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Press for hydrostatic extrusion with back-pressure and the properties of thus extruded materials

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ABSTRACT

A press for hydrostatic extrusion within the extrusion pressure range up to 2 GPa with back-pressure up to 0.7 GPa was designed and constructed. The press is equipped with an integrated pressure intensifier, and a control and recording system which permits recording the process parameters, such as extrusion pressure, back-pressure and its stability, time and speed of the extrusion, and enables monitoring the process on-line. The double-layer high-pressure chamber and the monobloc back-pressure chamber were analyzed using the finite element method with allowance made for the self-strain-hardening effect known as autofrettage. The maximum permissible load imposed on chambers and the resulting balance pressure established in the case of the two chambers being accidentally connected were also evaluated. Several cold extrusion processes assisted with back-pressure from 400 MPa to 700 MPa were conducted, experimenting with low or non-ductile materials, such as the ZW3 magnesium alloy, GJL250 grey cast iron, GJS500 nodular cast iron, bismuth of 99.999% purity, and molybdenum of 99.9% purity. The bulk, non-defected products with diameters ranging from 4 to 7 mm were obtained. The use of back-pressure permitted the materials to be plastically deformed during a single cold operation with the percent deformation from 36% in grey cast iron to more than 80% in Bi. Thanks to the strain-hardening due to the severe plastic deformation, the materials acquired excellent properties (YS = 392 MPa in the magnesium alloy, $\sigma_{d0.2}$ = 709 MPa in molybdenum, σ_{dM} = 1140 MPa in grey cast iron, and $\sigma_{d0.2}$ = 643 MPa in nodular cast iron) impossible to achieve by classical plastic deformation processes. The hardness of the materials was also increased adequately, and the refinement of their microstructure resulted in an increase of ductility. These advantageous results obtained by using the press indicate that hydrostatic extrusion with back-pressure has a great applicative potential.

1. Introduction

The great worldwide interest observed in new materials with specific properties stimulates progress in the techniques of their shaping by plastic deformation. Investigations to date have confirmed the capacity of the hydrostatic extrusion process (HE) to generate severe plastic deformation (SPD) in materials frequently in those which cannot be easily deformed by traditional methods such as rolling, drawing, forging, or conventional extrusion. For example, severe plastic deformation by HE resulting in significant grain refinement was applied for AA2017, CP titanium, copper, iron, aluminium and stainless steel (Pachla et al., 2006) with additionally enhanced effects when HE was combined with ECAP (Kulczyk et al., 2007). Thus, hydrostatic extrusion permits producing materials with better mechanical properties. It was presented among others by Kulczyk et al. (2006) for nickel, by Pachla et al. (2008) for titanium and recently by Kulczyk et al. (2012) for copper alloy. Analogously, after HE Garbacz et al. (2010) has shown an improvement in titanium fatigue and Oksiuta et al. (2010) in impact strengths of ODS ferritic steel. The high extrusion pressures also permit cold deforming brittle materials which show non-ductility, such as cast iron (Pachla et al., 2011) or magnesium alloys (Pachla et al., 2012a,b). Some of these materials, e.g. the so-called 'light' materials (aluminium alloys and titanium alloys), copper alloys or austenitic steel are of great significance in industry.

Hydrostatic extrusion was patented by Robertson (1893), whereas the earliest scientific experiments were conducted by Bridgman (1952) who was the first to design a pressure chamber based on the Lame equation. Extensive experiments with HE chiefly conducted by Pugh and Gunn (1963) during the next years led to the conception of back-pressure (BP). According to this conception the deformed material after its leaving the die to pass to the BP chamber, is subjected to compressive hydrostatic stresses induced by the pressurizing medium contained in the BP chamber. This permitted deforming brittle materials and those difficult to deform. The first positive results with BP applied to conventionally extruded

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bismuth, magnesium, and brass were published by Pugh and Green (1958). The first attempts at combining hydrostatic extrusion with back pressure (HE + BP) were made by Pugh and Low (1964) but they did not give spectacular results. Although, the back pressure has shown to be critical to prevent cracking in hydrostatic extrusion of Al–Cu–Si alloy (Yamada et al., 1972) in next years, investigations on the extrusion against back-pressure were not continued chiefly because of the complexity of the required equipment and its high cost.

However, the 'back-pressure' concept in metal forming started to be commonly applied to other materials and deformation processes. In cold forming of metal matrix composites a counter punch generating compressive state within the MMC during forming has been introduced (Wagener and Wolf, 1993). Other approach included fibre reinforced MMC with Al_2O_3 particles forward or backward cold extruded in AA6061 or AA6082 sleeve (Minghetti et al., 2001). Suitable counter pressure was necessary to prevent cracking of AZ31 magnesium alloy below 150 °C in conventional forward extrusion (Chandrasekaran and Yong, 2004) or during equal channel angular pressing ECAP (Xia et al., 2005). Ductility enhancement of brittle materials due to micro-cracks arrested by the external confining pressure was also discussed by Tirosh and Abraham (2007). This pressure was roughly estimated to be of the order of the material strength. The concept of counter pressure was also successfully adapted in hydromechanical deep drawing of stepped geometries leading to increased deep drawing ratio and better outer surfaces than in conventional deep drawing (Khandeparkar and Liewald, 2008).

In case of hydrostatic extrusion an alternative method to deform difficult materials became deformation at elevated temperatures. For very brittle magnesium alloys hydrostatic extrusion at temperatures between 100 and 300 °C was introduced (Bohlen et al., 2005; Swiostek et al., 2006). However, the mechanical properties of the materials fabricated by this method were not so good because of the increased activity of thermal phenomena such as recovery and recrystallization.

The paper presents a unique integrated press intended for hydrostatic extrusion with the outflow of the material into back-pressure (HE + BP) which is stabilized during the extrusion process. It also describes several HE + BP experiments with the use of this press for extruding materials which are not liable to cold plastic deformation applied by traditional methods and discusses the results obtained.

2. Construction of the press

The process of hydrostatic extrusion with back-pressure differs from classical hydrostatic extrusion in that, here, the material is forced into a sealed back-pressure chamber (BP). The back-pressure restricts the development of cracks and microcracks generated when the material is within the plastic zone of the die, or are initiated during the stress relaxation which takes place in the product after the extrusion.

Fig. 1 shows schematically the press intended for hydrostatic extrusion with back-pressure (HE + BP), designed and constructed at the Institute of High Pressure Physics, Polish Academy of Sciences, Unipress. There are three operational zones in the press, namely: (a) low-pressure zone with a pressure intensifier and a hydraulic supply unit, (b) high-pressure HE zone comprising a double-layer chamber designed to bear the maximum HE pressure of 2000 MPa, a plunger, and a sealed plug with a die, and (c) back-pressure zone BP with a single-layer chamber designed to withstand a pressure of 700 MPa, an external supply unit and an overflow valve for stabilizing the back-pressure.

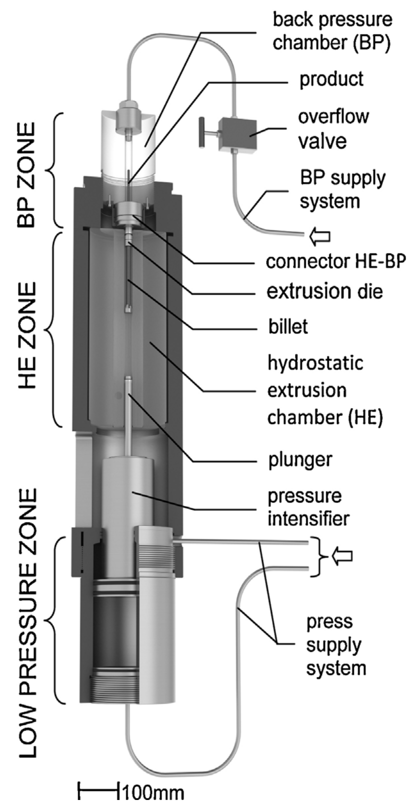

Fig. 1. Schematic representation of the press for hydrostatic extrusion with back-pressure (HE + BP), designed and constructed at Unipress.

2.1. *Pressure intensifier*

The press is equipped with a pressure intensifier connected to external hydraulic supply unit with an operating pressure of 32 MPa and efficiency of 28 L/min. The pressure intensifier is integrated with the press frame and controls the plunger movement within the HE chamber. The pressure intensifier, with the pressure multiplication ratio of 1:70, generates pressure of maximum 2000 MPa in the HE chamber and governs the plunger movements at a speed of max 12 mm/s.

2.2. *High-pressure (HE) zone – HE chamber and plunger*

The basic parameters of the HE chamber are given in Table 1. The double-layer HE chamber with the operating pressure of max. 2000 MPa was designed based on the Lame equation derived for thick-walled cylinders presented in Timoshenko (1930). The chamber layer was made of 45 HNMFA steel which has a high Young modulus within a wide hardness and strength range and is characterized by the susceptibility to through hardening in large volumes. The plunger with the length-to-diameter ratio $L/d = 9.52$ was made of high-speed S600 steel with high compressive strength and good resistance to buckling (high rigidity).

Table 1
Parameters of the hydrostatic extrusion chamber.

Maximum extrusion pressure	2000 MPa
Chamber diameter	22 mm
Chamber length	500 mm
Maximum plunger linear velocity	12 mm/s
Maximum billet diameter	18 mm
Maximum billet length	325 mm