

Handbook of Residual Stress and Deformation of Steel

Edited by

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Preface

Control of steel deformation is one of the most common concerns within the metals processing industry. Numerous surveys have been conducted by various organizations in recent years to assess the critical needs of the industry. In nearly every survey that has been conducted, distortion is either the greatest or second greatest concern among the steel heat treating community. Steel distortion control will exhibit tremendous effects on the profitability of the commercial enterprise. Therefore, it is not surprising that the ability to understand the overall distortion process and to be able to design solutions to this problem typically rank very high on these same surveys.

In view of the enormous visibility and importance of steel deformation problems, the editors decided to put together an engineering handbook on steel deformation. To address this subject properly, contributing factors to overall steel deformation problems, including material effects, machining, heating and cooling, must be examined.

This handbook contains 27 articles, divided into five sections: Effect of Materials and Processing, Measurement and Prediction of Residual Stress and Distortion, Residual Stress Formation in the Shaping of Materials, Residual Stress During Hardening Processes, and Residual Stress Formation During Manufacturing Processes.

There are five articles in the section Effect of Materials and Processing. "Material Factors" discusses the effects of various material properties such as thermal properties and the interactions of residual stresses on the transformation products formed and steel deformation during fabrication. Transformation plasticity is discussed in some detail along with the use of modeling to better understand these processes.

"Prestress Engineering of Structural Material" provides a global design approach to understanding the effects of residual stress generated during surface engineering manufacturing processes such as PVD and CVD on the material properties obtained. Some of the topics discussed in this chapter include developments in the measurements of residual stresses, advanced mechanical surface treatments, and modeling of fatigue behavior taking residual stresses into consideration.

The effect of residual stresses on fatigue behavior is discussed in detail in the next article. Examples of topics discussed include stability of residual stresses, some aspects of fatigue in

steels, influence of residual stresses on cyclic deformation behavior, influence of residual stresses on crack initiation and propagation, and effect of residual stresses on S-N curves; an overview of modeling of the effect of residual stresses on fatigue behavior is provided.

The next article provides an overview of the stability and relaxation behavior of macro and micro residual stresses in steel due to thermal and mechanical treatments. This discussion includes relaxation of residual stresses by annealing, residual stress relaxation by uniaxial deformation, and relaxation by cyclic deformation.

Hydrogen embrittlement of metals, as well as other types of brittle fracture, result from nucleation and development of micro-cracks caused by internal stresses. The last article in this section provides an overview of the effect of residual stress on hydrogen embrittlement and stress corrosion cracking (SCC) of steel. This discussion includes the effect of hydrogen on structure and transformation of steel, types of hydrogen embrittlement, delayed fracture in steel, crack initiation and growth, SCC of low alloy steels, crack initiation and growth mechanism of SCC processes, methods of estimating sensitivity to SCC, effect of alloying elements on resistance to SCC, and the role of structure and thermal processing in SCC.

In the section Measurement and Prediction of Residual Stress and Distortion, the first article describes a number of simple, inexpensive deflection (dissection) methods used to estimate residual stress of various types of components. The methods include Almen strip; Navy C-Ring; plate or bar slitting and deflection; tube slitting and opening; and bending of bars, H-beams, and channels.

The next article provides an overview of residual stress measurement methods. Topics include residual stresses arising from various manufacturing processes, measurement methods including strain measuring technique, post-stress relaxation measurement, sectioning and material removal methods. In addition, strain measurement methods such as x-ray and neutron diffraction, ultrasonic, birefringent and laser, optical gages, brittle coatings, Barkhausen noise, and chemical coatings are discussed. Semidestructive methods such as blind hole drilling and ring coring are discussed.

Measurement of residual stresses in coatings and thin films is important because their influence on mechanical and physical properties affect component service performance. "Stress De-

termination in Coatings" provides a guide for measuring residual macrostress in coatings. Specific topics include origin of residual stresses in coatings and residual stress measurement methods including the deflection method, x-ray diffraction, and hole-drilling. A comparison of these methods is provided.

The last article in this section provides a detailed review of methods used to measure and subsequent data analysis of inhomogeneous residual stress fields. This discussion includes residual stress as an inverse problem of experimental mechanics, indicator crack method of measuring residual stress, arbitrary cut-out indicator method, and experimental methods and equipment including photoelastic coating method, and optical interferometry. Although this is a relatively rigorous numerical discussion, practical examples also are provided.

Residual Stress Formation in the Shaping of Materials contains four articles. The first article covers residual stress in the steel forming processes. The steel forming processes included are cold forming such as wire drawing, and hot forming such as extrusion, rolling, and forging. The effects of residual stresses involved in these processes are reviewed, and specific topics include residual stress in cold metal forming such as bending of sheet, drawing of wire, rod, and tube, and residual stresses in deep drawn cup, sunk tubes, and radial forging products.

The effect of final shaping prior to heat treatment on residual stress formation is discussed in the next article. The effects of shaping processes including grinding, milling, turning, shot peening, and straightening on residual stress are discussed. Also discussed is distortion after final part shaping and experimental and computational studies of these processes.

The next article provides a practical overview of the factors affecting residual stress and distortion during final part shaping. Included are discussions of influence of component shape on heat treatment distortion, the effect of cross-section size and asymmetry, effect of heat treating procedure and machining process on final component shape, effect of sequence of heat treating and machining, influence of machining allowance and stress relieving procedure, influence of residual stresses caused by cutting, methods of manufacturing blanks and effect of original structure, hot-rolled steels or forgings and effect of banded segregation and carbide segregation, influence of heat treating methods, the effect of heating including the rules of heating,

quenching and system design, tempering, and equipment and racking.

A more focused, but practical, discussion on the effect of process equipment design on distortion follows. Subjects that are covered include distortion generating process equipment, methods that may be used to minimize equipment-related distortion, quench system design, and press quenching.

Residual Stress During Hardening Processes contains eight articles. The first article provides a detailed discussion on the residual stresses in carburized, carbonitrided, and case-hardened components. Topics include process considerations for carburized and carbonitrided components, transformations and stress evolution in carburized and case-hardened components, effect of heat treating operations on residual stress distribution, relationship between residual stresses and properties of carburized parts and modeling and prediction of residual stress field.

The article on residual stresses in steel nitriding includes a discussion of nitrided layer structure as a function of nitriding process, residual stresses in nitrided layers, influence of residual stresses on fatigue behavior of nitrided steel components, and modeling and prediction of residual stresses in nitrided steel components.

The article on residual stress formation in induction hardening processes include an overview of the induction hardening process and steels used for this process, magnetic flux concentrators, conditions in induction heating and quenching of machine parts, residual stress surface profiles after induction surface hardening, stress profiles in the machine part in the loaded state, workpiece distortion in induction surface hardening, induction surface hardening of gear wheels, fatigue strength of materials, and residual stresses after induction surface hardening and finish grinding.

The next article provides an overview of residual stresses and distortion resulting from reheating and quenching. Topics include phase transformation during heat treating including steel transformations, TTT and CCT diagrams, metallurgical crystal structure, estimation of volumetric change due to steel transformation upon quenching, cooling of steel with and without metallurgical transformation, tempering, basic distortion mechanism, relief of residual stresses, material movement due to thermal gradients during heating and cooling, material, component and process effects, retained austenite, quench severity and uniformity and process design effects on distortion, quench distortion and cracking, quenchant selection, measurement and evaluation of quenching power, estimation of heat transfer coefficient, wetting behavior and non-uniform quenching, surface conditions, and quench process modeling and simulation of residual stress and distortion after quenching.

A detailed approach to modeling and simulation of residual stress and distortion applied to quench processing follows. This discussion is based on a metallo-thermo-mechanics approach, and topics discussed include an overview of

metallo-thermo-mechanics and numerical simulation methodology with practical examples.

In the article on the control of residual stress formation and steel deformation during rapid heating and cooling, a particular emphasis is on intensive quenching. This is the first detailed, article-length discussion of this old, but little-known technology in the western world. Topics include mathematical model for calculation of thermal and stress-strain state, computation of stress-strain state, possibility of predicting hardening cracks, predicting the deformation of bearing rings during hardening, thermal stresses formed in carburized steel products due to excessive cooling rates, generalization of computational and experimental results for heating and cooling of parts with different geometries and thermal and physical fundamentals of processing of high-strength materials.

An often contradictory subject is the cryogenic processing of steels, and the detailed overview of the effect of cryogenic cooling on residual stress is presented here. Specific topics include role of residual stresses within martensitic transformation at cryogenic temperatures, evaluation of residual stresses after cryogenic cooling, influence of cryogenic cooling on residual stresses and dimensional stability of steels, and influence of cryogenic cooling on the structure and substructure of steels.

The practical use of controlled shot peening to induce compressive residual stresses is described in detail next. This discussion includes a historic overview of shot peening, elementary processes of shot peening, workpiece and material process parameters, process monitoring, process optimization, x-ray diffraction, and industrial examples.

In Residual Stress Formation During Manufacturing Processes, the first article includes an extensive discussion of residual stress and deformation problems arising from the casting process, and modeling of residual stress formation during casting. Discussion includes finite element analysis of heat flow during casting, formulation of the elasto-viscoplastic stress model, and deformation of a solidifying material.

The next article describes residual stress formation during the casting process, and it includes continuous and centrifugal casting. Topics discussed include inelastic behavior and unified constitutive theory of metallic material in solidification, analytical method of the thermal-mechanical problem for the casting process, residual stress formation during semicontinuous casting, residual stress formation during centrifugal casting, and residual stress formation during strip casting by the twin-roll method.

The origin and assessment of residual stresses during welding or brazing is discussed next. Welding residual stresses are discussed including residual stresses due to shrinkage, quenching, and phase transformations. Characteristic residual stress distributions in brazed components is also discussed.

The article "Residual Stresses in Powder Metal Processing" is divided into two parts. The

first part describes manufacturing of ferrous P/M parts including powder characteristics, compaction in rigid dies, isostatic compaction, sintering, heat treatment of P/M parts, hot pressing, roll compaction, powder forging, metal injection molding, spray forming, warm compaction, and rapid prototyping. The second part discusses residual stresses in P/M processing including powder production, compaction of metal powders, sintering of metal powders, pressure sintering and hot isostatic pressing, heat treatment of P/M parts, and microstructural development and properties.

"Residual Stress Formation and Distortion of Rail Steel" covers the cooling process including the cooling boundary conditions and heat transfer, residual stress state analysis, weight and friction—the rail end problem, experimental results; roller straightening including residual stresses in unused roller-straightened rails, behavior of rail steel under plastic deformation, simulation of roller straightening; and rails in service including residual stresses due to welding and residual stress formation in rolling contact.

The last article provides a detailed description of residual stress formation during hypoid gear manufacture. It includes an overview of residual stress formation in carburized and hardened work, profiles and peak magnitudes of residual stresses, measurement methods including the Sach's hole-drilling method, x-ray and neutron diffraction, influence of steel properties on residual stresses, influence of carburizing process parameters on residual stress formation, benefits of residual stresses on fatigue strength, and the effects of hardness, case depth, intergranular oxidation, influence of shot peening, change of residual stresses during fatigue, and distortion of carburized and hardened steels.

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