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Granular media-based tube press hardening

H. Chen*, A. Güner, N. Ben Khalifa, A.E. Tekkaya

Institute of Forming Technology and Lightweight Construction, TU Dortmund University, Baroper Str. 303, D-44227 Dortmund, Germany

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ABSTRACT

Press hardening process can benefit the formability of 22MnB5 in high temperature and high strength as a final product. It is widely used for weight reduction of car body without sacrifice of its crashworthiness. Nevertheless, not only strength but also stiffness is important for some vehicle components. Press hardening of tube using granular media is the possible technology to realize the press hardening process for tubular components, which have much higher stiffness as compared to sheet metal parts. To choose appropriate granular media, instrumented die compaction test and high pressure direct shear test were established to characterize the material property of granular material. A hot tensile test was used to determine the formability of 22MnB5 tube material. Interaction between granular media and tube material including friction coefficient and heat transfer coefficient was measured by shear test and heat transfer test. Based on these works, a thermal–mechanical coupled finite element model was used to analyses the process. In validation experiment, a T-shape specimen was formed and quenched. Process parameters such as loading force, interfacial friction, and tube geometry were also investigated via numerical and experimental research for a better understanding of the process. The interfacial friction between granular media and tube showed significant effects to the forming result. These effects were represented by process parameters such as friction coefficient, tube length, types of granular media. A multi-type granular media brought out higher pressure transfer effect and also reduced interfacial friction force, which showed better formability.

1. Introduction

The need to respond to the threat of climate change potentially leads to new developments in metal forming. It brings forward more and more challenges like reducing vehicle weight as well as improving the safety performance for manufacturing of auto parts and components (Allwood, 2011). Press hardening of boron micro-alloyed steel sheet 22MnB5 is a well-established manufacturing process for the production of ultra-high-strength-parts, which are used in modern car bodies, in order to fulfill the increasing requirements on crashworthiness and lightweight design (Karbasian and Tekkaya, 2010).

Boron micro-alloyed steels are designed to be heat treated and then quenched during the press hardening process. This technology takes the advantages of formability in hot state and high strength as a final product. The proportion of hot-formed parts in car body raised form 2% in 2000 to between 10 and 20% by weight (Banik et al., 2013). With the application of press hardening process, vehicle components can be produced with thinner blank, which brings a weight saving of up to 35% compared to conventional cold-formed parts, without sacrifice of strength. Nowadays press hardening has become the standard technique in the automotive industry for the production of the B-pillar.

This advanced technology stimulated many research activities. Merklein and Lechler (2006) used Gleeble machine to characterize the flow behavior of 22MnB5 under the temperature of 500–900 °C simulating the press hardening condition. Turetta et al. (2006) also investigated the formability of press hardening steel with established hot tensile test and Nakajima test. Instead of tensile test, Hochholdinger (2012) used upsetting test to obtain the flow curve. Merklein et al. (2008) established setups to determine the heat transfer coefficient and friction coefficient between press hardening steel and tool under different loading conditions. For finite element (FE) simulation, Bergman and Oldenburg (2004) developed a thick shell for thermal–mechanical coupled simulation. Åkerström (2006) developed thermal–mechanical material models for numerical simulation. Olsson (2009) implemented solid phase transformation material model into LS-DYNA for the coupling simulation among thermal field, mechanical field and microstructure field.

However, not only strength but also stiffness is important for some of the vehicle components, such as chassis. To enhance the

* Corresponding author. Tel.: +49 231 755 8449; fax: +49 231 755 2489.
E-mail address: Hui.Chen@iul.tu-dortmund.de (H. Chen).

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stiffness, components like sub frame, crash box, axle components are designed with hollow profile (Koç and Altan, 2001). Press hardening of sheet metal component is state of the art, but media-based tube hot forming for complex parts like tubes or profiles is limited by the used medium.

Media-based forming is a specialized type of die forming that uses a high pressure media to press material into a die. Oil and water are the commonly used liquid in media-based forming process, which is the conventional hydroforming. Conventional sheet metal hydroforming processes using oils as forming media are applicable up to 300 °C (Vollertsen, 2001), while the recrystallization temperature of aluminum alloy and magnesium alloy is below 300 °C. Neugebauer et al. (2006) has used heated oil for warm forming of aluminum and magnesium alloys sheet which had a low cold formability. In these processes, both tools and working media are heated. Nevertheless, this temperature is not sufficient for combining press hardening and tube hydroforming (Toros et al., 2008).

Alternative forming media must allow for heating to 1000 °C and for rapid quenching of the formed component without phase transformations or decomposition (Vadillo et al., 2007). Dykstra et al. (1999) used gaseous working media to realize the higher forming temperature. Gas offers the chance to provide higher temperatures due to its high temperature resistance in contrast to most fluids. A free bulging of domes using gas as forming media reached the temperature of 360 °C and increased formability and minimized forming times are achieved by Rauscher et al. (2005). Another application of using gas media is performed for tube hydroforming by Pfaffmann et al. (2000). Depending on the material to be formed, the forming temperature ranges from 400 °C to 1000 °C (Amborn et al., 2006). To characterize the tube material at high temperature, Elsenheimer and Groche (2009) has established hot tube bulging test under the temperature range of 480–575 °C for aluminum alloy AlMgSi0.5. Forming temperatures up to 1000 °C were reached during tube hot hydroforming using gaseous media, proving the compatibility of tube hydroforming and press hardening (Neugebauer and Schieck, 2010). The value of the heat transfer from the workpiece to the tool active element is huge enough to realize a nearly complete martensite structure in the main part areas. However, parts in contact with the die only at the end of the forming process do not exhibit a complete martensitic structure due to the insufficient heat transfer, leading to inhomogeneous product properties (Alexander et al., 2013). The gaseous media has a significant influence on the thermodynamic of the forming process (Drossel et al., 2014). Because of the high compressibility of gases, the technological demanding feeding of the gas and the high blank forces necessary to seal the tube and to avoid leakage (Pierschel et al., 2013).

Another high temperature resistant media is granular materials. Using granular material as forming media can allow high temperature and reduce the risk of leakage. Mennecart et al. (2011) realized press hardening process of tubular components using granular material as forming media under temperature of 1000 °C. Since the granular material such as quartz sand or ceramic beads have much small heat transfer coefficient as compared to steel, the cooling of 22MnB5 tube is mainly due to the heat transfer between tube and tools, which is enough for the complete martensitic transformation (Tekkaya et al., 2012). The advantage of the low heat transfer ability of granular media also prevents the cooling of the tube before complete forming. Granular media do not obey the mechanics of continuous liquids. Grüner and Merklein (2010) indicate that the finite size of the constituent particles influences the degree of forming and the curvature of formed shapes. Grüner and Merklein (2011) also investigated the pressure distribution inside the granular media, which is not hydrostatic and depends on the direction that the media is pressurized. Contact mechanics and friction among the particles as well as between the particles and the forming part influence the deformation of the granular media and reduce the blank draw in.

In the large scale of the working media form, the granular material in this granular media-based tube press hardening process can be studied using the principles of continuum mechanics at a macroscopic level. The phenomenological models such as Drucker–Prager Cap (DPC) plasticity models were used for modeling the granular material (Aydin et al., 1996). It can predict compaction force with displacement, the variation of displacement with time, and relative density and stress contours in powder compaction processes (Brewin et al., 2008). Triaxial test is the standard and most effective method to characterize granular material (Pavier and Doremus, 1999). However, triaxial compression tests in geology are generally in low loading pressure. High testing pressure up to 100 MPa in granular media-based tube press hardening is needed. Chtourou et al. (2002) established an apparatus which can reach a high pressure level up to 610 MPa. An economical approach to substitute the triaxial compression test to determine the cap parameters is using instrumented die compaction test (Doelker and Massuelle, 2004). The principle of these testing methods is based on acquisition of the axial force, radial force as well as punch displacement in die compaction test. The simplest way is to use strain gages sticking on the die for measuring the radial stress (Klemm et al., 2010). The die wall is regarded as rigid so that the stress can be obtained with foil strain gage sticking to the out surface of the die. Hong et al. (2008) established a similar die with strain gage pin fixed in the hole along the radial direction of the die. Piezoelectric transducers were also used to measure the radial pressure. The piezoelectric transducers were inserted through the cylindrical die wall to extract the material parameters for the modified DPC model (Han et al., 2008). Besides the instrumented compression test, Lu (2009) used a combination of numerical simulation methods, numerical optimization methods and common material testing techniques to determine the DPC parameters on ferrous powders.

The non-hydrostatic property of granular material makes the granular media-based tube press hardening differ from conventional tube hydroforming which uses liquid or gaseous media. The principle of choosing the suitable granular media is unclear. Function of different granular material as working media also needs to be investigated. Sophisticated thermal mechanical coupled FE model is essential for process investigation.

In this work, an instrumented die compaction test and a high pressure direct shear test were designed to characterize the granular material. Interaction between granular media and press hardening tube, such as heat transfer coefficient and interfacial friction coefficient was also determined by heat transfer test and shear test. Numerical and experimental investigations of a T-shape tube press hardening process were carried out. Drucker–Prager Cap model was introduced to describe the medium for the modeling. Some experiments were implemented to evaluate the frictional behavior and mechanical properties of the granular materials. Due to the non-hydrostatic pressure distribution of the granular materials, optimizations of process procedures were considered.

2. Process steps

The procedure of granular media-based tube press hardening is illustrated in Fig. 1. The tube or profile is heated up to austenitizing temperature in the furnace. It is maintained at that temperature for 3–5 min considering its thickness for the purpose of fully austenitizing. Then it is transferred to the die in a few seconds, while the temperature decreases due to heat radiation and convection with the air. The thermally expanded tube should not contact with the die to prevent the heat loss. After docking of the punch, the hot tube is filled with granular material at room temperature. This

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