

Ping Hu · Liang Ying  
Bin He

# Hot Stamping Advanced Manufacturing Technology of Lightweight Car Body



Science Press  
Beijing



Springer

# Hot Stamping Advanced Manufacturing Technology of Lightweight Car Body

Ping Hu · Liang Ying · Bin He

# Hot Stamping Advanced Manufacturing Technology of Lightweight Car Body

 Science Press  
Beijing

 Springer

Ping Hu  
School of Automotive Engineering  
Dalian University of Technology  
Dalian  
China

Bin He  
School of Automotive Engineering  
Dalian University of Technology  
Dalian  
China

Liang Ying  
School of Automotive Engineering  
Dalian University of Technology  
Dalian  
China

ISBN 978-981-10-2400-9      ISBN 978-981-10-2401-6 (eBook)  
DOI 10.1007/978-981-10-2401-6

Jointly published with Science Press, Beijing, China

Library of Congress Control Number: 2016947930

© Science Press and Springer Science+Business Media Singapore 2017

This work is subject to copyright. All rights are reserved by the Publishers, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publishers, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publishers nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made.

Printed on acid-free paper

This Springer imprint is published by Springer Nature  
The registered company is Springer Science+Business Media Singapore Pte Ltd.

# Preface

Since the reform and opening up more than 30 years ago, automobile industry, as the pillar industry of national economy in our country, has played an important role in improving the national standard of living and the quality of travel. The support from all fields has also contributed to the unprecedented development of our country's automobile industry. Two oil crises in 1970s made automobile industry face three big challenges: safety, energy saving and environmental protection. How to design and manufacture cars featured with energy saving and safety is the eternal pursuit goal of automobile industry in the future. The automobile in new ages not only needs to meet all kinds of collision safety laws and regulations such as front crash, side impact, offset collision, etc., but also has to reduce their own curb weight in order to get better fuel economy and achieve energy conservation and emission reduction. Studies have indicated that using new materials with high specific strength and good lightweight effect, such as high-strength steel, aluminum alloy, magnesium alloy and carbon fiber enhanced composite material, in automobile lightweight design and manufacture is the most effective way to achieve this goal. However, new materials such as high-strength steel plate, aluminum alloy and magnesium alloy all have disadvantage of poor toughness and plasticity, which has limited its application in car body, and new technology and new method therefore must be adopted to realize the design and manufacture. High-strength steel hot stamping technology emerges in this new situation.

Hot stamping technology is a new manufacturing technology combining the new material and new technology effectively to manufacture automobile parts. In hot stamping, the original steel plate of boron alloy steel is heated to a temperature of about 950 °C, then transferred to the water-cooling tools for stamping, quenching and forming, finally obtaining the lightweight components with satisfying performance. Hot stamping technology not only can solve the problem of poor formability, unmanageable springback and manufacture precision of high-strength steel sheet, but also can obviously improve the strength and hardness of steel during the forming and quenching process, and obtain ultrahigh-strength hot stamping car body structural parts with tensile strength as high as 1500 MPa. In addition, car body parts with hardness gradient composite properties based on the optimization

of forming process can also effectively improve the characteristics of anti-collision and energy absorption, to improve the safety of the car. Based on the background of automobile lightweight and the advantages introduced above, high-strength steel hot stamping technology is booming in the global automotive body manufacturing industry. From the perspective of making China the world's biggest automobile producer with annual production up to 20 million in 2015, the development prospect of this technology is extremely broad, the corporate demand is also very big.

At present, the study of high-strength steel hot stamping technology abroad is very mature. The hot stamping technology was used in the aviation industry such as United States NASA (National Aeronautics and Space Administration), and nuclear industry at the beginning of the last century. The hot stamping technology suitable for auto parts production was first developed by N. Jernverkin 1973, and opened up its industrialization tour in the 1990s. It has been gradually applied and popularized on a global scale in big companies such as BMW and Volvo. As the mature hot stamping technology has been strictly closed in China, it had to be researched and developed from the very beginning in China. The AMT (Advanced Manufacture of Technology) research team led by Prof. Ping Hu in Dalian University of Technology have been studying on the hot stamping technology for more than 10 years, starting from the research field of mechanics for manufacturing process, focusing on the establishment of basic mechanics theory and the constitutive equation and the finite element algorithm for hot stamping. They have developed the KMAS\_HF hot stamping sheet forming software with independent intellectual property rights, being the first to break the foreign monopoly and successfully develop a complete set of hot stamping process database and complete sets of production line with completely independent intellectual property rights.

The related scientific research achievements have been published in journals at home and abroad under the premise of not leaking the core technology. The research results have also been successfully applied and demonstrated in the industry in Japan KOBELCO Steel Company, China's Chery Automobile Co., Ltd., FAW Technology Center, JiLin VAFT Lightweight Technology Co., Ltd., and other related units.

As the industry's first monograph that systematically introduces the hot stamping technology from aspects of experiment, theory, method, and industrial application, this book comprehensively introduces the developing situation, equipment and process mechanism of the hot stamping technology. This book mainly introduces the related basic theory about multi-field coupled relationship among heat, stress and phase transformation, the finite element simulation technology and the actual engineering application of hot stamping products in automotive lightweight, together with the theoretical background for sheet metal hot stamping technology and its engineering significance in the field of auto parts. The book also provides a useful reference for other new technology related temperature and phase transformation, such as aluminum–magnesium alloy hot stamping. We sincerely hope the book will be beneficial for advanced manufacturing engineers, automotive design engineers, and researchers in other related fields.

The latest achievements and progress of hot stamping technology in the last 5 years are included in this book, which is organized in ten chapters. The contents include the research achievements and patents of the author and the AMT group for years, and have referred to the related scientific papers published in recent years. Chapter 1 introduces the basic knowledge of sheet metal stamping, including the development of stamping technology, the core basic knowledge such as process, tools, press machine, the production process, as well as the basic requirement of stamping process for material property, which lays a foundation for the subsequent introduction of hot stamping technology. Chapter 2 provides a systematic and concise introduction about the high-strength steel hot stamping technology and the main single equipment technology based on mass production line to make the readers have a macrolevel understanding of the technology. Chapter 3 expounds the process factors that affect the performance of high-strength steel and the original results of process optimization by authors' team in recent years. It also puts emphasis on illustrating the process mechanism to produce auto body parts with tailored properties. Chapter 4 mainly elaborates the hot stamping mechanical theory and constitutive equation for high-strength steel plate from a phenomenological level. Through experiments and theoretical analysis, quantitative research on multi-field coupling heat, stress, and phase transformations in hot stamping process is introduced, together with the stress-strain relationship derived from the law of mixture, and the hot stamping constitutive model of total strain theory and incremental theory, which have established the basic mechanics theory of hot stamping based on phenomenological significance. Chapter 5 establishes the single crystal and polycrystalline finite deformation constitutive integration algorithm under the condition of variable temperature based on the finite element algorithm by taking elastic-plastic deformation gradient and stress as basic variables. Combined with the thermal tensile curves, numerical simulation and experimental verification under thermal coupling are carried out. Chapter 6 focuses on the heat transfer theory in hot stamping process, including the mixed heat transfer theory between blank-tools and tools-channel in the process of transfer, punching, and quenching. The heat transfer coefficient between blank-tools and tools-channel is measured by inverse calculation and experiments. The factors such as high-temperature oxidation and the steel blank surface roughness are also studied in this chapter. Chapter 7 discusses the factors influencing the plasticity and deformation resistance of hot stamping materials, and establishes the high-temperature material constitutive model, which is suitable for multi-field coupling analysis, based on high-temperature material mechanics performance. Combined with the first set high-temperature forming limit TFLD test equipment developed independently in China, the 3D forming limit surface 3D-TFLD suitable for high-temperature formability prediction is obtained. In Chap. 8, the high-strength steel hot stamping FEM simulation algorithm is discussed from the four key problems of numerical simulation: the discussion of the variational equation in temperature field modeling and simulation, cell division, transient spatial domain, and discrete time domain. Meanwhile the fundamental equation and the solving method of the hot stamping phase transformation are analyzed and described. Based on the hot stamping

multi-field coupling numerical simulation needs, this paper expounds the static explicit algorithm and dynamic explicit algorithm. Chapter 9 mainly introduces the application of hot stamping components and hardness gradient parts in lightweight car body. According to practical engineering, the hot stamping technology is applied to the typical body bearing parts such as door anti-collision beam, side wall, body beam frame, and the school bus pillars. And the application and optimization of typical body structures such as B Pillar are conducted with the hardness gradient composite properties of hot stamping. Chapter 10 mainly introduces the key technologies involving tool optimization design and manufacture in hot stamping technology. It also analyzes the fatigue and life of hot stamping die.

The relevant research work in this book is strongly supported by projects such as the Key Project of the National Natural Science Foundation of China, “973” National Basic Research Project of China and “04” Great Project of the Ministry of Industrialization and Information of China. After years of interdisciplinary collaboration research, from scientific theory to process practice, from the scientific problems to product research and development, the systemic research progress has been made. To promote the new technology of hot stamping automotive components manufacturing combining new material, new process and new equipment and to guide the innovation and development of auto parts manufacturing industry and then provide a new train of thought for the design and development of new cars are the purpose and motivation for the author to write the book. Errors are inevitable in this book due to the continuous development of hot stamping technology and the limitations of the author. Any comments from readers will be appreciated.

Dalian, China

Ping Hu  
Liang Ying  
Bin He



# Acknowledgment

This book is funded by the Key Project of the National Natural Science Foundation of China (No. 10932003). This support is gratefully acknowledged.

Special thanks go to Dr. Ning Ma, Minghua Dai, Dan Zhao, Dongyong Shi, Wenquan Liu, Ye Yu, Xi Zhao, and others for their significant contribution to the research and development of hot stamping technology. Without their effort, it is impossible to complete this book. The author also wishes to thank VAFT, Changchun auto Parts Co., Ltd., who provided special hot stamping laboratory equipment and relevant experience. Thanks to Dantong Wang, Yang Liu, Xianda Zhang, Fubo Zhang and other students, who gave unstinted effort in editing this book.

In addition, Science Press has done a lot of productive work in editing the manuscript, we sincerely thank all the people and units who have made contribution to the publication of the book.

# Contents

<b>1</b>	<b>The Basis of Sheet Metal Forming Technology</b> .....	1
1.1	The Development of Stamping Technology .....	2
1.2	The Basics of Sheet Metal Forming .....	4
1.2.1	The Process of Traditional Cold Stamping .....	4
1.2.2	The Cold Stamping Tool.....	5
1.2.3	Stamping Press .....	7
1.2.4	The Production Process of Stampings .....	9
1.3	Materials for Cold Stamping and Its Formability .....	11
1.3.1	Requirements on Materials for Cold Stamping .....	11
1.3.2	The Formability of Materials .....	12
1.4	Summary .....	17
	References.....	18
<b>2</b>	<b>Hot Stamping Technology and the Main Equipment</b> .....	19
2.1	The Hot Stamping Technology of High Strength Steel.....	19
2.1.1	Brief Introduction of Hot Stamping Technology .....	19
2.1.2	Hot Stamping Process .....	21
2.1.3	Finite Element Simulation Analysis of Hot Stamping Technology .....	28
2.1.4	The Research Status of Hot Stamping .....	30
2.2	Hot Stamping Production Lines and the Key Equipments .....	32
2.2.1	Continuous Ring Heating Furnace.....	33
2.2.2	High-Temperature Resistant Robot Arm and Automatic Transfer Device for Loading and Unloading.....	35
2.2.3	Key Technologies for Design and Manufacture of Hot Stamping Dies .....	36
2.2.4	High-Speed Hydraulic Press for Hot Stamping .....	38

- 2.2.5 Central Intelligence Control Automatic Integrated System. . . . . 39
- 2.2.6 Subsequent Shot Blasting, Trimming, and Punching Equipment. . . . . 40
- 2.3 Summary . . . . . 42
- References. . . . . 42
- 3 Performance of Hot Stamping High Strength Steel (HSS) Technology . . . . . 45**
  - 3.1 Process and Principle of Hot Stamping HSS . . . . . 45
    - 3.1.1 Hot Stamping Plate . . . . . 45
    - 3.1.2 Hot Stamping Technology and Mechanism . . . . . 48
  - 3.2 Research in the basic technology of hot stamping . . . . . 50
    - 3.2.1 Mechanical Properties of Hot Stamping Steel . . . . . 50
    - 3.2.2 Effect of Heating Temperature on the Mechanical Properties of Hot Stamping Steel. . . . . 53
    - 3.2.3 Effect of Holding Time on the Mechanical Properties of Hot Stamping Steel Plate . . . . . 57
    - 3.2.4 Effects of Cooling Rate on the Mechanical Behavior of Hot Stamping Steel Plate . . . . . 59
  - 3.3 The Study of Hot Stamping Material Toughness Process Experiment . . . . . 63
    - 3.3.1 Hot Stamping Steel Strength-Toughness Tempering Process . . . . . 63
    - 3.3.2 Hot Stamping Steel Strength-Toughness High Temperature Quenching Process . . . . . 70
  - 3.4 Tailored Properties of Hot Stamping Part. . . . . 74
    - 3.4.1 Forming Mechanism of Hot Stamping Gradient Strength Steel . . . . . 75
    - 3.4.2 Experimental Research on District Cooling Process of Gradient Strength Part. . . . . 76
    - 3.4.3 Exponential Relation Between Strength-Hardness-Cooling Rate of Hot Stamping Steel. . . . . 83
  - 3.5 Summary . . . . . 90
  - References. . . . . 91
- 4 The Basic Theory and Constitutive Equation of High Strength Steel for Hot Forming . . . . . 95**
  - 4.1 Multifield Coupled Relationship Among Heat, Stress and Phase Transformation. . . . . 95
    - 4.1.1 Theoretical Analysis . . . . . 95
    - 4.1.2 The Determination of the Parameters. . . . . 97

4.1.3	The Analysis and Discussion on the Experiment Results . . . . .	100
4.1.4	Thermal-Mechanical Transformation Coupled Constitutive Model . . . . .	102
4.2	Hot Forming Stress and Strain Analysis . . . . .	104
4.2.1	Mixed Law . . . . .	104
4.2.2	Strain Analysis . . . . .	104
4.2.3	Stress Analysis . . . . .	105
4.3	Constitutive Model of Hot Forming . . . . .	107
4.3.1	Hot Forming Constitutive Relation of Total Strain Theory . . . . .	107
4.3.2	Hot Forming Constitutive Relation of Incremental Theory . . . . .	107
4.4	Summary . . . . .	108
	References. . . . .	109
<b>5</b>	<b>Constitutive Integration Algorithm of Crystal Thermal Deformation</b> . . . . .	<b>111</b>
5.1	The Constitutive Integration Method of Single Crystal Finite Deformation at Variable Temperature Conditions . . . . .	111
5.1.1	Elastic Deformation Gradient as Basic Variable . . . . .	111
5.1.2	Plastic Deformation Gradient as Basic Variable . . . . .	114
5.1.3	Stress as the Basic Variable in the Algorithm . . . . .	116
5.2	Comparison Between Two Deformation Gradient Algorithms . . . . .	120
5.2.1	Elastic and Plastic Deformation Gradient . . . . .	120
5.2.2	The Implicit and Explicit Algorithms . . . . .	121
5.3	The Constitutive Integration Method of Polycrystalline . . . . .	122
5.3.1	The Construction of Taylor Model . . . . .	123
5.3.2	The Multiscale Finite Element Model . . . . .	124
5.4	The Numerical Calculation and Experimental Verification of Thermal Tensile of the High Strength Steel . . . . .	127
5.4.1	The Thermal–Mechanical Coupling Tensile Experiment . . . . .	127
5.4.2	Comparison Analysis of the Numerical Simulation . . . . .	130
5.5	Summary . . . . .	133
	References. . . . .	133
<b>6</b>	<b>Heat Transfer in Hot Stamping Process of High-Strength Steel</b> . . . . .	<b>135</b>
6.1	Heat Transfer Theory and Behavior Analysis . . . . .	135
6.1.1	Basic Principle [1, 2]. . . . .	135
6.1.2	Heat Transfer Behavior Analysis . . . . .	137

6.2	Determination of Heat Transfer Coefficient in Hot Stamping Process. . . . .	138
6.2.1	Method . . . . .	138
6.2.2	Determination of Interfacial Heat Transfer Coefficient Between Blank and Tool. . . . .	139
6.2.3	Determination of Convectonal Heat Transfer Coefficient Between Tool and Cooling Water . . . . .	143
6.3	The Other Factors Influencing the Heat Transfer Coefficient of Hot Stamping Process . . . . .	150
6.3.1	The Effect of High-Temperature Oxidized Scale . . . . .	150
6.3.2	The Influence of Heat Transfer Coefficient About Steel Sheet Surface Roughness . . . . .	160
6.4	Summary . . . . .	163
	References. . . . .	163
<b>7</b>	<b>The Formability of High-Strength Steel for Hot Stamping . . . . .</b>	<b>165</b>
7.1	The Concepts of Plasticity and Deformation Resistance . . . . .	165
7.2	Factors Influencing Plasticity and Deformation Resistance of Hot Stamping Steel . . . . .	166
7.2.1	Chemical Composition . . . . .	166
7.2.2	Metallic Structure . . . . .	167
7.2.3	Deformation Temperature and Work Hardening . . . . .	167
7.2.4	Deformation Rate . . . . .	168
7.2.5	Cooling Rate . . . . .	170
7.2.6	Deformation Degree . . . . .	170
7.2.7	Size Factor . . . . .	171
7.3	Material Properties of High-Strength Steel at Elevated Temperature . . . . .	171
7.3.1	Uniaxial Tensile Experiment of High-Strength Steel at Elevated Temperature . . . . .	171
7.3.2	Hardening Model of High-Strength Steel at Elevated Temperature. . . . .	173
7.3.3	Effects of Hardening Capacity on Formability. . . . .	175
7.3.4	Effects of Directional Anisotropy on Formability . . . . .	177
7.4	Prediction of Forming Limit for Hot Stamping. . . . .	179
7.4.1	Introduction of Forming Limit and Instability Theory. . . . .	179
7.4.2	Test Principle of Forming Limit at Elevated Temperature. . . . .	182
7.4.3	Test Equipment and Test Procedure of Forming Limit at Elevated Temperature . . . . .	184
7.4.4	Three-Dimension Thermal Forming Limit Diagram and Its Application . . . . .	186
7.5	Summary . . . . .	190
	References. . . . .	190

<b>8</b>	<b>Hot Stamping Simulation Algorithms of High-Strength Steels</b> . . . .	193
8.1	Basic Descriptions of the Hot Stamping Simulation . . . . .	193
8.2	Several Key Points in Numerical Simulation of Hot Stamping . . . . .	195
8.2.1	Key technology of Multi-field Coupled Problem . . . . .	195
8.2.2	Problems of High Temperature Contact Friction . . . . .	196
8.2.3	The Simulation Technology of Temperature Field . . . . .	197
8.2.4	The Simulation Technology of Phase Field . . . . .	198
8.3	The Model Building and Simulation of Temperature Field in Hot Stamping . . . . .	199
8.3.1	Summary of Temperature Field FEA in Hot Stamping Process . . . . .	199
8.3.2	Variational Equation of Temperature Field . . . . .	203
8.3.3	The Basic Equation of Temperature Shell Elements . . . . .	207
8.3.4	Discreteness of Space Domain and Time Domain in Shell Transient Temperature Field . . . . .	213
8.4	The Modeling and Simulation of Phase Field in Hot Stamping . . . . .	214
8.4.1	Summary of Phase Field . . . . .	214
8.4.2	The Basic Equation of Phase Field . . . . .	215
8.4.3	The Solving Method of Phase Field . . . . .	217
8.5	Hot Stamping Multi-Field Coupled Numerical Simulation . . . . .	218
8.5.1	Static Explicit Algorithm for Hot Stamping Multi-Field Coupled Numerical Simulation . . . . .	218
8.5.2	Dynamic Explicit Finite Element Formulation of Multi-Filed Coupled Hot Stamping Simulation . . . . .	226
8.6	Summary . . . . .	240
	References . . . . .	241
<b>9</b>	<b>Lightweight of Car Body Structure Applied by Hot Stamping Parts</b> . . . . .	243
9.1	Lightweight of Car Body Structure Applied by Hot Stamping Parts . . . . .	243
9.1.1	Hot Stamping Door Anti-crash Beam and Its Process Optimization . . . . .	243
9.1.2	Application of Hot stamping Parts Based on CAE Crash of Whole Vehicle . . . . .	247
9.1.3	Application of Hot stamping Parts in Concept Body Lightweight Design . . . . .	251
9.1.4	The Application of Hot stamping Component in Lightweight Design of Large School Bus . . . . .	260

- 9.2 The Application of Gradient Hardness Hot stamping Component in Vehicle Bodywork. . . . . 264
  - 9.2.1 The Research of Crash Energy Absorption Property of Gradient Hardness Hot stamping Component . . . . . 265
  - 9.2.2 The Application of Gradient Hardness Hot stamping B-Pillar in Vehicle Bodywork and Optimization Design . . . . . 269
- 9.3 Summary . . . . . 275
- References. . . . . 276
- 10 The Optimization Design and Manufacture of Hot Stamping Mold . . . . . 279**
  - 10.1 The Key Technology of Hot Stamping Mold Design . . . . . 279
    - 10.1.1 The Whole Structure of Mold . . . . . 279
    - 10.1.2 The Selection of Material . . . . . 280
    - 10.1.3 Surface Engineering of Mold. . . . . 281
    - 10.1.4 Optimization Design of Mold Cooling System . . . . . 283
  - 10.2 The Optimization of Cooling System in Hot Stamping Dies . . . . . 284
    - 10.2.1 Optimization of Subsystem Decomposition . . . . . 284
    - 10.2.2 Virtual Prototype of the Optimization of Mold Cooling . . . . . 285
    - 10.2.3 Optimizing Core Technology Decomposition . . . . . 288
    - 10.2.4 Optimization Examples . . . . . 289
  - 10.3 The Manufacturing of Hot Stamping Mold. . . . . 292
    - 10.3.1 Mold Heat Treatment . . . . . 292
    - 10.3.2 Mold Surface Strengthening Treatment . . . . . 292
  - 10.4 The Thermomechanical Fatigue Test and Life Prediction Simulation of Hot Stamping Die. . . . . 294
    - 10.4.1 Fatigue Type of Hot Stamping Die . . . . . 294
    - 10.4.2 Thermomechanical Fatigue Test Device . . . . . 295
    - 10.4.3 Experimental Principle and Content. . . . . 295
    - 10.4.4 Experimental Results. . . . . 297
    - 10.4.5 Life Prediction Simulation. . . . . 303
  - 10.5 Summary . . . . . 308
  - References. . . . . 308
- Index . . . . . 311**