Lecture Notes in Mechanical Engineering

Uday S. Dixit
M. Kanthababu
A. Ramesh Babu
S. Udhayakumar *Editors*

Advances in Forming, Machining and Automation

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Lecture Notes in Mechanical Engineering

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Editors

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Editors
Uday S. Dixit
Department of Mechanical Engineering
Indian Institute of Technology Guwahati
Guwahati, Assam, India

M. Kanthababu
Department of Manufacturing Engineering
Anna University
Chennai, Tamil Nadu, India

A. Ramesh Babu
Department of Mechanical Engineering
PSG College of Technology
Coimbatore, India

S. Udhayakumar
Department of Mechanical Engineering
PSG College of Technology
Coimbatore, India

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Foreword

First, I would like to congratulate the editors of five different volumes of proceedings of 8th International and 29th All India Manufacturing Technology, Design and Research Conference (AIMTDR) proceedings being published by Springer. These volumes are very good collection of the research and review papers on the manufacturing processes like Modern Machining processes (Volume-1), Additive Manufacturing and Metal Joining (Volume-2), Simulation, Product Design and Development (Volume-3), Forming, Machining and Automation (Volume-4) and Micro- and Nano-Manufacturing and Surface Engineering (Volume-5). These five volumes are comprehensive collection of the research papers focusing on the most recent research and developments in the area of manufacturing processes.

These subject areas continue to be dominant manufacturing technologies, say, the *technologies of future*, namely 3D printing (additive manufacturing), which generally lacks speed, surface finish and dimensional accuracy. To compensate these weaknesses of 3D printing in the real-life production, I could also see good papers on micro-/nano-manufacturing and nano-finishing. Theoretical analysis, optimization and simulation of manufacturing processes would definitely provide the necessary insights into the physics and mechanisms of these processes, as well as their basic understanding. These five volumes would be invaluable to the researchers working in research laboratories and engineers in industrial organizations working on shop floors for learning, consulting and applying some of the findings deliberated in the conference by the authors of different research papers.

Such conferences encourage the interaction between the research scholars, faculty members and user industries' representatives from different parts of the world. Unfortunately, this could not happen in this hybrid conference to the desired extent due to the pandemic effects across the globe. Apart from these contributed papers, there were many online and offline keynote lectures delivered by the researchers from different countries including India. I am sure that these papers should be of great help to the readers of these proceedings. This proceedings/collection of the papers should be of great help to the academia and industries as well as reference books in different sub-fields of manufacturing processes.

I would like to congratulate the authors for their contributions to all these five volumes of the proceedings and the Editorial Committee Members for their untiring efforts made in bringing out these research papers' collections in five volumes. I will also like to thank the technical committee members in general and ex-vice-president of NAC, Prof. Uday S. Dixit, for inviting me to write this foreword.

Bhopal, India

Dr. V. K. Jain
Professor (Retired), IIT Kanpur

Member, National Advisory
Committee, AIMTDR 2021

Preface

All India Manufacturing Technology, Design and Research (AIMTDR) is a reputed international conference series focused in the domain of manufacturing. The first All India Machine Tool Design and Research conference, also abbreviated as AIMTDR, was organized by Jadavpur University, Kolkata, in the year 1967. Those were the days when the main focus of manufacturing was toward efficient design and utilization of machine tools. PSG College of Technology, Coimbatore, organized the 7th and 15th AIMTDR conferences in 1976 and 1992, respectively. Other institutes who organized this conference before the 15th AIMTDR conference are Central Machine Tool Institute (CMTI), Indian Institute of Technology (IIT) Bombay, IIT Madras, University of Roorkee, IIT Kanpur, Central Mechanical Engineering Research Institute and IIT Delhi, some of them multiple times. After the 15th AIMTDR conference, the necessity of widening the scope of the conference arose. It was decided to encompass entire manufacturing technologies in its fold, rather than just focusing on the technologies related to machine tools. Accordingly, the phrase "machine tool design" was replaced by "manufacturing technology, design." Thus, the conference series was rechristened as All India Manufacturing Technology, Design and Research, without making any alteration to the acronym AIMTDR. Thus, the 16th AIMTDR conference with the new unabridged title was organized at CMTI, Bangalore, in 1994. It is interesting to note that CMTI had renamed itself from Central Machine Tool Institute to Central Manufacturing Technology Institute in 1992, adapting to the current trends in manufacturing.

AIMTDR received its international status in the year 2006, when the first International and 22nd National AIMTDR was organized at IIT Roorkee. Subsequent conferences were held at IIT Madras, Andhra University, Jadavpur University, IIT Guwahati, College of Engineering Pune and Anna University. The recent edition of the conference, viz. the 8th international and 29th national conferences, was jointly organized by the Departments of Mechanical Engineering of PSG College of Technology, Coimbatore, and PSG Institute of Technology and Applied Research, Coimbatore, during December 9–11, 2021, in virtual mode. The theme of AIMTDR 2021 was "*Transformational Changes in Manufacturing*."

After a rigorous review process, about 250 technical papers from academia and industry were accepted for the presentation at the conference. In addition, eight keynote talks on advanced technologies such as the development of high precision machine tools, simulation of material flow, nanostructured surfaces, additively controlled material mechanics, product development platforms, next-generation milling, diamond turning and hybrid machining were delivered by the experts. Further, two case studies from the industry highlighting the innovation practices and challenges in machine tool structure design were presented.

Select papers from the conference are being published by Springer in the series—*Lecture Notes in Mechanical Engineering*, in five volumes—Volume-1: *Advances in Modern Machining Processes*, Volume-2: *Advances in Additive Manufacturing and Metal Joining*, Volume-3: *Advances in Simulation, Product Design and Development*, Volume-4: *Advances in Forming, Machining and Automation* and Volume-5: *Advances in Micro and Nano Manufacturing and Surface Engineering.*

Volume-4 entitled *Advances in Forming, Machining and Automation* covers a wide variety of technical papers related to bulk-forming, incremental forming, laser bending, hydroforming, textured tools, laser-assisted machining, cryogenic grinding, condition monitoring, robotics, intelligent manufacturing, industrial Internet of Things, computer vision, enterprise manufacturing intelligence, etc. These papers clearly indicate the changing trends in the era of Industry 4.0. We hope that researchers, as well as practicing engineers, will find this volume useful.

We sincerely thank the members of the National Advisory Committee of AIMTDR, organizers, reviewers, authors and participants. Special thanks to Springer for publishing the select papers of AIMTDR since AIMTDR 2014. Readers are requested to send us feedback about this volume.

Guwahati, India — Uday S. Dixit, uday@iitg.ac.in
Chennai, India — M. Kanthababu, kb@annauniv.edu
Coimbatore, India — A. Ramesh Babu, arb.mech@psgtech.ac.in
Coimbatore, India — S. Udhayakumar, suk.mech@psgtech.ac.in

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About the Editors

Dr. Uday S. Dixit is Professor in the Department of Mechanical Engineering, Indian Institute of Technology, Guwahati. He obtained his Bachelor's degree in Mechanical Engineering from the Indian Institute of Technology, Roorkee in 1987. He obtained his M.Tech. and Ph.D. in Mechanical Engineering from the Indian Institute of Technology, Kanpur in 1993 and 1998, respectively. He has more than two decades' experience in carrying out research in the area of metal forming and machining. Apart from FEM, he uses fuzzy set theory and neural networks in his research. Before taking up a research career, he worked as a machine tool designer in HMT Ltd. Pinjore, India. He has published 139 peer reviewed international journal papers and published 17 books. e-mail: uday@iitg.ac.in

Dr. M. Kanthababu is Professor in the Department of Manufacturing Engineering in Anna University, Chennai, India and Director of the Centre for Intellectual Property Right and Trade Mark, Anna University. He obtained his B.E. from Bharathiyar University, M.S. and Ph.D. from the Indian Institute of Technology, Madras. Prof. Kanthababu's research interests include manufacturing technology, composite materials and machining, and automation in manufacturing. He has published 32 peer reviewed international journal papers and two books, and holds one patent. e-mail: kb@annauniv.edu

Dr. A. Ramesh Babu is Professor in the Department of Mechanical Engineering, PSG College of Technology, Coimbatore. He obtained his B.E. from Osmania University, M.Tech. from University of Mysore and Ph.D. from the Indian Institute of Technology, Madras. He pursued his Post-Doctoral Research at Lehrstuhl für Qualitätsmanagement und Fertigungsmesstechnik, Universität Erlangen-Nürnberg, Germany. He worked for Amada Co. Ltd., Japan (at Amada Soft India), world's leading machine tool manufacturers specilized in sheet metal cutting and bending machinery. His research interests include CAD/CAM, Artificial Intelligence in Manufacturing,

Robotics, Augmented Reality, Image processing, Industrial IoT and Product development. He has published 20 technical papers in various reputed international journals and international conferences and contributed for book chapters. e-mail: arb.mech@psgtech.ac.in

Dr. S. Udhayakumar is Assistant Professor in the Department of Mechanical Engineering, PSG College of Technology, Coimbatore. He obtained his B.E. from Bharathiar University, M.E. and Ph.D. from Anna University, Chennai. His major areas of research include manufacturing automation, mechatronics and energy harvesting. He has published more than 60 papers in reputed International and National Journals/Conferences. He has received the 'Institution of Engineers—Young Engineer' award, 'PSG Teacher of the Year' award and 'Institution of Engineers—Young Achiever' award. He has been involved in two technology transfers and has filed four patents. e-mail: suk.mech@psgtech.ac.in

Forming

A Novel Method for Identification of Mechanical Properties During Impact Forming of SS 304L Sheet

S. K. Barik, R. Ganesh Narayanan, and N. Sahoo

Abstract The present investigation focuses to utilize a shock tube facility to perform dynamic forming of a 1-mm-thick SS 304L sheet at an intermediate strain rate. The strain rate evolution is acquired experimentally by mounting a strain rosette on the specimen. During this analysis, the rate-dependent flow stress–strain properties are evaluated at the measured strain rate by the tensile test of the deformed sheet after the shock tube-based experiment. The rate-dependent material properties are identified by testing the deformed tensile sample in the universal testing machine at a crosshead speed of 1 mm/min. The tensile test data of the deformed sheet illustrates that the yield stress and the ultimate tensile stress of the material increase as compared to the results obtained from the base sheet. Moreover, the rate-dependent stress–strain data is validated with the flow stress curve obtained from the Cowper-Symonds flow stress model. Both the flow stress curves demonstrate a good correlation with a slight over prediction. The new method for determining the rate-dependent mechanical properties is reliable and can be implemented in other high strain rate forming processes.

Keywords Shock tube · Tensile test · Strain rate · Impact loading · The flow stress model

1 Introduction

Stainless steel is commonly used in automobile industries because of its good mechanical properties, higher formability and increased resistance to corrosion [1]. Several research activities confirm that during transportation application, the material is exposed to different strain rates in the range of 10^2–10^3 [2]. Further, the mechanical properties of the stainless steel are strongly dependent on the loading rates [3]. Thus, it is important to characterize the deformation behaviour of the stainless steel sheets at different strain rates.

S. K. Barik (✉) · R. G. Narayanan · N. Sahoo
Department of Mechanical Engineering, Indian Institute of Technology Guwahati, Assam 781039, India
e-mail: saibal@iitg.ac.in

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Generally, the quasi-static tensile test and the split Hopkinson pressure bar (SHPB) test have been used in most of the investigations to describe the material's mechanical properties at low and high strain rates, respectively. It is difficult to attain intermediate strain rates with the normal test set-up. In the SHPB test set-up, the lowest strain rate of 600 s^{-1} is reported [4]. Recently, Grolleau et al. [5] modified the SHPB into a dynamic bulge testing device and performed a dynamic material test at intermediate strain rates. Further, Ramezani and Ripin [6] conclude that this approach is limited due to strain inhomogeneity because of the increased complexity in the setup.

In the last two decades, high energy rate forming devices have been widely used to obtain the bi-axial forming behaviour of the materials over a wide range of strain rates [7–9]. The shock tube facility has recently been used on a lab scale to study the dynamic response of thin sheets [10–13]. It is generally used to establish an impulsive loading environment for a small duration. The uniformity in loading and ease of handling make the shock tube facility advantageous to utilize as a dynamic testing device. Different levels of shock loading provide different loading conditions that help to study the dynamic mechanical behaviour of the material. Stoffel [10] used a shock tube during the investigation of the dynamic behaviour of the sheet metals. Justusson et al. [11] utilized the shock tube during the bi-axial forming of the aluminium sheets and validated it with the FE model results. Barik et al. [12] investigated the forming behaviour of aluminium alloy sheets using a shock tube and validated the forming outputs to the results obtained from FE simulation. They obtained the rate-dependent material parameters by the tensile test of the sheet deformed using the shock tube and incorporated during FE simulation. The predicted results matched quite well with the experimental outputs.

The tensile test of the deformed sheet is new and reliable to determine the rate-dependent mechanical properties. There has never been an attempt to use the shock tube to acquire the mechanical properties of the SS 304L sheet in the intermediate strain rate range. As a result, the shock tube is used in this study to perform impact loading on SS 304L sheet. During the experiment, a strain rosette is fixed on the sheet to capture the strain evolution during the deformation. The stress–strain data under that strain rate is obtained by the tensile test of the sample cut from the sheet deformed using a shock tube. Further, the tensile test data is validated with the flow stress curve obtained from the Cowper-Symonds model.

2 Experimental Methodology

2.1 Mechanical Properties of the Material

In the current investigation, SS 304L sheet of 1 mm thickness having chemical composition Cr %: 18.20, Ni %: 8.01, Mn %: 1.00, Si %: 0.36, P %: 0.031, C %: 0.056, S %: 0.002 is considered for the analysis. The tensile properties of the base sheet are characterized along 0°, 45° and 90° to the rolling direction in a universal testing

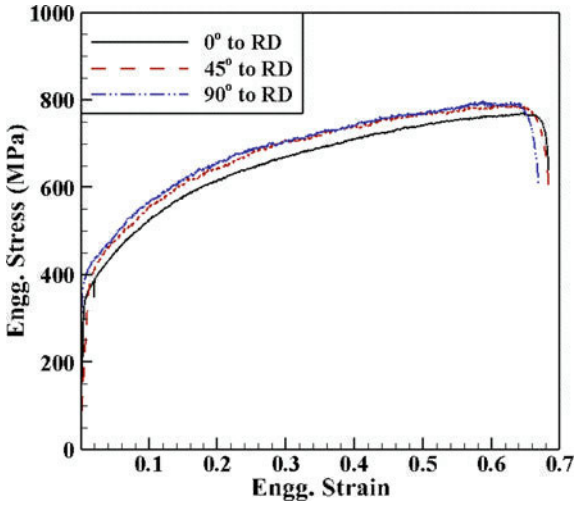

Fig. 1 Engineering stress and strain curves for SS 304L base sheet

Table 1 Mechanical properties of the base sheet

Material	RD	σ_{ys} (MPa)	σ_u (MPa)	K (MPa)	n	e_u (%)	e_t (%)	r
SS 304L	0°	341 ± 2	746 ± 3	1484 ± 3	0.39	64.8 ± 3.4	68.5 ± 3.2	1.02
	45°	384 ± 3	790 ± 3	1562 ± 3	0.38	61.7 ± 4.8	68.5 ± 4.8	0.99
	90°	378 ± 3	798 ± 4	1498 ± 4	0.36	58.7 ± 3.2	65.4 ± 4.1	0.98

Gauge length: 25 mm; σ_{ys}: Yield stress; σ_u: Ultimate tensile stress; K: Strength coefficient; n: Strain hardening coefficient; r: Plastic strain ratio

machine (UTM) at 1 mm/min crosshead speed as per ASTM-E8 and represented in Fig. 1. ASTM-E517 is used to identify the plastic strain ratios (r) of the sheets. Table 1 depicts the mechanical properties of the base sheet.

2.2 Shock Tube Experiment

In the present investigation, a shock tube facility as illustrated in Fig. 2 has been utilized to perform dynamic loading on sheets. The details about the experimental facility can be found elsewhere [12, 13]. The pressure difference created between the driver and the driven section of the shock tube helps during the sudden rupture of the diaphragm. It generates a shock wave, which propagates at a high velocity towards the end of the shock tube. After imparting the end of the shock tube, the shock wave reflects and generates higher pressure than the incident shock wave. The high-pressure field zone is created inside the shock tube for a short period. This impulsive environment can be used to deform a sheet in bi-axial mode at different strain rates by placing it at the end of the shock tube.

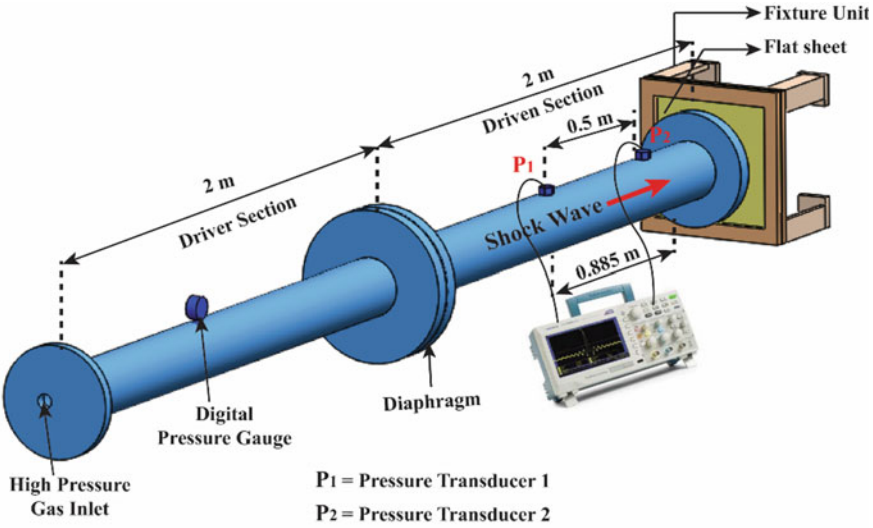

Fig. 2 Illustration of the shock tube experimental facility

During the shock tube experiment, 31.02 ± 0.68 bar of bursting pressure is attained. The detailed instrumentation in the shock tube is mentioned in the previous work of Barik et al. [12]. The pressure–time signals acquired from the pressure transducers positioned in the driven part of the shock tube are illustrated in Fig. 3. The experimentally obtained Mach number (M_s), incident pressure and reflected pressure is 1.94 ± 0.02, 4.32 ± 0.82 bar and 19.02 ± 0.55 bar, respectively.

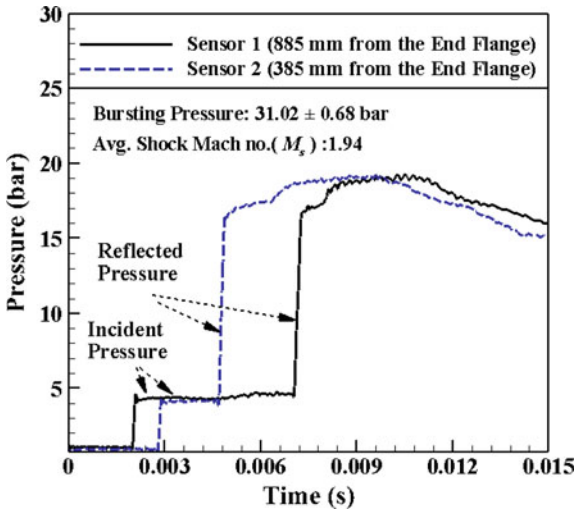

Fig. 3 Pressure–time history obtained from the experiment

It is observed that SS 304L becomes rate-dependent when the rate of loading reaches a threshold limit [3]. SHPB has been used in many studies to characterize the mechanical properties of SS 304L sheets at high strain rates [14]. During the high strain rate forming, Cowper-Symonds (CS) flow stress model is also used, which takes into account the rate-dependent effect during material forming. The Cowper-Symonds (CS) flow stress model is given by

$$\sigma = \sigma_{qs}\left(1 + \left(\frac{\dot{\bar{\varepsilon}}}{C_m}\right)^{\frac{1}{P}}\right) \tag{1}$$

where σ_{qs} is the quasi-static constitutive behaviour of the sheet, σ is the dynamic flow stress, $\dot{\bar{\varepsilon}}$ is the effective strain rate, C_m and P are the strain rate factors that scale the material's initial quasi-static stress to represent the dynamic mechanical behaviour. In this study, the dynamic mechanical properties of the sheet are identified by the tensile test of the sheet deformed using a shock tube. The tensile sample is cut from the deformed sheet's mid location along 0° to the RD (Fig. 4), and then it is tested in UTM at 1 mm/min crosshead speed.

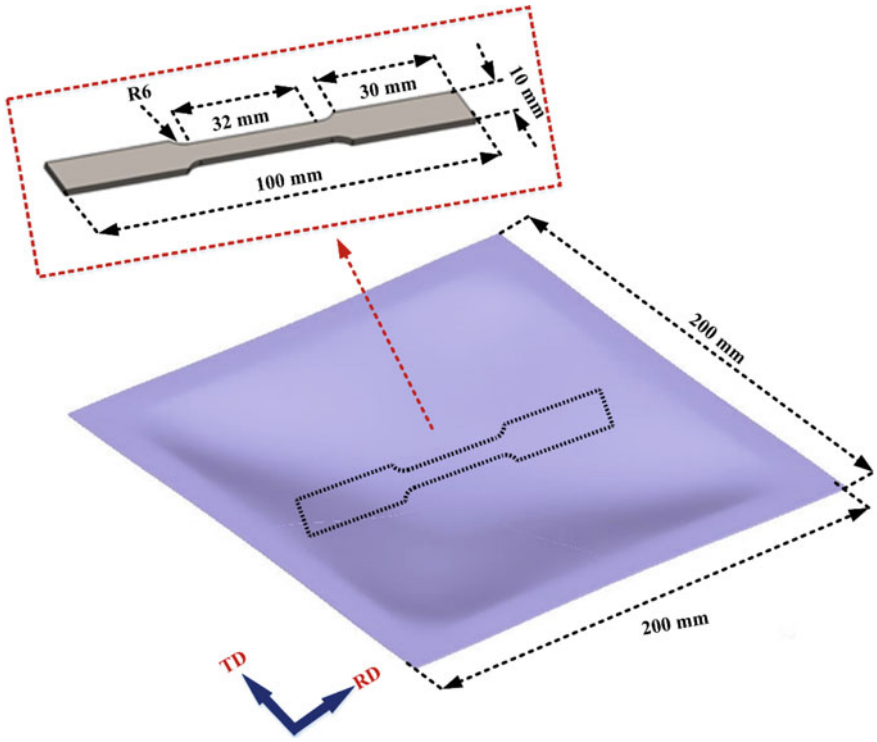

Fig. 4 Tensile test sample obtained from the sheet deformed using the shock tube

2.3 Strain Rate Evolution Measurement

During this study, the strain rosette is used to measure the strain rate evolution during the shock wave-based deformation analysis. Generally, in many high strain rate forming experiments, a high-speed 3D digital image correlation (DIC) system has been utilized to determine the transient variation of the forming parameters [11]. However, it is witnessed that the strain gauge can also be used to measure the strain rate and the results have a good agreement with the results obtained from DIC [15]. Thus, a strain rosette is attached at the centre of the sheet (Fig. 5) to quantify the in-plane strain as well as strain rate along 0°, 45° and 90° to the RD. Details about the strain rosette can be found elsewhere [12]. The strain rosette is connected by the Wheatstone quarter bridge circuit (Fig. 5). When the pressure developed by the shock wave generates impact loading on the sheet, the strain gauge's resistance changes and it causes instability in the Wheatstone bridge.

The output voltage from the Wheatstone bridge circuit is obtained in millivolts. It is difficult to predict the strain outputs from the measured signal. Thus, the voltage outputs are amplified in INA 128, DC voltage amplifier and then captured in an oscilloscope. The voltage outputs can be converted into strain rate signals. The strain rate signals obtained from the strain rosette along 0°, 45° and 90° to the rolling direction are represented in Fig. 6. The effective strain rate ($\dot{\bar{\varepsilon}}$) can be obtained using Hill's 1948 yield criterion [16], which takes into account the peak strain rate along 0° and 90° during the calculation. Hill's 1948 yield criterion is expressed as

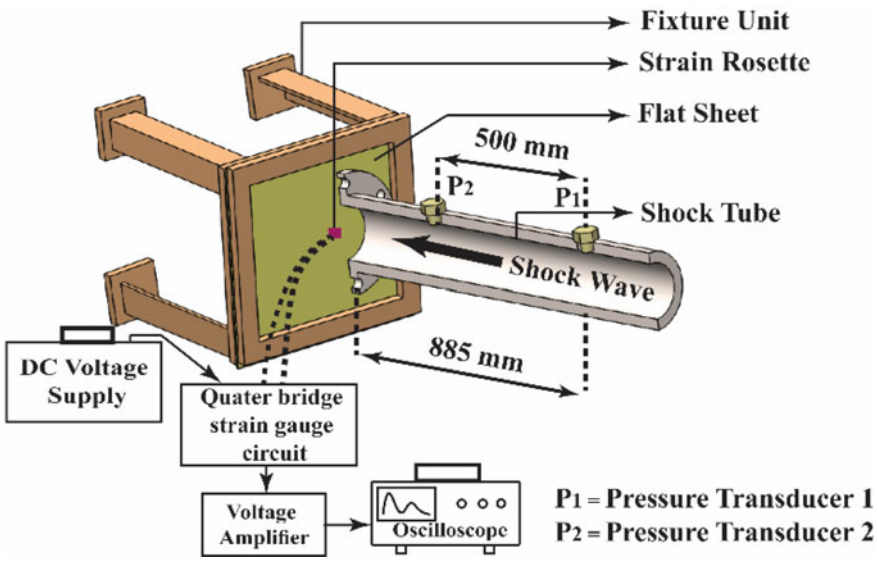

Fig. 5 Strain gauge mounted on the specimen during the experiment

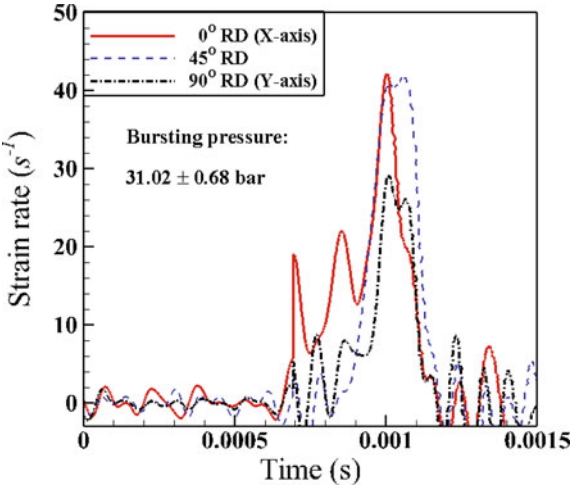

Fig. 6 Strain rate developed during the shock tube-based forming of flat sheet

$$\dot{\bar{\varepsilon}}^2 = \frac{(G+H)}{(FG+FH+GH)^2} \left[F^2(G+H)\dot{\varepsilon}_1^2 + G^2(F+H)\dot{\varepsilon}_2^2 + H^2(F+G)\dot{\varepsilon}_3^2\right] \quad (2)$$

where $\dot{\bar{\varepsilon}}$ is the effective strain rate, $\dot{\varepsilon}_1$ is the strain rate along 0° to RD, $\dot{\varepsilon}_2$ is the strain rate along 90,° and $\dot{\varepsilon}_3$ is the strain rate along the thickness direction. Identification of $\dot{\varepsilon}_3$ is difficult, and it is neglected during $\dot{\bar{\varepsilon}}$ calculation. Hill's constant (F, G and H) can be correlated to the plastic anisotropy parameters (r_0 and r_{90}) by the relations $F = r_0$; $G = r_{90}$; $H = r_0 r_{90}$ [16]. The values of r_0 and r_{90} are identified experimentally as mentioned in Table 1. The effective strain rate ($\dot{\bar{\varepsilon}}$) calculated experimentally is 34.26 s^{-1}.

3 Results and Discussion

3.1 Determination of Rate-Dependent Mechanical Properties

The tensile test results obtained from the deformed sheet are compared to the base sheet (Fig. 7). Table 2 depicts the mechanical properties of the deformed sheet. It is observed that both the yield stress and the ultimate tensile stress of the material rise as compared to the base sheet. The material's strength coefficient (K) increases significantly as a result of the action of strain hardening. However, after the deformation, the strain hardening coefficient (n) does not vary as much.

Furthermore, the identified rate-dependent tensile properties are validated with the dynamic stress–strain curve obtained from the CS model. During the calculation, the quasi-static flow stress data (σ_{qs}) obtained from the base sheet along 0° to RD

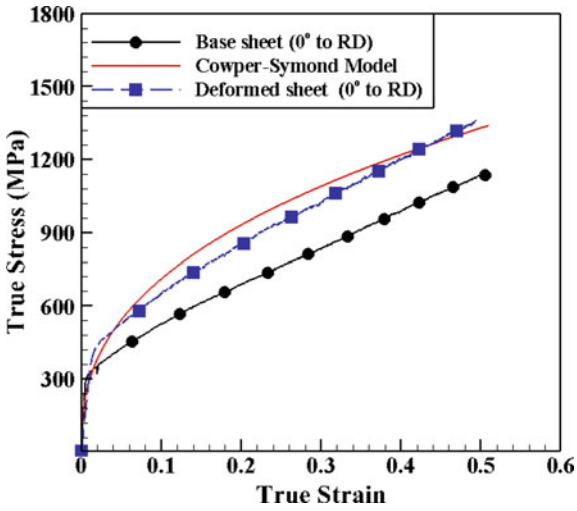

Fig. 7 Comparison of the stress–strain curves obtained from the deformed sheet to the Cowper-Symonds model

Table 2 Comparison of tensile properties of the deformed sheet with the base sheet

Tensile properties (0° to RD)	Base sheet	Deformed sheet
σ_{ys}(MPa)	341 ± 2	386 ± 3
σ_u(MPa)	746 ± 3	828 ± 3
n	0.39	0.39
K	1484 ± 3	1730 ± 5

is considered. The values of $C_m = 17{,}772\ s^{-1}$ and $P = 3.16$ for SS 304L sheets are obtained from literature [17]. The effective strain rate ($\dot{\bar{\varepsilon}}$) of deformation is calculated experimentally as $34.26\ s^{-1}$ (reported in Sect. 2.3). The results illustrate that rate-dependent flow stress data obtained from the CS model slightly deviated from the data obtained from the tensile test of the deformed sheet. The correlation coefficient (R) between both the flow stress curves is obtained as 0.963, which is an acceptable limit. It confirms that the approach of obtaining the dynamic mechanical properties by the tensile test of the deformed sheets is reliable and can be used to predict the dynamic forming behaviour of the sheet. A similar approach can be implemented in another rate-dependent forming processes to identify the rate-dependent mechanical properties.

4 Conclusions

The present work aims to identify the rate-dependent mechanical properties of a 1-mm-thick SS 304L sheet. For this analysis, a tensile sample is cut from the mid

location of the sheet deformed using the shock tube and tested in UTM. The rate-dependent flow stress–strain data is also validated with the Cowper-Symonds flow stress model. The following conclusions are drawn from the results.

i. The tensile test data obtained from the deformed sheet has a reasonable correlation with the Cowper-Symonds model. Thus, the same procedure can be followed during the identification of mechanical properties in other high strain rate forming processes.
ii. The yield strength and ultimate tensile strength obtained from the deformed sheet are higher than the base sheet. The strength coefficient (K) of the material raises significantly after deformation because of the strain hardening phenomenon. However, there is less variation in the strain hardening coefficient.
iii. During the shock tube-based experiment, the strain rosette can able to acquire the strain rate of deformation. The peak strain rate confirms the rate of loading during the experiment.

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