓
Beer	–	30	✓	✓	✓	✓	✓	✓	✓	–
Beet Suger Liquors	0–40	30	✓	✓	✓	✓	✓	✓	✓	–
Benzaldehyde	100	30	–	–	✓	✓	–	–	–	–
Benzene	100	30	✓	✓	✓	✓	✓	✓	✓	✓
Black Sulphate Liquor	100	100	–	✓	✓	✓	–	–	–	–
Boric Acid	0–20	100	–	✓	✓	✓	×	✓	×	✓
Bromine Dry	100	50	✓	✓	–	✓	–	–	–	×
Butadiene	100	30	✓	✓	✓	✓	✓	✓	✓	–
Butane	100	30	✓	✓	✓	✓	✓	✓	✓	–
Butyl Acetate	100	30	–	–	✓	✓	✓	✓	–	–
Butyric Acid	0–100	100	–	×	✓	✓	×	✓	–	✓
Calcium Chloride	0–25	30	✓	✓	✓	✓	✓	✓	–	✓
Calcium Hydroxide	0–30	100	–	–	✓	–	–	–	–	✓
Cane Suger Liquors	100	90	✓	✓	✓	✓	✓	✓	✓	–
Carbon Dioxide	100	450	✓	✓	✓	✓	✓	✓	✓	✓
Carbon Tetrachloride	100	30	–	✓	✓	✓	✓	✓	✓	✓
Caustic Soda	see Sodium hydroxide									
Chlorine, Dry	100	550	–	✓	–	×	✓	✓	✓	wet
Chlorobenzene	100	30	–	–	–	–	–	–	–	–
Chlorosulphonic Acid	100	30	–	–	–	–	–	–	×	–
Chloroform	100	100	✓	✓	✓	✓	–	–	–	✓
Chromic Acid	0–100	30	×	×	–	–	–	✓	×	✓
Citric Acid	100	30	–	–	✓	✓	–	✓	×	✓
Coffee	–	100	✓	✓	✓	✓	✓	✓	–	–
Copper Sulphate	0–30	100	×	×	✓	✓	✓	✓	×	✓
Cresylic Acid	100	30	–	–	–	–	–	✓	–	–

Table 1.6. Selection of spring material under chemical products [6]

✓ = almost applicable
– = need to study
× = not applicable

chemicals	Density %	Temperature °C	Monel 400	Inconel 600	Inconel 625	Incoloy 825	Stainless 302	Stainless 316	Brass	Titan alloy
Dichloroethane	100	30	✓	✓	✓	✓	–	–	–	✓
Ethyl Acetate	100	30	–	–	✓	✓	✓	✓	–	–
Ethyl Cellulose		30	–	–	✓	✓	–	–	–	–
Ethyl Chloride	100	30	✓	✓	✓	✓	–	–	–	–
Ethylene Dichloride	100	30	✓	✓	✓	✓	–	–	–	–
Ethylene Glycol	100	30	–	–	✓	✓	✓	✓	✓	–
Fatty Acids	100	30	✓	✓	✓	✓	–	✓	–	–
Ferric Chloride	100	30	×	×	–	–	×	×	×	✓
Ferric Nitrate	100	30	×	×	✓	✓	–	–	–	–
Ferric Sulphate	0–30	30	–	×	✓	✓	✓	✓	×	✓
Fluoboric Acid	25	30	–	–	–	–	×	–	–	×
Fluosilicic Acid	20	30	×	–	–	–	–	–	–	×
Formaldehyde	0–100	30	✓	✓	✓	✓	✓	✓	✓	✓
Formic Acid	0–100	100	–	–	✓	✓	×	–	×	✓
Fuel Oil	100	30	✓	×	✓	✓	✓	✓	✓	✓
Furfural	30–100	100	–	–	✓	✓	–	–	–	–
Gelatine	0–40	50	–	✓	✓	✓	✓	✓	×	–
Glucose		30	✓	✓	✓	✓	✓	✓	–	–
Glutamic Acid		30	–	–	✓	✓	–	✓	–	–
Glycerine	100	30	✓	✓	✓	✓	✓	✓	×	✓
Glycerol	0–100	150	✓	✓	✓	✓	✓	✓	×	×
Hydraulic Oil	–	–	✓	✓	–	✓	✓	✓	✓	✓
Hydrazine	100	35	×	×	✓	×	✓	(1)	–	–
Hydrobromic Acid	40	30	×	×	×	–	–	–	–	✓
Hydrochloric Acid							×	×	×	×
Hydrocyanic Acid	100	35	×	✓	✓	✓	✓	✓	×	–
Hydrofluoric Acid	10–100	35	✓	–	–	–	×	×	×	×
Hydrogen Peroxide (acid free)		30	–	–	–	✓	✓	✓	×	–
Hydrogen Sulphide	0–20	150	–	–	✓	✓	✓	✓	×	✓
Hydroquinone		35	–	✓	✓	✓	✓	✓	–	–
Insulin	100	35	✓	✓	✓	✓	–	–	–	–
Lactic Acid	80	30	×	–	✓	✓	–	✓	–	✓
Lead Acetate	20	30	–	✓	✓	✓	–	–	–	✓
Lemon Juice		30	–	✓	✓	✓	✓	✓	–	–
Linseed Oil	100	30	✓	✓	✓	✓	–	–	–	✓
Lithium Chloride		30	✓	✓	✓	✓	✓	✓	–	✓
Lithium Hydroxide	10	30	✓	✓	✓	✓	–	–	–	–
Magnesium Carbonate		30	✓	✓	✓	✓	–	–	–	–
Magnesium Chloride	0–50	30	✓	✓	✓	✓	–	✓	×	✓
Magnesium Hydroxide		30	✓	✓	✓	✓	✓	✓	–	✓
Magnesium Nitrate		30	×	–	✓	✓	–	–	–	–
Magnesium Sulphate	30	30	✓	✓	✓	✓	✓	✓	–	✓
Maleic Acid		30	–	–	✓	✓	×	✓	–	✓
Mercuric Chloride		30	×	×	✓	×	×	×	×	✓
Mercuric Cyanide		30	×	×	–	–	–	–	–	✓
Mercuric Iodide		30	×	×	✓	×	–	–	–	–
Mercurous Nitrate		30	×	–	✓	✓	–	–	–	–
Methyl Alcohol	0–100	100	✓	✓	✓	✓	✓	✓	✓	✓
Methyl Chloride	100	30	✓	✓	✓	✓	✓	✓	–	–
Methyle Ethyl Ketone		100	–	–	✓	✓	✓	✓	–	–
Milk		30	–	✓	✓	✓	✓	✓	×	–
Mine Water		65	×	✓	✓	✓	✓	✓	✓	–
Molasses		30	✓	✓	✓	✓	✓	✓	✓	–
Mono (sodium, potassium or ammonium) Phosphate		30	✓	✓	✓	✓	–	–	–	–

Table 1.6. Selection of spring material under chemical products [6]

✓ = almost applicable
– = need to study
× = not applicable

chemicals	Density %	Temperature °C	Monel 400	Inconel 600	Inconel 625	Incoloy 825	Stainless 302	Stainless 316	Brass	Titan alloy
Napthenic Acid	100	30	✓	✓	✓	✓	–	✓	–	–
Nickel Chloride		30	–	–	✓	✓	×	×	×	×
Nitric Acid	0–65	30	×	–	✓	✓	×	–	×	✓
	100	80	×	×	✓	✓	×	×	×	–
Nitrobenzene	100	100	–	–	–	–	–	–	–	–
Oils, Crude	100	30	✓	✓	✓	✓	✓	✓	–	✓
Oils, Essential	100	30	✓	✓	✓	✓	–	–	–	–
Oils, Mineral	100	30	✓	✓	✓	✓	✓	✓	✓	–
Oils, Palm	100	30	✓	✓	✓	✓	✓	✓	–	–
Oils, Peanut	100	30	✓	✓	✓	✓	✓	✓	–	–
Oils, Sulphanated	100	30	✓	✓	✓	✓	–	✓	–	–
Oils, Vegetable	100	30	✓	✓	✓	✓	✓	✓	✓	–
Oleic Acid	100	30	–	✓	✓	✓	✓	✓	×	–
Oleum	20	30	×	✓	✓	✓	–	–	–	–
Orange Juice		30	✓	✓	✓	✓	–	–	–	–
Oxalic Acid		30	–	–	✓	–	–	✓	×	×
Palmitic Acid	100	30	✓	✓	–	✓	–	✓	×	–
Paraffin	100	35	✓	✓	✓	✓	✓	✓	✓	–
Petrole	100	30	✓	✓	✓	✓	✓	✓	✓	–
Phenol	100	30	–	✓	✓	✓	✓	✓	–	✓
Phenol Sulphonic Acid	100	30	–	–	✓	✓	–	–	–	–
Phosphoric Acid	0–25	30	✓	✓	✓	✓	–	✓	×	✓
	25–85	85	✓	×	✓	✓	×	×	×	✓
Phthalic Anhydride	100	30	✓	✓	✓	✓	✓	✓	–	–
Picric Acid	100	30	×	×	–	–	✓	✓	×	–
Potassium Bicarbonate	0–30	30	✓	✓	✓	✓	✓	✓	✓	–
Potassium Carbonate		30	✓	✓	✓	✓	✓	✓	–	–
Potassium Chlorate		30	–	–	✓	✓	–	✓	–	–
Potassium Chloride		30	✓	✓	✓	✓	–	✓	×	✓
Potassium Chromate	0–30	30	–	✓	✓	✓	×	✓	–	–
Potassium Cyanide	0–30	100	–	–	–	–	–	–	–	–
Potassium Dichromate	0–20	30	–	–	✓	✓	✓	✓	–	✓
Potassium Fericyanide	0–30	30	–	–	–	–	–	–	–	✓
Potassium Hydroxide	0–50	30	✓	–	–	–	✓	✓	×	×
	0–50	100	✓	–	–	–	✓	✓	×	×
Potassium Nitrate		30	–	–	✓	✓	–	–	–	–
Potassium Sulphate	10	30	–	✓	✓	✓	✓	✓	✓	✓
Propane	100	100	✓	✓	✓	✓	✓	✓	✓	–
Salicyclic Acid		30	✓	✓	✓	✓	–	–	–	–
Sea Water	100	100	✓	✓	✓	✓	×	–	✓	✓
Silicon Tetrachloride	100	30	✓	✓	✓	✓	×	×	–	–
Silver Nitrate		30	×	–	–	–	–	–	–	✓
Soap	100	30	✓	✓	✓	✓	✓	✓	✓	✓
Sodium Acetate		30	–	–	✓	✓	✓	✓	–	✓
Sodium Bicarbonate		30	–	–	✓	✓	✓	✓	✓	–
Sodium Bisulphate	10	30	✓	–	✓	–	×	✓	×	✓
Sodium Bromide	0–50	30	–	–	–	–	–	–	–	✓
Sodium Carbonate	30	30	–	–	✓	✓	×	✓	–	✓
Sodium Chloride		30	✓	–	✓	✓	–	✓	×	✓
Sodium Hydroxide	0–50	30	✓	✓	✓	✓	✓	✓	×	✓
	50–75	30	✓	✓	✓	✓	×	×	×	✓

Table 1.6. Selection of spring material under chemical products [6]

✓= almost applicable
– = need to study
× = not applicable

chemicals	Density %	Temperature °C	Monel 400	Inconel 600	Inconel 625	Incoloy 825	Stainless 302	Stainless 316	Brass	Titan alloy
Sodium Metaphosphate		30	–	✓	✓	✓	✓	✓	×	–
Sodium Matascilicate	0–50	30	✓	✓	✓	✓	–	–	–	–
Sodium Nitrate	10	30	–	✓	✓	✓	✓	✓	×	✓
		30	–	✓	✓	✓	–	–	×	✓
Sodium Peroxide	100	100	–	–	–	–	✓	✓	×	–
Sodium Phosphate		30	✓	✓	✓	✓	✓	✓	×	✓
Sodium Sulphate		30	✓	✓	✓	✓	✓	✓	✓	✓
Sodium Sulphide		30	–	✓	✓	✓	30%	30%	×	✓
Steam	100	450	✓	✓	✓	✓	✓	✓	✓	✓
Stearic Acid		30	✓	✓	✓	✓	×	✓	×	✓
Sugar (Liquid)		30	✓	✓	✓	✓	✓	✓	–	–
Sulphuric Acid	0–15	30	✓	–	✓	✓	×	×	×	×
	15–75	30	–	×	✓	✓	×	×	×	×
Sulphurous Acid	0–60	100	–	–	–	–	×	–	×	< 6%
Tall Oil	100	30	✓	✓	✓	✓	×	–	–	–
Tannic Acid	10	30	–	–	–	–	–	–	–	✓
Tartaric Acid	58	30	–	–	✓	✓	–	✓	×	✓
Tetraphosphoric Acid	100	30	×	–	✓	✓	–	–	–	–
Toluene	100	100	✓	✓	✓	✓	✓	✓	✓	–
Tricholorethylene	100	100	✓	–	–	–	✓	✓	✓	–
Turpentine	100	30	✓	✓	✓	✓	✓	✓	×	–
Urea	50–100	375	–	–	✓	✓	–	–	–	–
Vineger	100	30	✓	✓	✓	✓	×	✓	×	–
Vinyl Chloride	100	30	✓	✓	✓	✓	✓	✓	–	–
Water	100	100	✓	✓	✓	✓	✓	✓	✓	–
Xylene	100	100	–	✓	✓	✓	✓	✓	✓	–
Zinc Annonium Chloride	0–40	100	–	–	✓	–	×	×	×	–
Zinc Chloride	0–100	30	–	–	✓	–	×	×	×	✓
Zinc Nitrate	10	30	×	–	✓	✓	–	–	–	–
Zinc Sulphate	20	30	–	–	✓	✓	–	✓	×	✓

Table 1.6. Selection of spring material under chemical products [6]

chemical compositions (%)

	Fe	C	Si	Mn	Al	Cu	Ni	Co	Cr	Mo	Ti	Others
Monel 400	≦ 2.5	≦ 0.3	≦ 0.5	≦ 2.0		28.0/ 34.0	≦ 63.0					
Inconel 600	6.0/ 10.0	≦ 0.15	≦ 0.5	≦ 1.0		≦ 0.5	≧ 72.0		14.0/ 17.0			
Inconel 625	≦ 5.0	≦ 0.10	≦ 0.5	≦ 0.5	≦ 0.4		Balance	≦ 1.0	20.0/ 23.0	8.0/ 10.0	≦ 0.4	Nb + Ta 3.15/4.15
Incoloy 825	Balance	≦ 0.05	≦ 0.5	≦ 1.0	≦ 0.2	1.5/ 3.0	Ni (+Co) 38.0/46.0		19.5/ 23.5	2.5/ 3.5	1.6/ 1.2	
Stainless 302B25	Balance	≦ 0.12	0.20/ 1.0	0.50/ 2.00	≦ 0.030		8.0/ 11.0		17.0/ 19.0			
Stainless 316	Balance	≦ 0.07	0.20/ 1.0	0.50/ 2.00	≦ 0.030		10.0/ 13.0		16.5/ 18.5	2.25/ 3.00		

metallurgical structure shall be hard and fine tempered martensite without including any pearlite or bainite. The hardenability of steel increases with adding alloy elements except for cobalt and aluminum. It can be estimated by temperature-time-isothermal transformation diagram (TTT diagram or S curve), continuous cooling transformation diagram (CCT diagram), Jominy end-quench test etc., for each steel grade.
Since the as-quenched steel springs are brittle and easy to fracture, the tempering is normally applied after quenching. A plotted curve of mechanical property at room temperature, against tempering temperature is called as the tempering characteristic curve. Too low temperature tempering should be avoided as explained above. Alloying elements (such as silicon, chromium, molybdenum, etc.) can keep the quenched steel more resistant to softening as tempering. For these reasons, alloy steel is often used for thick gauge steel springs. Since the fatigue strength and relaxation resistance can be also affected by alloy elements of steel, the spring material selection becomes important. The recent studies related with the development of new spring steel materials for the weight-saving of automobiles can be introduced in Sect. 2.1.2 (10) and Sect. 2.1.3 (2)

(11) For the applications where electrical conductivity is required, copper alloys are suitable. Adding alloy elements or impurities to pure metal can decrease the electrical conductivity. As for piano wire and hard drawn wire, the electrical conductivity decreases at the initial stage of wire drawing, then it recovers up to total reduction of 60 to 75% of wire drawing reduction, and decreases again as increasing the reduction. For the applications where the electrical current is relatively small, the plated piano wire and hard drawn wire can be sometimes used.

Information Sources on Spring Materials

Information sources on spring materials are classified into documents sources (data-books) and databases searchable in computers.

The most substantial document sources may be books, magazines, reports, etc., published by the Japan Society of Spring Research, JSSR (now, the Japan Society of Spring Engineers, JSSE), which has been established around sixty years before.

The society has been publishing Transactions of Japan Society of Spring Research (annually), preprint textbooks of spring or autumn meetings (twice a year), various technical committee reports, bulletins of the Japan Society of Spring Engineers (monthly), etc. Many of these publications supply technical information on spring materials. In the vol. 2, spring technology series, "Kinds of springs and their applications" [3], spring materials conventionally used for various kinds of springs are briefly described. Elevated temperature heat-resistant spring material data book [5] and its second volume [7] contain data on spring materials to be used over the room temperature.

In monthly Japanese Journal of the society of materials science, Japan, original papers dealing with a wide range of materials' fatigue properties and lectures related with materials failures have been carried. From the Japan Society of Mechanical Engineers, data books on fatigue fracture of metallic materials were published [8, 9].

As described earlier, elastic moduli of cold-worked polycrystalline metallic materials show anisotropy because of texture formation. A technical book that collected anisotropic properties of metallic materials was published from the Japan society of mechanical engineers [10]. National Research Institute for Metals (now, National Institute for Materials Science) in Japan published two data-sheet books on elastic moduli and Poisson's ratios for carbon steels, low alloy steels, spring steels, tool steels and stainless steels [11, 12].

As an introductory textbook for steel materials, there is, for example, a Japanese book "Iron and steel materials" published by the Japan Metals Society [13]. As for heat-treatment and properties of steels, there is a detailed and old handbook, "Heat-Treatment of Steels, fifth edition (in Japanese)" [14]. Information on stainless steels can be obtained from a book "Stainless Steel Handbook, third edition (in Japanese)" [15]. As for phosphorus bronze alloys for spring applications, there is a Japanese book written by Nishihata and Harada [16].

As English documents, Metals Handbook series (now Materials Handbook series) would be valuable ones; especially, Vol. 1 for steels and high-performance alloys [17], Vol. 2 for non-ferrous alloys and special purpose alloys [18], and Vol. 13 for corrosion resistance alloys and corrosion [19]. In Japan, "Metals Data Handbook (in Japanese)" [20] describes various properties of metallic materials.

There are many books on plastics or polymers. As an example, an English book, Materials Sciense of Polymers for Engineers, [21] can be referred to.

In Chap. 27 of the book "Engineering Materials 2, An Introduction to Microstructures, Processing and Design", relation between part design and material choice is described [23] though not specific to springs. Similar handbook that dealt with material selection process for design and data sources which supply material information, was published from ASM International [24].

JIS handbooks in which the Japanese Industrial Standards (JIS) on spring materials and their inspections are contained, are listed in the Sect. 5.3, Chap. 5. In Sect. 5.2, the same chapter, comparison tables are included, in which each JIS standard related to spring materials is compared with the corresponding similar foreign standards.

At the copying service center of the Japan Science and Technology Agency, service of copying science and technical articles can be available with some expense. Details are explained in the Sect. 5.3, in the Chap. 5.

In North America, the Spring Manufacturers Institute (or SMI) has been publishing quarterly journals "SPRINGS" and books on spring technology. In the magazine "SPRINGS", articles on spring materials and spring design have been taken.

In Sheffield, England, there was an organization called the Spring Research and Manufacturers' Association (or SRAMA). From this organization, a data book "SPRING MATERIALS SELECTOR" was published [6]. SRAMA was later reorganized to the Institute of Spring Technology (or IST) and the UK Spring Manufactures Institute (or UKSMI).

New and revised ISO international standards on springs and springs related technologies are now taken into consideration by the TC committee of springs. The European Spring Federation (or ESF) has developed and implemented European standards (EN norms) on spring technologies. In Japan, the Japan Spring Manufacturers Association (JSMA) can be responsible for considering spring related ISO and JIS standards.

Computer Assisted Information Source on Spring Materials

Searching spring materials information utilizing either CD-ROM or DVD databases, and on-line WEB search can be accessible.

BANEX [25] is a database specifically designed for cold wound helical springs and materials, where the data of fatigue strength and permanent set are included. Although this database was edited by the JSSR, in 1992, the computer operation system is not compatible with the Microsoft Windows. However, the data can be usable.

IST in UK has published a database 'Spring Materials Selector CD-ROM' in collaboration with the European Spring Federation, ESF. CD-ROM version (in Japanese) of the Transactions of JSSR, No. 1 (1952) to No. 48 (2003), was published in 2003.

As for the databases for materials in general though not specific to spring technology, there are many databases available from website. Japan Science and Technology Agency, JST runs database service named "JST Online Information System" [26]. Also in Japan, National Institute of Informatics runs similar service [27]. Through links from these websites, materials fact databases supplied by some Japanese organizations [28–30] can be available. At the data free way site of the National Institute for Materials Science in Japan [28, 31], pages on links to materials information and search-engines for materials information are operated. Other major websites are referred to as references [26–30, 32, 35, 36].

National Institute of Informatics made a survey on how databases are widespread in Japan. The survey was made against national or public universities and research institutes. The result suggested that around 250 databases existed in the field of engineering and technology, but materials databases were scarce. Internationally, activity of CODATA (Committee on Data for Science and Technology) is worthy of special mention [32].

Among websites dealing with materials strength information, Japan Science and Technology Agency has developed a multi-functions-integrated basal database system [33], in which spring related information is contained as the

Table 1.7. Data and databases on materials strengths

Metallic materials strength database (JST)
Pressure vessels databases (JST & JPVRC)
Databook on Fatigue Strength of Metallic Materials, Vol. 1–3 (Society of Materials Science, Japan)
Database on metallic materials fatigue crack propagation resistance (Society of Materials Science, Japan)
Stress Intensity Factors Handbook (Society of Materials Science, Japan)
Stress corrosion cracking and corrosion fatigue strength data sheets for metallic materials (Society of Materials Science, Japan)
Materials strength data sheets: Fatigue data sheets (National Institute for Materials Science, Japan)
Materials strength data sheets: Creep data sheets (National Institute for Materials Science, Japan)
Reliability design data book for metallic materials (Society of Materials Science, Japan)

functional alloy database. Preferred method of utilizing this system can be shown in another article [34].

Outside Japan, Alloys-DB [35] from the Joint Research Centre (JRC)'s Institute of Advanced Materials (IAM) in Petten, Netherlands and the database of ASM International [36] are usable. Information from these organizations can also be obtained in CD-ROM.

Some of fact-data books and databases on materials strength open to public in Japan are listed in Table 1.7. The database system based on the fatigue data book published from the Society of Materials Science, Japan, can be available from the same society for a fee. A data book carrying data on materials strength was published from the Society of Materials Science, Japan [37]. A design data book for designing with reliability was developed by the Society of Materials Science, Japan [38], based on the Material Strength Databases for Reliability Design (MSDRD) developed by the material strength probability model research committee in Japan. A materials strength data book containing fatigue and creep data sheets, published from the National Institute for Materials Science are also available [39].

Basic Characteristics of Spring Materials

Basic characteristics of spring materials to be taken in consideration in material selection process, are; (1) static mechanical properties, especially tensile strength, elastic limit, spring deflection limit, hardness and elastic modulus, (2) dynamic properties, especially, fatigue strength (fatigue life at a constant stress amplitude, or fatigue endurance limit), (3) creep (progressive deformation of material at constant stress) or stress relaxation (time-dependent decrease in stress under constant constraint), that causes permanent set, and

(4) corrosion resistance, in addition, for springs in which electric current flows or for applications where magnetic disturbance is undesirable, (5) electrical conductivity or magnetic properties.

Besides these characteristics, the elastic modulus which can greatly affect to spring characteristics, is discussed here:

An elastic modulus of metallic material under constant temperature has been regarded as a microstructure insensitive constant decided only by chemical compositions. However, the demands for more precise mechanical evaluation of parts have been increasing to apply more precise elastic modulus.

It seems to be based on the above background that the testing method of elastic modulus has been newly designated as a JIS standard. Figure 1.3 shows test results on 2% tin(Sn)-phosphor bronze sheets by Nishihata et al. [16]. The figure shows the relation between the modulus of elasticity, E, both in the parallel and transverse direction to rolling and the reduction of cold rolling. It can be seen from the Fig. 1.3, that the difference of the elastic modulus between the two directions increases and the anisotropy develops as the degree of cold rolling becomes high. In spring wire, the elastic modulus can change with the degree of drawing and also the stress relieving after drawing. Figure 1.4, as an example, shows that the shear modulus (modulus of rigidity) of SUS304 stainless steel wire changes with the reduction of area by cold drawing and the stress relief [40]. The Fig. 1.4 says, that the shear modulus tends to decrease with the wire drawing, and recover by the following stress relief, to some extent.

It is considered that the preferred alignment of crystal orientation called texture formation and multiplication of dislocations (dislocation is a linear crystal defect and their movements promote plastic deformation) can contribute to the change of elastic modulus with cold working (it is known that in the iron and stainless steel single crystals the elastic modulus depends

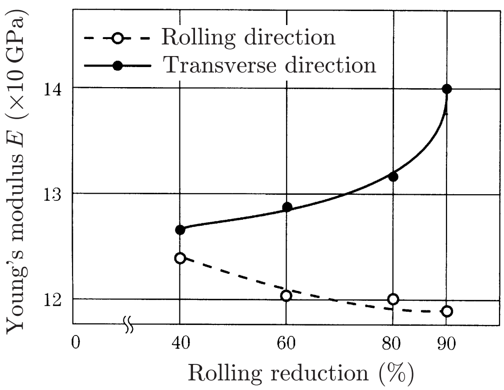

Fig. 1.3. Effect of rolling reduction on Young's modulus and its anisotropy for Sn 2% bearing phosphor bronze [16]