CIRP Annals - Manufacturing Technology xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

CIRP Annals - Manufacturing Technology

journal homepage: http://ees.elsevier.com/cirp/default.asp

Enhanced granular medium-based tube and hollow profile press hardening

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ARTICLE INFO

Keywords:
Metal forming
Hot stamping
Hydroforming

ABSTRACT

Active and passive control strategies of internal pressure for hot forming of tubes and hollow profiles with granular media are described. Force transmission and plastic deformation of granular medium is experimentally investigated. Friction between tube, granular medium and die, and the external stress field are shown to be essential for the process understanding. Wrinkling, thinning and insufficient forming of the tube establishes the process window for the active pressure process. By improving the punch geometry and controlling tribological conditions, the process limits are extended. Examples for the passive pressure process reveal new opportunities for hot forming of tubes and hollow profiles.

1. Introduction

Press hardeningof sheets, which combines hot forming and quenching, enables the production of components with strengths of over 1500 MPa [1]. Hot forming of boron micro-alloyed steel sheets (basically 22MnB5) is state of the art [2]. Crash-relevant components, for instance, also need high stiffness besides high strength. Hollow profiles provide high structural rigidity at compact space. For forming hollow structural parts like sub-frames or axle components, tube hydroforming is widely used [3]. High strength hollow profiles can be manufactured by combining tube hydroforming and press hardening. This requires an adequate working medium withstanding the austenitisation temperature of steel at 950 °C to 1000 °C. Gaseous fluid medium offers the potential for hot tube hydroforming, for instance of aluminium and titanium structures [4]. Hydroforming of tubes made of 1.4512 ferritic stainless steel and press hardening steel 22MnB5 have been realised using gas at temperatures of 950 °C and 1000 °C respectively [5]. A gas pressure generator has been used providing internal pressures of up to 80 MPa for tube press hardening [6]. Gas is also used as passive forming medium for press hardening of torsion beams [7]. In this application the heated tube is sealed on both sides and internal pressure is built up by compressing the tube. The critical cooling rate for martensitic transformation is achieved by applying compressed air. One disadvantage of using gaseous medium is that it only contributes to the cooling process by 15% compared to the total tool cooling [8]. The final hardness of tubes formed by gas differs locally and depends mainly on the pressure rate, the maximum pressure value, and the tool temperature [9]. Another disadvantage of using gas is its high compressibility.

An alternative working medium for high temperature applications with high-pressure conditions is granular material, such as zirconia beads or quartz sand. Ceramic beads are used for sheet hydroforming of MS1200 steel at 600 °C [10]. With granular medium, high temperatures of up to 1000 °C and high pressures of up to 100 MPa have been realised for press hardening of tubes using the granular material as active pressure medium [11] (Fig. 1a). In this study it has been shown that granular material with less compressibility, lower internal friction, and optimum particle size improves the forming pressure. The Drucker–Prager Cap (DPC) plasticity model has proven to be suitable for thermal-mechanically coupled numerical modelling of the press hardening process. However, due to the non-hydrostatic and frictional properties of granular media, the process limits are restricted. In

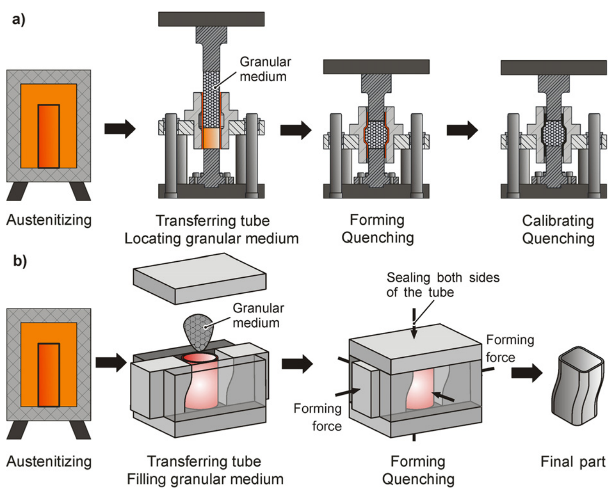

Fig. 1. Tube press hardening by granular medium: (a) active, (b) passive.

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http://dx.doi.org/10.1016/j.cirp.2016.04.010
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[12] the idea of using a granular material as passive pressure medium (Fig. 1b) has been introduced for the first time.

This paper aims at utilising the physics of granular medium during hot forming to predict the processing window of press hardening of hollow profiles with active and passive granular medium and at extending the limits of the process.

2. Granular material as forming medium

Force transmission and plastic deformation proceed fundamentally different in granular medium than in gas and liquid. Two-dimensional horizontal experiments were carried out to understand the behaviour of granular medium during the tube forming process. The process is represented by a die with rigid side walls confining the granular medium (epoxy resin discs, Vishay PS 4) through which a displacement-controlled punch is driven (Fig. 2a). Deformation of the medium can be monitored by tracking the disc positions, while internal forces are visualised by using stress-birefringence [13].

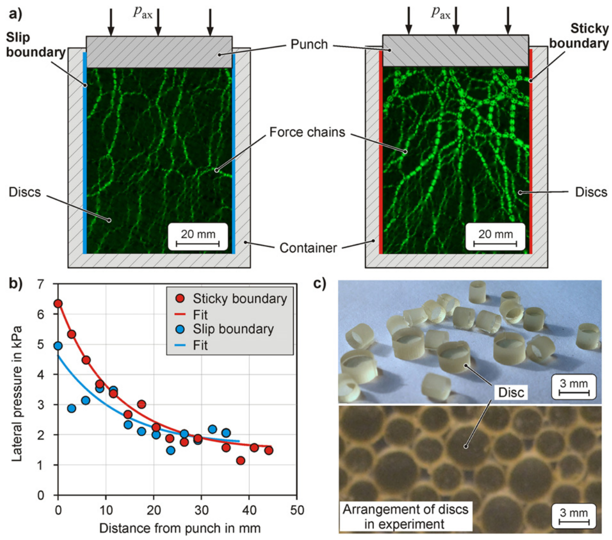

Fig. 2. Analysis of forces within granular medium in a compression test: (a) visualisation of the force transmission for two friction levels; bright areas indicate particles under stress, (b) lateral pressure with an exponential fit, (c) geometry of the utilised discs.

2.1. Force transmission in granular medium

The pressure induced by a punch pushed into the granular medium provokes a network of force chains, which involves only a fraction of all particles (Fig. 2a). When the granular medium is deformed the force chains form and break, leading to large fluctuations of the contact forces in space and time [14]. Thus, granular medium can be treated as homogeneous medium only on scales much larger than the particles.

The force chains are supported by individual particle contacts at the die walls and fade with growing distance to the punch. This behaviour induces a strong dependence of the force transmission on the friction between particles and die walls. Much stronger forces build up close to the punch when the die walls prevent slipping of the particles ('sticky boundary') than in a frictionless case ('slip boundary') for same punch displacement. These forces also fade at a stronger rate than in a die with discs free to slip at the die walls. A quantitative evaluation reveals that the decay of forces fits well with an exponential decay (Fig. 2b).

2.2. Plastic deformation of granular medium

The granular medium deforms elasto-plastically, in contrast to gas and liquid usually used in tube hydroforming. The forming of a tube intrinsically requires the plastic deformation of the granular medium used. The deformation of granular medium occurs markedly localised, comparable with the formation of shearbands. The localisation is determined by the internal friction angle and the external stress field [15]. The latter makes the plastic deformation punch shape-dependent. The force chains align locally with the punch surface and spread more isotropically with inclined punch surfaces (Fig. 3a). This translates into different deformation behaviour of the granular medium in the compression experiments, as exposed by removing one side wall (Fig. 3b). Particle displacement is localised under compression by the flat punch, while the motion of the round punch induces a displacement nearly throughout the sample for the same punch displacement.

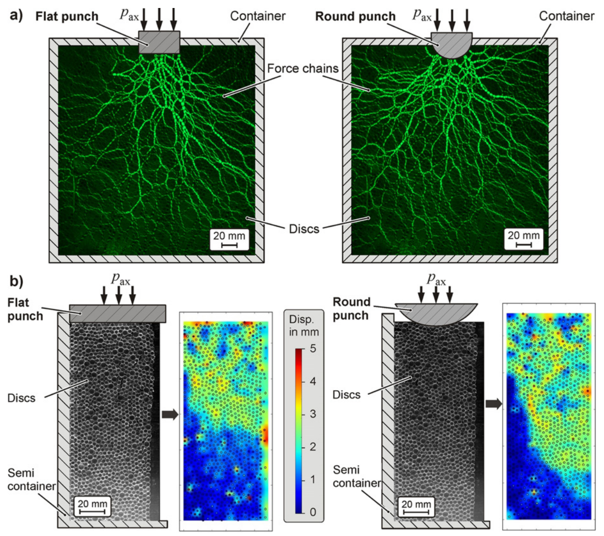

Fig. 3. Dependence of the force chain pattern (a) and plastic deformation of the granular medium (b) on the punch shape represented by the particle displacement. All figures are rotated by 90°.

In conclusion, the frictional nature of the granular medium and the localisation of plastic deformation can be expected to strongly affect the tube forming process. The friction among the particles and with the tube walls yields an exponential decay of externally applied forces within the medium, while the shape of the punch can enhance the force propagation and the plastic behaviour of the granular medium. This knowledge is used in the next section for understanding and extending the process window.

3. Enhancing active medium-based tube press hardening

To overcome the process restrictions imposed by the properties of granular media, experimental and numerical analyses based on the generic tube expansion process specified in Fig. 4 are done utilising the knowledge presented in Section 2. The numerical (finite element) model is described in [11]. Zirconia beads and quartz sand are used as forming media. Only results for zirconia beads will be presented. The expanded outer radius of the tube r_f is determined by the forming limit diagram of the workpiece material 22MnB5 given in [16] for the initial tube radius r_0 as the maximum possible deformed radius. In classical tube hydroforming external axial feeding is necessary to compensate tube thinning and to reduce the forming pressure. One inherent benefit of tube forming using granular medium is that the complicated external axial feeding can

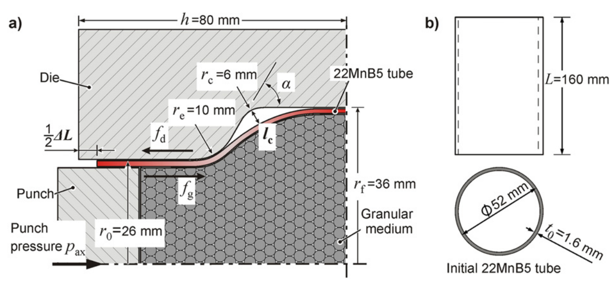

Fig. 4. (a) Generic tool design for active granular medium-based hot forming of tubes, (b) initial tube dimensions made of 22MnB5.