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Energy and resource-efficient forming of gas cylinders by friction-spinning

DAHMS Frederik[1,a *] and HOMBERG Werner[1,b]

[1]Paderborn University, Forming and Machining Technology, 33098 Paderborn, Germany

[a]fd@luf.upb.de, [b]wh@luf.upb.de

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Abstract. Friction-spinning as an innovative incremental forming process enables large degrees of deformation in tube and sheet metal-forming due to a self-induced heat generation in the forming zone. This paper presents new process designs for energy and resource-efficient forming of gas cylinders by friction-spinning without the use of an external heat supply. The self-generated heat enables friction-spinning process to reduce the energy demand in the manufacture of gas cylinders, which are usually manufactured with external heat (mostly fossil fuels), by 95 %. Typical gas cylinder contours, such as flattened and spherical bottom ends and cylinder necks, are manufactured by friction-spinning of AW 6060 tubular profiles with specifically designed tool path strategies. It is shown that friction-spinning enables the manufacture of typical gas cylinder contours with sufficient wall thickness and the required gas tightness without the input of external heat. Thus, this process can contribute to an increase in the energy and resource efficiency of forming processes.

Introduction

Friction-spinning as an innovative incremental hot-forming process enables large degrees of deformation in the field of tube and sheet metal forming due to a friction-induced heat generation in the forming zone in an efficient way [1]. The self-induced partial heating of the components not only enables significantly higher degrees of deformation, but also a defined influence on the mechanical properties such as hardness, microstructure [1] and residual stress distributions [2,3].

However, friction-spinning is also suitable for meeting today's social demand for a reduction in emissions and energy consumption of manufacturing processes. This is illustrated by the example of the manufacture of seamless aluminium gas cylinders, which are usually manufactured using external heat [4]. Comparable incremental processes such as flow-forming [5, 6], metal-spinning [7, 8] or tube-spinning [9] usually use gas burners with fossil fuels for the manufacture of these aluminium gas cylinder contours to enable the necessary degrees of deformation and to ensure the gas-tight sealing [10]. Due to its self-induced heat generation, friction-spinning offers the potential to reduce the energy consumption of comparable manufacturing processes by 95 % [11]. In addition, by eliminating the necessity of external heat supply, the manufacturing process can be realised solely through renewable energy, which provides the possibility of climate neutrality of the manufacturing process.

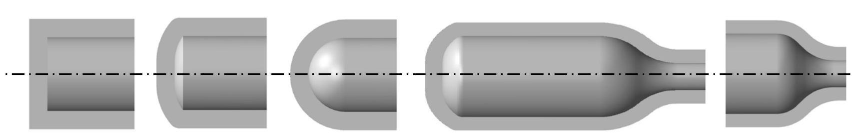

Fig. 1. Example of a gas cylinder and its typical contour elements: flattened and spherical bottom ends and cylinder neck.

Regarding the forming of flattened bottom ends of cylinders it has already been shown that friction-spinning enables the gas and liquid-proof sealing of tube ends with defined wall thickness distributions [12]. Nevertheless, when manufacturing complete gas cylinders, it is necessary to form more complex contours that comply with the standards for aluminium gas cylinders such as DIN EN ISO 7866 [13]. With the aim of energy and resource-efficient manufacturing of gas cylinders, such as the widely used carbonating cylinders, new process designs of the friction-spinning process are developed and investigated. The novelty of this process is that it eliminates the use of gas burners in the manufacture of gas cylinders, thus saving enormous amounts of energy. It also avoids the surface defects of the workpieces (such as surface oxidation) and impacts on the machine and the tools caused by the gas burner. To evaluate this novel process, essential process characteristics, such as force and temperature profiles, and also specific gas cylinder properties such as the workpiece contour, wall thicknesses and gas tightness are determined.

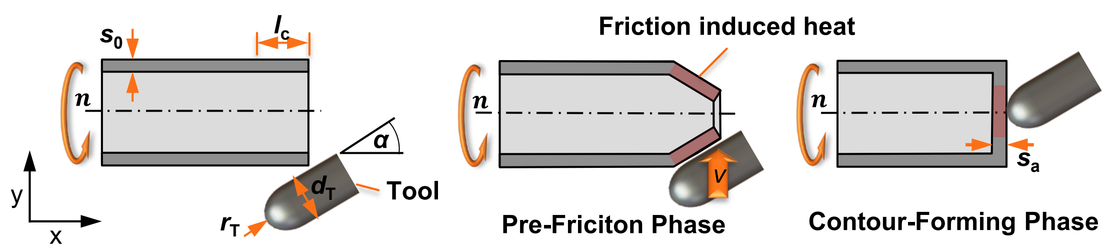

Fig. 2. Friction-spinning process for the forming of sealed-up tubes (flattened cylinder bottom ends. Rotation-speed n, feed rate f, tool-angle α, tool diameter dT, tool radius r_T, initial wall thickness s_0, wall thickness of the cylinder bottom end s_a, tool contact length l_c.

Process Design and Experimental Setup

Typical gas cylinder contours [13], such as flattened and spherical bottom ends and cylinder necks (*cf.* Fig. 1), are manufactured by friction-spinning of tubular profiles with specifically designed tool path strategies. The manufactured parts are assessed concerning their contour, wall thickness and tightness. Generally, the workpieces are manufactured using heat-treatable 3.3206 (EN-AW 6060 initial temper state T6) tubular profiles (100 x 40 x 5 mm) with the LUF in-house design friction-spinning machine (FSV) which is computer controlled by Sinumerik 840D by Siemens AG, Germany. The main spindle drive has a power of 100 kW and enables maximum rotational speeds of 3000 rpm. The tools used have a diameter of 20 mm and are made of the steel alloy 1.3343 (hardened).

The general process-design of the manufacture of sealed-up tubes (flattened bottom ends) by friction-spinning of tubes is subdivided into the pre-friction phase and the contour-forming phase (*cf.* Fig. 2). In the pre-friction phase, a conical basic contour is formed using the large contact area with the tool to induce heat to the workpiece by friction. In the subsequent contour-forming phase, different workpiece contours are formed by specific tool path strategies and the targeted selection of the tool contact area. In the case of a flattened cylinder bottom, the tool path is linear and directed radially (cf. Fig. 3, FB). For the manufacture of more complex contours, such as spherical bottoms and cylinder necks, special curved tool paths have been developed, but due to the limitations of the current version of the FSV machine control, these are interpolated by linear tool paths.

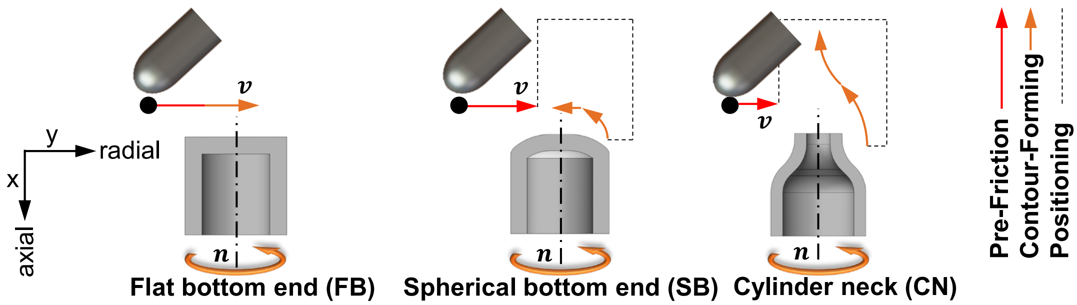

Fig. 3. Tool path designs for flat and spherical bottom ends and cylinder necks.

For the manufacture of the spherical bottom ends (Fig. 3, SB), the pre-friction phase is performed with a large contact area to induce heat and to form an initial cone shape by a linear path in the radial direction. The contour forming then is performed using the tip of the tool, i.e. a point contact and with a curved path that ends in a radial direction. By flattening the path of tool to the end, a centrical flattened bottom section can be realised, too.

For the manufacture of the cylinder necks (Fig. 3, CN), the pre-friction phase is also performed with a large contact area to induce heat and to form an initial cone shape by a linear path in the radial direction. In this case, this path is kept shorter so that the tube is not closed at the end of the process. Contour forming is then performed with the tip of the tool, and therefore a point contact, and with a curved path which does not close the end of the tube by ending in the axial direction. By the combination of tool path design SB and CN complete gas cylinders (*cf.* Fig. 3) are manufactured.

The manufactured parts are evaluated regarding their *contour* by:

- Axial cutting (separating) so that the cut surface lies exactly in the component axis.
- Repeatable positioning of the specimen with a measurement standard on a scanner.
- Image capture with 600 dpi.
- Digital determination of the wall thickness and contour by comparison with the measurement standard.

The *tightness* of the manufactured gas cylinder is demonstrated by applying a hydraulic pressure of 250 bar. For this purpose, a thread is cut into the open end of the gas cylinders to connect them with a pressure gauge, a locking valve and a hydraulic pump by hydraulic hoses (*cf.* Fig. 4, (b)). First, the air is pressed out of the hydraulic hose. Then a hydraulic pressure of 250 bar is applied with the pump, and the valve is closed. After one hour of pressure setting, the pressure is set again to exactly 250 bar and checked with the pressure gauge after 24 hours. The same procedure is also performed with helium at 25 bar.

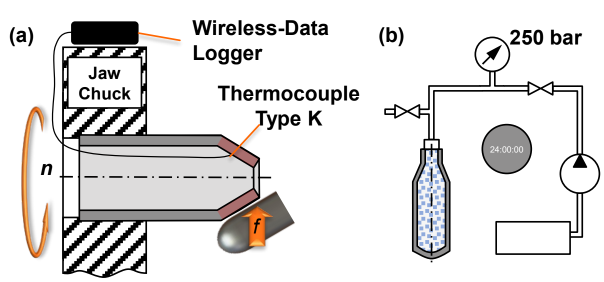

Fig. 4. Telemetric temperature measuring set-up in the friction-spinning process (a) and tightness measuring set-up (b).

The complexity of *temperature measurements* in the friction-spinning process results from its process characteristics (friction of the tool on the surface and rotation of the workpiece), and, with aluminium, especially optical temperature measurements are usually not feasible due to its complex emissivity characteristics [14]. In addition, a basic black coating on the driven tool does not endure the forming process, so reflections of the ambient heat radiation cannot be ruled out. In a previous work, good results were obtained with a telemetric method using type k thermocouples with a radio data logger (measuring amplifier) [2]. Thermocouples type k are mechanically joined in corresponding holes at two discrete measuring points at 5 mm and 15 mm distance to the end of the tube (*cf*. Fig. 4, (a)). Thus, the measuring amplifier can be mounted on the rotating jaw chuck, and the measured values can be transmitted wirelessly, which will provide new valuable insights into the temperature profile of the friction spinning process even in optically non-measurable areas.

Force measurements are performed using a 6-axis load cell (50 kN, ME-Meßsysteme GmbH, Hennigsdorf, Germany) mounted between the tool holder and the support system. Forces are measured in the radial and axial direction of the workpiece.

Results and Discussion

Essential process characteristics, such as force and temperature profiles and also specific gas cylinder properties, such as the workpiece contour, minimum wall thicknesses were measured and tightness was proved.

Contour and wall thickness.

Starting with an initial wall thickness of 5 mm the thickness is reduced to at least 3.6 mm in the case of the flattened bottom end (a), 3.5 mm in the case of the spherical bottom end (b) and 3 mm in the case of the spherical bottom end (c). The cylinder neck's initial wall thickness of 5 mm is reduced to at least 3.9 mm (d). In all cases, the formation of burrs on the outer contour is observed (*cf.* Fig. 5, red marks). This is attributed to the interpolation of the curved paths by linear paths. Therefore, the burrs of the manufactured gas cylinders were removed by turning (e). It can be concluded from this that the manufacture of typical gas cylinder contours with the friction-spinning process is possible in principle, but the integration of accurate path curves into the process control is necessary. The inner contours of the bottom ends show curved shapes, especially in the centre, where the tube ends are joined. To create a more homogeneous inner contour, auxiliary tools may be used.

All the manufactured bottom ends are sufficiently joined, as shown in Fig. 5 ((a)-(c)). To prove this, three complete cylinders (e) were manufactured by the combination of the process designs of the spherical bottom end SB2 (c) and the cylinder neck CN (d). By testing three of the cylinders as shown in Fig. 4 (b), it can be stated that the manufactured bottom ends are tight, i.e. sufficiently connected to withstand a hydraulic load of 250 bar and are thus suitable as pressure vessels. In addition, the gas tightness of the cylinder was also assessed with helium at 25 bar using the same method. There was no measurable pressure loss over a period of 24 hours.

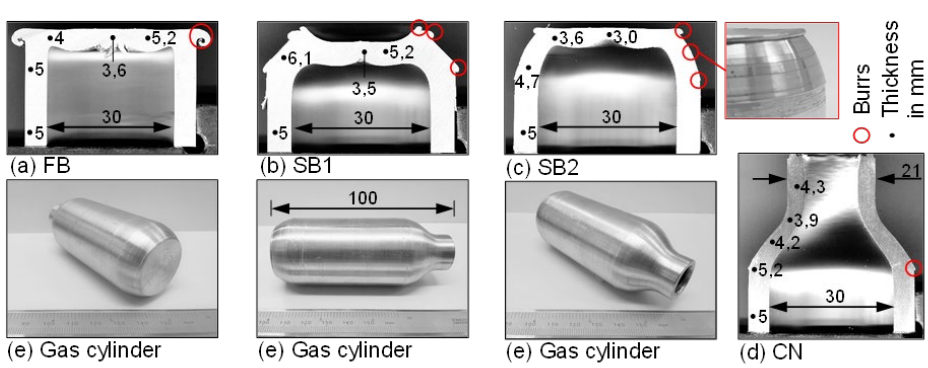

Fig. 5. Manufactured by friction-spinning: (a) flattened bottom end, (b - c) spherical bottom end, (d) cylinder neck and (e) gas cylinder. Rotation speed n = 1500 rpm, feed rate v = 30 mm per min.

Process Forces.

First, the process forces are measured to characterise the new process designs of the friction spinning process. Fig. 6 shows the force profiles and the maximum forces reached in the forming process of the cylinder necks (CN) and spherical bottom ends (SB) in dependence on the process parameters feed rate *v* and rotation speed *n*. In the pre-friction, phase the process forces increase sharply and reach a first peak after 4 seconds (*cf.* Fig. 6, (a-b)). The high level of process forces is maintained for a longer time in the case of the spherical bottom ends due to a longer pre-friction phase. In the contour-forming phase, the process forces do not increase as steeply as in the pre-friction phase. This is because the initial shape was already generated in the pre-friction phase and thus the deformation has a less abrupt onset. The comparatively shorter pre-friction phase of the cylinder neck forming process causes that the forces in the contour-forming phase are significantly greater than those of the bottom end forming process. The highest process forces occur in the horizontal direction (Fx) (*cf.* Fig. 6, (c-d)). They reach their maximum when the feed rate is high (90 mm/min), and the rotation speed is low (500 rpm). In the case of the cylinder necks 5512 N and of the spherical bottom ends 5320 N. Significantly lower maximum process forces are reached with a low feed rate of 30 mm per minute and a higher rotation speed of 1500 rpm. In the case of the cylinder necks 1339 N and of the spherical bottom ends 1767 N. As the process parameters significantly influence the process forces, the temperature profiles are also determined, as these have major influence on the yield stress and therefore can explain the occurring process forces.

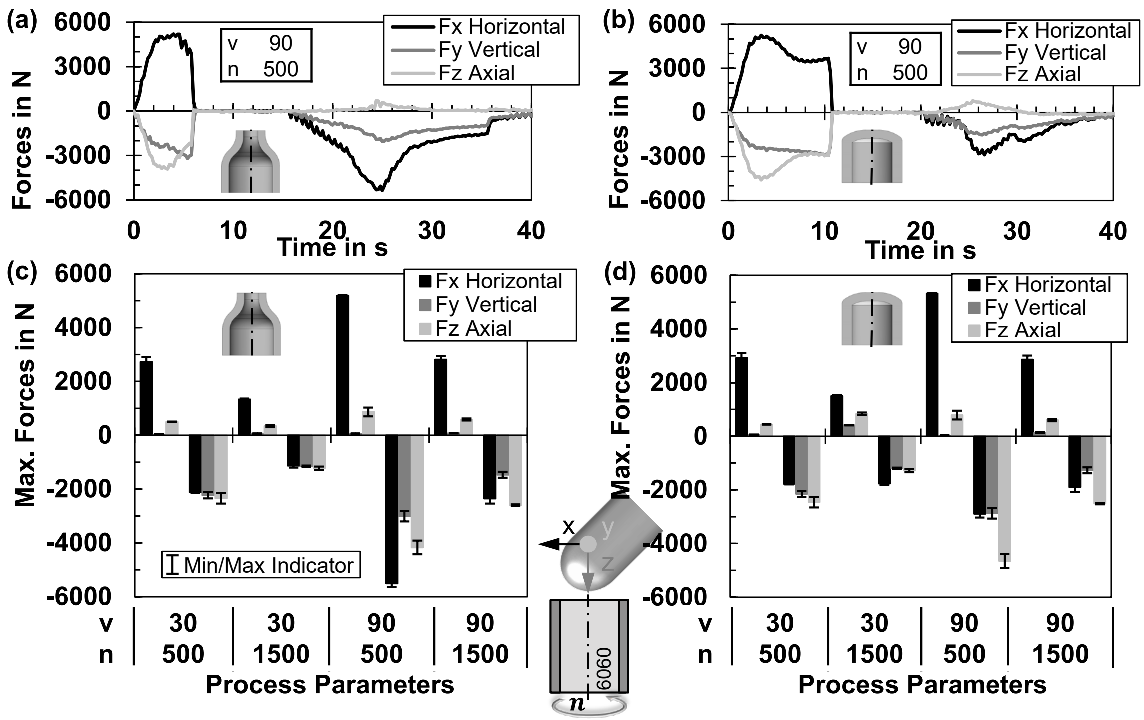

Fig. 6. Force profiles (a-b) and maximum forces (c-d) of the manufacture of the cylinder necks (CN) and spherical bottom ends (SB) by the friction-spinning process in dependence on the process parameters feed rate v [mm/min]and rotation speed n [1/min].

Temperature profiles.

Since the workpiece temperature has a huge influence on the yield stress, and thus on the process forces, corresponding temperature profiles were determined. Fig. 7 shows the temperature profiles of the manufacture of the spherical bottom ends (SB) by the friction-spinning process measured with thermocouple type k at 5 and 15 mm distance to the tube's end in dependence on the process parameters feed rate *v* and rotation speed *n*. Form the first contact with the tool, the workpiece temperature strongly increases to a first peak at the end of the pre-friction phase. While re-positioning the tool for contour-forming the workpiece temperature decreases. In the contour-forming phase, the temperature again steeply increases to a second peak. In the following, heat is emitted until the reversal point for forming the flat bottom end, where a third peak of workpiece temperature is reached.

The described temperature profile is increased by the rotation speed and decreased by the feed rate so that a maximum workpiece temperature at 5 mm distance to the tube's end of 594°C is reached by a rotation speed of 1500 rpm and a feed rate of 30 mm per min (*cf.* Fig. 7, (a)). With a high feed rate of 90 mm per min and a low rotation speed of 500 rpm the maximum workpiece temperature reaches only 455°C. At a distance of 15 mm to the tube's end the temperature profile follows the same pattern, but with the same process-parameters maximum temperatures of only 558 and 387°C are reached (*cf.* Fig. 7, (b)). This is because the contact time with the tool is lower at this measuring point.

Derived from the determined temperature profiles the material bonding of the tube end in the centre of the bottom end is a solid-state bonding mechanism. This means that the adhesion is achieved by the diffusion of interfacial atoms, resulting in strong and uniform material bonding [15].

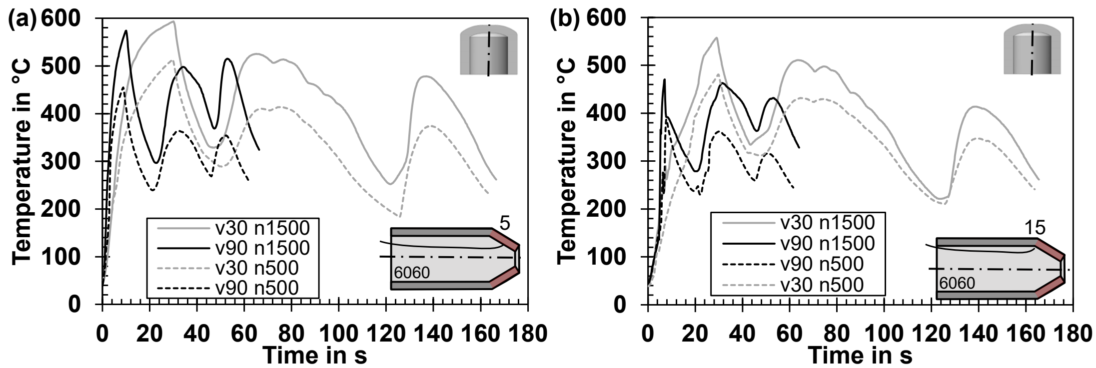

Fig. 7. Temperature profiles of the manufacture of the spherical bottom ends (SB) by the friction-spinning process measured with thermocouple type k at 5 and 15 mm distance to the tube's end in dependence on the process parameters feed rate v [mm/min]and rotation speed n [1/min].

In Fig. 8 the temperature profiles of the manufacture of the cylinder necks (CN) measured with thermocouple type k at 5 and 15 mm distance to the tube's end in dependence on the process parameters feed rate *v* and rotation speed *n* are shown. Form the first contact with the tool, the workpiece temperature increases sharply and reaches a first peak at the end of the pre-foaming phase. With the re-positioning of the tool for the contour-forming the workpiece temperature decreases. then, In the contour-forming phase the temperature again steeply increases to a second peak. In contrast to the manufacture of the spherical bottom ends, the highest temperatures are achieved in the contour-forming phase, which is attributable to the shorter pre-friction phase.

The described temperature profile is increased by the rotation speed and slightly decreased by the feed rate, so that a maximum workpiece temperature at 5 mm distance to the tube's end of 593°C is reached by a rotation speed of 1500 rpm and a feed rate of 30 mm per min (*cf.* Fig. 8, (a)). With a high feed rate of 90 mm per min and a low rotation speed of 500 rpm, the maximum workpiece temperature reaches only 485°C. At a distance of 15 mm from the end of the tube, the temperature profile follows the same pattern, but with the same process parameters only maximum temperatures of 551 and 403°C are reached (*cf.* Fig. 8, (b)).

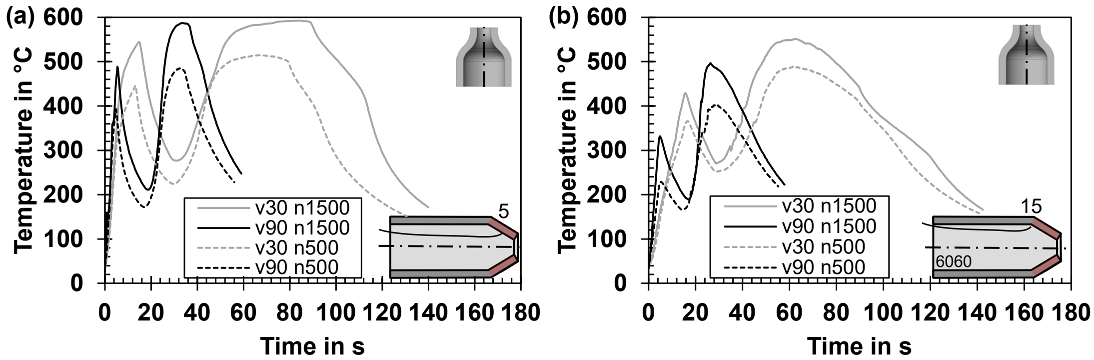

Fig. 8. Temperature profiles of the manufacture of the cylinder necks (CN) by the friction-spinning process measured with thermocouple type k at 5 and 15 mm distance to the tube's end in dependence on the process parameters feed rate v [mm/min]and rotation speed n [1/min].

With both contours, it can be seen that the higher rotation speed increases the workpiece temperature, which is due to more frictional heat input. This also interacts with the feed rate, which, if it is low, allows longer heat input. At the higher rotation speed, however, this effect is less. In this regard, the determined temperature profiles show a causal relationship with the determined maximum process forces. The higher the temperature, the lower the process forces, which is due to the lower yield stress. In this respect, the next step is to clarify to what extent the different temperature profiles cause recrystallization processes. This is investigated in the following through hardness tests.

Hardness.

Since there are process parameter-dependent temperature profiles and temperature gradients along the workpiece contour, corresponding hardness profiles were measured using the Vickers hardness test method according to DIN EN ISO 6507-1 [16] with a Nexus 4000 hardness testing device, Innovatest Company, Maastricht, Netherlands. First, an initial hardness of 86 HV0,3 was determined for the tubular profiles. Fig. 9 (a-b) shows that all specimens are softened by the manufacture process. On average of all measured parts, the hardness value (HV0.3) decreases by 38%. This is attributed to dynamic recovery and recrystallization due to the high workpiece temperatures combined with the high degrees of deformation [17]. Only at measuring point 5 of the bottom end which was manufactured with a high feed rate and a low rotation speed a significantly lower softening of 26% can be observed (*cf.* Fig. 9, (a)). This correlates with the observation that at a distance of 15 mm to the tube's end the maximum temperatures of only 387°C are reached, and thus the temperature at measuring point 5 is even lower (*cf.* Fig. 7, (b)). Under this condition, less dynamic recovery and recrystallization can be assumed and consequently less softening. However, the hardness profile over the entire contour cannot be influenced by the process parameters investigated.

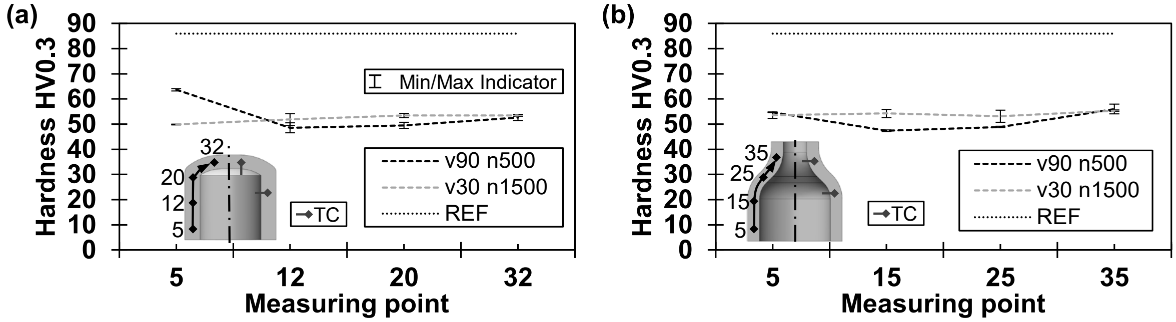

Fig. 9. Hardness profiles of the manufactured cylinder necks (CN) and spherical bottom ends (SB) in dependence on the process parameters feed rate v [mm/min]and rotation speed n [1/min].

Discussion.

In the experimental investigations, the resulting contours and the new process characteristics were evaluated. It is shown that friction-spinning enables the forming of the required contours for the manufacture of gas cylinders, and tightness, i.e. the essential property of gas cylinders, is fulfilled. The reduction of the wall thickness by up to 40 % does not lead to tightness failures. This is attributed to the fact that the friction spinning process allows sufficient material bonding of the cylinder's bottom ends through pressure welding-like processes, i.e. diffusion of interfacial atoms.

However, in terms of lightweight construction, the requirement arises to reduce the wall thickness to a rational minimum. Nevertheless, it can be assumed that there is a critical material-dependent standard dimensional ratio (SDR) to withstand this forming process, which must be determined in the next step. The use of tailored tubes will be investigated to overcome this limitation. For example, the internal flow-forming process developed at LUF can be used to manufacture these tailored tubes [18]. With this process, the wall thickness can be partially reduced to a specified minimum by flow-forming on the inner side of the tube, leaving the necessary wall thickness in the forming zone. The design and evaluation of this new process combination and chain will be part of future research. Additionally, a more homogeneous outer contour can be achieved by real curve paths and a more homogeneous inner contour can be achieved by the use of auxiliary tools. Furthermore, it should be investigated whether functional integrations, such as the forming of a thread, can be realised in the manufacturing process of the cylinder necks.

The investigated process characteristics, forces and temperature profiles are significantly influenced by the process-parameters feed rate and rotation speed. The process forces can be strongly affected and kept relatively low, leading to longer process times and higher workpiece temperatures. These process characteristics cause softening of the material due to recrystallization. However, gas cylinders usually have to be heat-treated before they can be introduced to the market with certification [19]. In the case of aluminium 6060, this is realised by annealing and ageing, which restores the initial mechanical properties. Furthermore, under this constraint, the processes can also be designed for a minimum energy consumption.

However, the actual power and the *total energy consumption* of forming machines strongly depend on their specific characteristics, which is why it is extremely challenging to compare different manufacturing processes performed on different machines, especially if the established processing is not transparent. And it also does not seem plausible to subtract the energy consumption of an empty run to obtain a pure transformation energy consumption, since energy is lost in specific amounts in every process despite the efficiency of the machine, and the actual energy consumption of comparable processes in the manufacture of these contours is unknown. In this work, however, we have demonstrated that the friction-spinning process at least does not require external heat input for the manufacture of these contours.

According to Lossen [11], depending on the process parameters, 70 to 735 kJ of pure forming energy is consumed during the friction-spinning process, which generates heat of about 500°C in the workpiece due to friction and deformation work. In comparison, the energy of 1300 to 1730 kJ is required to generate this heat in the workpiece (tube end of 40 x 5 x 80 mm of aluminium 6060) with an acetylene torch [11]. This calculation is based on a heating time of 30 - 40 seconds, a burner/torch surface of 1.13 cm² and 2.55 cm² and a mixture ratio of 1:3 [11]. In this context, it has to be stated that of course other potential forming processes also induce heat by deformation work, but with the friction-spinning process, the heat and thus the energy of an acetylene torch can be completely dispensed. Although the exact reduction of energy consumption cannot be determined reliably from this, friction-spinning provides the possibility to exclusively use renewable energy for the manufacturing process of gas cylinders and therefore can contribute to an increase in energy and resource efficiency.

Summary

In this paper, new process designs for energy and resource-efficient forming of gas cylinders by friction-spinning are presented. Typical gas cylinder contours, such as flattened and spherical bottom ends and cylinder necks, are manufactured by friction-spinning of AW 6060 tubular profiles with specifically designed tool path strategies. It is investigated how the process parameters influence the process properties and the mechanical properties of the workpiece. These newly developed process designs of the friction spinning process investigated here considerably expand the application possibilities of the process and also offer a great opportunity to increase energy efficiency in the manufacture of high-volume products. An essential factor here is the demonstrated adaptability of the friction-spinning process. The specific variation of the contact area of the bar-shaped standard tool enables, on the one hand, the free forming and, on the other hand, the targeted areal heat input by friction to extend the process limits. The synergetic combination of these two elements in one process design enables, for example, the production of contours typical of gas cylinders, which are difficult to manufacture without the addition of external heat in comparable and established forming processes. Thus, it is possible to limit the energy supply to electrical energy from renewable sources. Nevertheless, the actual energy consumption of this process compared to other processes and also the life cycle of the components manufactured with it, such as a carbonisation cylinder, still need to be investigated in future research.

Acknowledgment

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