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# Friction-spinning—Grain structure modification and the impact on stress/strain behaviour

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ABSTRACT

The friction-spinning process is an innovative incremental forming technique that enables high degree forming operations in the field of tube and sheet metal forming. The integration of friction-sub-processes from friction welding in a metal spinning process permits selfinduced heat generation of the part. Compared with conventional spinning processes, this in-process heat treatment allows the extension of existing forming limits and the production of more complex geometries from tubes and sheets. Additionally, the material/part properties like hardness, stress, grain structure/orientation, surface conditions *etc.* can be adjusted in a defined way during the forming process. This can be achieved using appropriate process parameter settings in combination with the degree of deformation. The choice of feed rate, relative motion and friction coefficient gives rise to a defined temperature profile and allows the use of specific process control strategies to produce parts with different material properties in different areas. Thus, the production of a new class of individually adjustable components is enabled. For example, these parts could be designed for load-optimized applications like complex hollow parts in aluminium or steel. This paper presents the results of the grain structure investigations and clarifies the influence of different process parameters in aluminium tube processing, especially during flange forming operations. A flange will thus be formed from an aluminium tube and, by using an additional tool system, its wall thickness can be adjusted in a defined manner. The paper addresses the influence of the significant process parameters (feed rate, rotation speed, temperature, wall thickness reduction and forming time) on grain structure refinement during flange forming. In addition, the impact of the material properties (hardness, stress/strain behaviour) is considered.

## 1. Introduction

In the area of metal forming, innovative approaches are being continuously investigated in a bid to achieve more efficient manufacturing processes permitting more economic material usage or to realize forming operations with a higher degree of deformation. These developments result from the call for innovative, lightweight structures with a high strength and stiffness and a simultaneous reduction in material, weight and energy consumption (Jeswiet et al., 2008), not solely in the general engineering and transport sectors (Kleiner et al., 2004). A good approach to achieving these targets is the use of incremental forming methods in combination with and without heat treatment strategies.

### 1.1. Incremental forming

Incremental forming processes are processes that generate the required final geometry of the components through a sequence of local impacts of geometrically simple tools on the workpiece and not by direct transfer of the tool shape to the workpiece (*e.g.* deep drawing). Forming processes like conventional metal spinning are suitable for the production of axis-symmetrical hollow parts from sheet metal or tubular workpieces by step-by-step deformation. Typical products are workpieces with complex contours made from sheets or tubes in small- or medium-sized batches (Bergs and Wehrmeister, 2005; Quigley and Monaghan, 2000). An overview related to recent developments concerning spinning processes could be found in Wong et al. (2003); Music et al. (2010) or Xia et al. (2014). Basically, spinning processes can be classified into conventional- and shear forming/flow forming (Runge,

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1993), also called shear spinning, power spinning, spin forging or tube spinning (Wong et al., 2003). Moreover, spinning can be divided according to the forming temperature into cold and hot spinning. By using elevated temperatures often higher deformation become possible so that large and complex parts could be realized (Han et al., 1989). Especially, Zhan et al. (2015) reviewed the section of hot spinning with the focus of lightweight metals, which are difficult to deform. Another incremental process is Single Point Incremental Forming (SPIF), which is more suitable for very small- or small-sized batches with high or complex geometric requirements. The tool movement here can be realized by CNC lathe or milling machines for manufacturing non-axis-symmetrical and axis-symmetrical parts from sheet metal (Filice et al., 2002). A further class of incremental sheet forming (ISF) is the paddle forming process. This process is characterized by a short line contact between the tool and workpiece and permits an increase in the amount of deformation that is possible; it can be applied to the edges or faces of tubes and sheets (Allwood and Shouler, 2007). In the area of profile forming, the incremental tube forming process (ITF) is a process which combines incremental tube spinning with a continuous tube bending process (Tekkaya et al., 2014). The process achieves a significant reduction in the bending moment and bending forces with a simultaneous reduction in springback, making it possible to manufacture tubes with variable diameters and freely definable bending curvatures (Becker et al., 2014).

These processes have basically low forming forces compared to conventional processes. However, the manufacture of innovative products *e.g.* complex hollow component structures in semi-finished sheet metal, tube or profile products is restricted by the work hardening which results during the process. One potential way of avoiding this restricted formability is the use of elevated temperatures during the process (Zhan et al., 2015). This counteracts the work hardening, reduces forces and makes it possible to manufacture complex structures. Current approaches, *e.g.* for the spinning process, use burner systems (Neugebauer et al., 2006), furnaces (Awiszus et al., 2005), induction heating (Huang et al., 2011), heating by hot air in a chamber (Mori et al., 2009) or laser systems (Bergs and Wehrmeister, 2005) or a sequential thermomechanical treatment (TMT) (Chang et al., 1999), but this reduces efficiency in terms of energy consumption, manufacturing time, investment and maintenance costs. In addition, the temporal and local control of the heat input for influencing or improving the material properties, especially for burner systems, cannot be fully utilized for industrial applications. Defined adjustment and control of a specific temperature profile in the part is not possible in an accurate manner and, consequently, unwanted effects can occur, such as strength reduction, changes in microstructure and a reaction with the atmosphere (Music et al., 2010).

### *1.2. Friction-spinning process*

Based on these strategies with quit low efficiency and unused potential, the innovative friction spinning process was developed, taking in elements from both the metal spinning and the friction welding processes. Implementing specific process features from both processes opens up the possibility for a localized, incremental, warm-forming operation and compensates the effect of work hardening directly in the process. With the right choice of process parameters, such as rotation speed and feed rate, it is possible to set defined temperature profiles in the formed part and thus increase the formability and application range, especially compared with conventional metal spinning. It thus becomes possible to manufacture multifunctional components with locally varying mechanical properties that satisfy the demands of lightweight design. Hence, friction spinning permits a significant reduction in costs by saving on both manufacturing steps and time, since additional processes, such as welding or heat treatment, are no longer necessary. Further new potential was identified in the area of hybrid forming through friction spinning. The first promising results from the combined forming of similar and dissimilar materials with the generation of a metallic joint or a form closure were successfully manufactured and are the subject of further investigations. Basically, the friction spinning process is not only limited to a specific semi-finished product or material but can also be used for sheet metal blanks, tubes and profiles (Homberg and Lossen, 2013) consisting of different materials like aluminium, steel alloys and non-ferrous metals (Hornjak, 2013). The range of geometries that can be produced for tube and sheet forming (Lossen and Homberg, 2014) and general information about hardness, grain structure, residual stresses and surface roughness is set out in the above-mentioned associated papers (Homberg and Lossen, 2013; Hornjak, 2013; Lossen and Homberg, 2014). This paper analyses the specific process temperatures, hardness and grain structure development and their influence on the material properties (stress and strain) in aluminium flange forming as an extended version of the ICTP Paper “Friction-Spinning – Possibility of Grain Structure Adjustment”.

The paper starts with an explanation of the processing of flanges as a variant of friction-spinning and describes the experimental setup (Chapter 2). The experimental results from the aluminium forming are illustrated and discussed in chapter 3. For the flange geometry presented, the resulting process temperature range, which is of major importance for the adjustment of part properties, is illustrated in chapter 3.1. The following chapters set out the hardness (3.2) and grain structure (3.3) results. The resultant consequences on the mechanical properties are discussed on the basis of tensile strength/elongation at fracture and a comparison with the initial material is drawn in the last chapter 3.4.

## 2. Aluminium flange forming – process principle and experimental setup

The basic process principle of friction-spinning of a tubular component in order to manufacture a flange geometry is shown in Fig. 1. The tube is clamped through the auxiliary tool, *e.g.* a supporting plate, in the chuck (not illustrated) and is set in rotation with the tube (Fig. 1 (1–2)). After this, the rotating tube comes into contact with a stationary friction tool as a result of the activated feed rate. The relative motion between the tube and the tool, in combination with the forming force, results in friction and induces local heat generation in the part. The phase from the first tool contact to the maximum tool intervention contact (*cf.* Fig. 1 (2–3)) is the pre-friction phase. This phase is used to achieve a rapid temperature increase in the specimen on the basis of the resulting forces and the cold plasticity of the material and results in a typical cone geometry on account of the tool angle. Once the formed material has fully engaged with the tool, the pre-friction phase has finished and the maximum temperature load is achieved. Consequently, the increased material plasticity makes it possible to start the forming phase and enables high-degree forming operations (*cf.* Fig. 1 (3–4)).

At the beginning of the forming phase in the process strategy employed, the tool switches the forming direction from an axial to a radial movement (*cf.* Fig. 1 (2–3)). During the process, no lubricants are used at any point, since this would prevent the generation of a sufficiently high temperature in the workpiece. In this analysis, the characteristics of the specimen (initial tube temper state T6) and tool system remain constant (including the tool angle and diameter). Only the rotation speed and feed rate are configured variably over a range from 200 to 900 rpm and 0.25 to 4 mm/s. It is also possible to implement a multi-pass flange forming process, *cf.* Fig. 2 (4–6) . This strategy is based on the one-pass flange forming strategy and forms the manufactured flange back to the initial tube geometry. After this, a new flange forming pass can be started, permitting the generation of a higher degree of deformation in the component. This can be used to influence grain structure, such as with multi-pass equal-channel angular pressing (Nakashima et al., 2000) or multi-pass spinning process (Wang et al., 2017). This allows the flange forming process to be repeated up to five times without component failure.