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Metal forming beyond shaping: Predicting and setting product properties

A.E. Tekkaya (1)[a,*], J.M. Allwood (1)[b], P.F. Bariani (1)[c], S. Bruschi (2)[c], J. Cao (1)[d], S. Gramlich[e], P. Groche (1)[f], G. Hirt (2)[g], T. Ishikawa (2)[h], C. Löbbe[a], J. Lueg-Althoff[a], M. Merklein (2)[i], W.Z. Misiolek[j], M. Pietrzyk (1)[k], R. Shivpuri (1)[l], J. Yanagimoto (1)[m]

[a] Institut für Umformtechnik und Leichtbau, Technische Universität Dortmund, Dortmund, Germany
[b] Department of Engineering, University of Cambridge, Cambridge, United Kingdom
[c] Department of Industrial Engineering, University of Padova, Padova, Italy
[d] Mechanical Engineering Department, Northwestern University, Chicago, IL, USA
[e] Institut für Produktentwicklung und Maschinenelemente, Technische Universität Darmstadt, Darmstadt, Germany
[f] Institut für Produktionstechnik und Umformmaschinen, Technische Universität Darmstadt, Darmstadt, Germany
[g] Institut für Bildsame Formgebung, RWTH Aachen, Aachen, Germany
[h] Metal Forming and Processing Laboratory, Nagoya University, Nagoya, Japan
[i] Institute of Manufacturing Technology, Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany
[j] Institute for Metal Forming, Lehigh University, Bethlehem, PA, USA
[k] Department of Applied Computer Science and Modelling, AGH University of Science and Technology, Krakow, Poland
[l] Department of Industrial Engineering, The Ohio State University, Columbus, OH, USA
[m] Institute of Industrial Science, The University of Tokyo, Tokyo, Japan

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ABSTRACT

Metal forming is not only shaping the form of a product, it is also influencing its mechanical and physical properties over its entire volume. Advanced analysis methods recently enable accurate prediction of these properties and allow for setting these properties deterministically during the forming process. Effective measurement methods ensure the setting of these predicted properties. Several real examples demonstrate the impressive achievements and indicate the necessity of a paradigm change in designing products by including manufacturing-induced effects in the initial dimensioning. This paradigm change will lead to lightweight components and serve environmentally benign designs.

1. Introduction

Most of the energy embedded in a product is hidden in the primary energy of fabricating the material itself [7]. In this sense, metal forming is one of the most environmentally benign class of manufacturing processes due to its high material utilization [91]. Metal forming as 'Net-Shape Manufacturing Process' has been largely recognized as a process that shapes the final geometry of a product by plastic deformation. The fact that plastic deformation alters the mechanical properties of the product over its volume is not yet widely appreciated in design of products [24]. In the conventional cycle of product design, the designer develops the product geometry on the basis of specifications of loading conditions and material properties (material ability) of virgin materials (Fig. 1a). Due to uncertainties, a 'safety factor' greater than 1 is applied to the nominal load, resulting in an increase of dimensions in the final design, and embodying more energy than necessary. Generally, the manufacturing process is not considered in specifying the material ability in the design process although it can substantially alter this ability.

Back in 2002, Zeng et al. [234] demonstrated the described importance of including information about manufacturing-induced properties in a crash simulation. The simulation result in Fig. 2a is based on nominal thickness and material properties of virgin sheet metals and showed that severe buckling occurred in the middle of the supporting beam. Fig. 2b used the tube thickness obtained after hydro-forming and manufacturing-induced material properties in the crash simulation. The simulation predicted that buckling did not occur in the middle section, instead it occurred at the corner section. This is due to the fact that over 20%

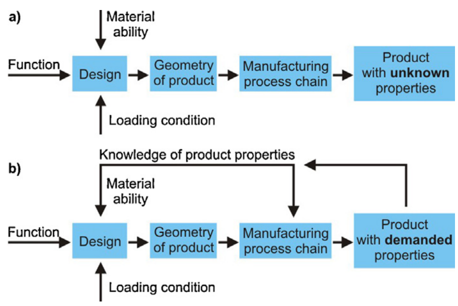

Fig. 1. (a) Conventional product design and manufacturing. (b) New approach in designing and manufacturing products,[24].

* Corresponding author. Phone: +49 231 7552681; fax: +49 231 7552489.
E-mail address: erman.tekkaya@iul.tu-dortmund.de (A.E. Tekkaya).

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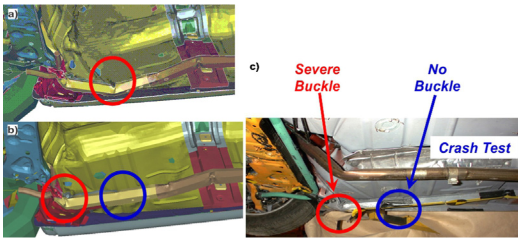

Fig. 2. Crash simulation and test [234]: (a) simulation with nominal properties. (b) Simulation with manufacturing properties. (c) Experiment.

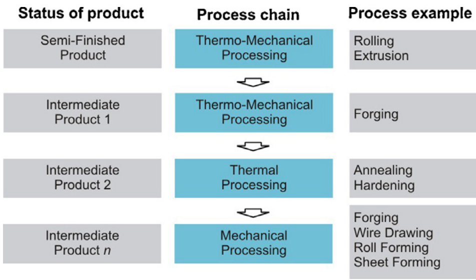

Fig. 3. Chain of product manufacturing by thermal, thermo-mechanical, and mechanical processing.

thinning existed at the corner during the hydro-forming process. Fig. 2c shows a photo of the real crash test, which confirmed the results of the simulation which used information about the manufacturing-induced properties. Without knowing the influence of the manufacturing process on the material properties and thickness distribution, one would arbitrarily choose a high-value 'safety factor' to uniformly increase the thickness across the entire tube in order to be on the safe side.

In order to close the gap between the product design and the manufacturing process, the specification of the material ability and after-forming dimensions have to be incorporated in the manufacturing process, as illustrated in Fig. 1b.

Given the ability of metal forming in changing mechanical properties over the entire volume of the product, a great opportunity lies in the design process if one can take a holistic approach seamlessly integrating the design of forming processes and the design of a product. This requires, on the one hand, the prediction of these properties and, on the other hand, the control of these properties in the manufacturing process. The knowledge of local material properties such as strength, formability, damage, residual stresses, texture, and microstructure can be transferred to the early stages of manufacturing and tailor-made products can be manufactured. This approach delivers a high potential to provide the sound technological basis for selecting the realistic safety factor and, hence, lightweighting the product [213].

Metal forming consists of a process chain that primarily includes thermal and mechanical processing. Table 1 summarizes the mechanical, surface, and physical product properties that can be changed by these two types of processes.

Table 1
Product properties changed during forming by thermal and mechanical processes.

Mechanical properties	Surface properties
• Mechanical resistance	• Surface topography
• Impact resistance	• Wear resistance
• Creep resistance	• Corrosion resistance
• Fatigue resistance	• Hydrophobic resistance
• Formability	Physical properties
• Toughness	• Electrical properties
• Residual stresses	• Magnetic properties
• Anisotropy	• Optical properties
• Accumulated damage	

Thermal processing consists of heat treatment processes. These processes are either applied before (annealing) or after the metal forming process (hardening or annealing). Sometimes the heat treatment is conducted together with the forming process: thermo-mechanical processing is basically used for *semi-finished products* (by *primary forming processes*), such as in rolling, extrusion, but also in *part* forming (*secondary forming processes*), such as in forging and hot stamping. Mechanical, surface, and physical product properties are finally set by cold forming processes, such as impact forging, wire drawing, roll forming, and sheet forming (Fig. 3). Machining and surface treatment processes occasionally follow the final metal forming process but basically influence only the near-surface properties.

The objective of this paper is to reveal the potential of predicting and setting the mechanical and physical properties in metal formed products. Thermo-mechanical and metal forming processes are in the focus and mere thermal processing is not covered by this paper. Several other properties, like Young's modulus and density, that are not listed in Table 1 can be changed by plastic forming and heat treatment. However, these parameters are out of the scope of this paper.

The starting point of this paper is a comprehensive knowledge about the metallurgical basis of material properties (Section 2). With the knowledge about the influencing mechanisms on the micro-scale, the prediction of macro-scale mechanical product properties during manufacturing processes becomes possible (Section 3). The achievement of the desired properties needs to be measured during the processes, requiring special monitoring techniques (Section 4). Several examples of forming processes and process chains**,** where the prediction and control of mechanical product properties during the forming process are already successfully performed, are reviewed (Section 5). Next, a paradigm change in the design process of products utilizing the manufacturing properties is proposed (Section 6). The paper is concluded by providing conclusions and an outlook.

2. Metallurgical basis of material properties

The entire casting and deformation history has a strong influence on the mechanical and physical properties of the product achieved during forming as well as during the subsequent heat treatment operations. In general, the effects of the chemical composition of the material and mechanical process parameters on the product microstructure and final mechanical properties are very complex, but they can be simplified and conceptually illustrated as in Fig. 4.

This multistep process sequence of converting a cast structure into a wrought one is often known in literature as thermo-mechanical treatment. This section aims at giving a basic review of the fundamental metallurgical phenomena affecting the mechanical properties of products formed under mechanical/thermo-mechanical processing conditions [98].

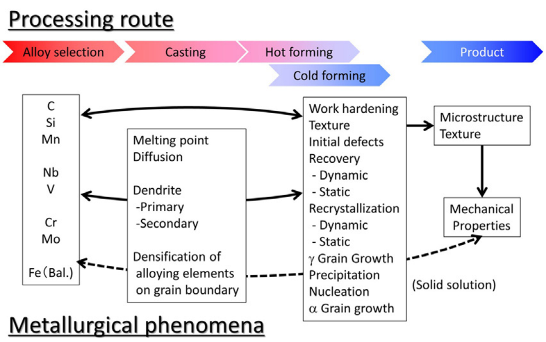

Fig. 4. Influence of the alloying elements as well as casting and forming parameters on the microstructure and properties of a steel product.

2.1. Chemical composition

The chemical composition is a primary factor determining the physical properties of structural metals. On the basis of the chemical composition of the alloy and phase diagram characteristics, the