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The influence of process variables on the gas forming and press hardening of steel tubes

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ABSTRACT

In this paper, a study on the innovative process of hot tube metal gas forming and hot press hardening (Hot Metal Gas Press Hardening – HMG-PH) is presented. The aim is to provide new insights into the influence of process variables (gas pressure, tool temperature, tube pre-heating temperature, etc.) on the hardening phenomenon and on the quality of the produced tubular components (calibration radii, minimum wall thickness, etc.). Several experiments are described on two different kinds of steel, using a reference die geometry, specifically designed for investigating the typical critical issues of the process. The study demonstrates that the hardening phenomenon is strongly local not only because the hardness distribution is non-uniform over the final part, but especially because the hardening of different regions depends on different process parameters: in regions that need calibration, hardening is governed more by the pressure vs. time curve, i.e. by its rate and its maximum value and less by the tool temperature; in regions that rapidly go in contact to the die, hardening is governed more by the tool temperature and less by the pressure vs. time curve. Another relevant conclusion is that an optimal value of pressurization rate can be found that maximizes formability. Finally, the study proves that, on the formed tubes, obtaining small calibration radii and obtaining high values of hardness are conflicting objectives. The physical mechanisms behind these behaviours are discussed.

1. Introduction

A strong trend towards using high-strength and super-high strength materials has established in car body designs. Press-hardened parts, with a maximum tensile strength of as much as 1900 MPa, play an important role because they are structural components, critical to crash performance. The main characteristic of the hot forming process of press-hardening is a combination of part shaping with a heat treatment taking place during the actual forming process. The benefits of press-hardening are evident both in the production phase (lower press forces, improved part shape accuracy and fewer forming steps due to higher true strain) and in the utilization phase (improved crash performance due to adapted component properties and lower component mass at the same level of stiffness). Using tubes and profiles offers further substantial potential for savings in terms of lightweight structural components. Nevertheless, the process of hot press hardening for steel tubes, formed with internal pressure, is not yet widespread nor industrially established and more scientific and practical knowledge is strongly needed about this specific topic. As follows, a state of the art review is proposed about the process of forming a non-superplastic metal tube with internal pressure at elevated temperatures.

This topic has been scientifically investigated in the last 15 years, since when the Hot Metal Gas Forming (HMGF) research consortium was founded in the USA, with the aim of developing the process and proving its production readiness for widespread use in the automotive and aerospace industries (Dykstra, 2001).

Since then, the scientific literature on hot internal forming of tubular steel, aluminium, titanium and magnesium alloys has focused on several lines of study: (1) the development of new tools and equipment and/or demonstration of case studies; (2) studies related to metallurgy and materials properties of incoming materials and formed products. Another important category of studies concerns process modelling, aimed at developing process design guidelines and studying the influence of process parameters. Process modelling is generally based on either (3) experimentally validated FEM simulations or (4) completely experimental studies.

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1.1. Development of new tools and equipment, demonstration of case studies

As a clear indication that the process is still not mature and not industrially established, a large number of available papers focus, consistently over the years, on the proposal of new methods or systems or on the description of specific case studies. As an example, Zarazua et al. (2007) describe a prototype HMGF system for steel tubes; Yi et al. (2008) propose a new equipment for combined heating – comprised of an induction coil plus a heating element – applied to the warm hydroforming of aluminium alloy tubes; Maeno et al. (2009) propose a machine for hot gas bulging process of aluminium alloys using resistance heating; Hwang et al. (2010) propose a machine for tube hydroforming of magnesium alloys at elevated temperatures; Sun and Smith (2010) propose a novel Closed-Volume Thermally Activated (CVTA) Tube Hydroforming method, obtained by conducting a high level of heat through the walls of a thick-walled, metallic, water-containing closed tube. Neugebauer et al. (2011) describe their tube press hardening method, developed for forming high strength steels. Recently, Maeno et al. (2014) propose a new gas forming process of ultra-high strength steel hollow parts using air filled into sealed tubes and resistance heating, developed in order to omit the subsequent heat treatment.

Case studies have been described by Keigler et al. (2005), where the prototyping of an aluminium tube made by temperature controlled hydroforming process is shown. In Schieck et al. (2010) magnesium wrought alloys and high-strength steels are used to demonstrate solutions and potentials for implementing tempered forming processes based on active media. Kenichiro Mori (2012) presents the hot stamping of a V-shaped steel tube using resistance heating.

1.2. Metallurgy and materials properties of incoming materials and formed products

Following another typical research line, several authors focus their attention on material-related issues. As an example, Yuan et al. (2006) present the results of hydro-bulging test carried out at elevated temperature on 5A02 aluminium tubes; Liu and Wu (2007) investigate by Electron Backscattered Diffraction (EBSD) and Electron Microscopy an AZ31 magnesium alloy tube has been deformed by HMGF. Elsenheimer and Groche (2009) describe a new testing technique, capable of realizing high process temperatures and constant strain rates. He et al. (2012) present the results of free bulging test carried out at high temperatures, to evaluate the formability of AA6061 extruded tubes.

1.3. Process modelling mainly based on numerical simulations

Simulation is a key topic within the development of the HMGF technology and its variants. Vadillo et al. (2007) simulate tube bulge tests and forming processes with dies of stainless and high strength steels. Grüner and Merklein (2010) study the accuracy of the Drucker-Prager Cap material model to describe tube hot forming with a granular medium. Seo et al. (2010) deal with the numerical modelling of hot press forming process of a boron steel tube. Hwang and Wang (2010) study the effects of loading paths with different feeding speed ratios and initial tube positions on the contact area at the counter punch surface at the bulge stage, for y-shape tube hydroforming of magnesium alloys at elevated temperatures. D'Amours and Béland (2011) use LS-Dyna for modelling the warm forming of 7075 aluminium alloy tubes.

1.4. Process modelling mainly based on experimental campaigns

Not many studies are available, which thoroughly investigate the role of process parameters on an experimental basis. Nevertheless, this kind of knowledge is essential for the ultimate goal of developing reliable process design guidelines and enabling the development of the tube hot internal forming process. As one of the few examples, Liewald and Pop (2008) determine the maximum circumferential strain at different forming temperatures and strain rates of AZ31 tubes bulged in a die with square cross-section. Liu et al. (2010) also work on magnesium alloy tubes, studying the effects of temperature and axial feeding on the success of tube forming operations. Maeno et al. (2011) investigate the hot gas bulging process of an aluminium alloy tube, in order to optimize the axial feeding loading curve. Drossel et al. (2014) performed analytical and numerical calculations to study the influence of the active medium on the thermodynamics of the forming process of high strength steel tubes.

From the state of the art review an important lack of experimental data and studies clearly emerges. Comprehensive studies on the process phenomenology of hot tube metal gas forming and hot press hardening are still needed, in order to better understand the role of the most important process variables (gas pressure, tool temperature, tube pre-heating temperature, etc.) on the quality and the performance of the produced tubular components (surface hardness, calibration radii, minimum wall thickness, etc.). This paper is a contribution in filling this gap of knowledge.

2. Description of process and tool technology

To successfully integrate the heat treatment into the metal forming process based on active media it is necessary to pre-heat the incoming tube to a temperature higher than 840 °C. The thermal process guidance is closely driven by the process window for press-hardening of sheet metal components. The component parts built to date have been formed or calibrated with a maximum forming pressure of 70 MPa. A cycle time of 35 s was achieved in the experimental stage. Fig. 1 shows the detailed process of the Hot Metal Gas Press Hardening (HMG-PH). This kind of forming process is a subgroup of Hot Metal Gas Forming (HMGF).

The experiments were performed with the hydraulic press Schuler SHP 50000 (Fig. 2), which has a total press force of 50,000 kN and can transmit a force of up to 835 kN on the sealing punches. The maximum stroke of the axial cylinders is 300 mm. For our demonstrator is a closing force of 2.000 kN sufficient. The active medium nitrogen is compressed by the compressor unit Maximator® RM/800/1/VP/240/800/So (Fig. 2) up to 75 MPa and supplied to the tool without further tempering. The high pressure compressor has an accumulator with a volume of 20 l at a maximum adjustable operating pressure of 75 MPa. The required gas inlet pressure has a range from 3 MPa to 30 MPa. The filling of the compressor with nitrogen was realized by a gas cylinder battery with an operating pressure of 30 MPa. The heating of the semi-finished products were done by using a chamber oven because the temperature in the oven is here well regulated.

With the experimental tool it was possible to carry out tests both with heated and cooled tools. In addition, the experimental tool was engineered in shell design to implement a close-contoured cooling system. Furthermore, the tool was heated with standard cartridge type heaters. These heating and cooling systems not only make it possible to study the impact that tool temperature has on the press-hardening process. They also make it possible to study tailored tempering for adjusting graded properties in the component part. Furthermore, the test tool was also equipped with

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