

Internal Flow-Turning – extended manufacturing possibilities in tailored tube production

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Abstract. The motivation behind the development of a new approach to the manufacture of tailored tubes is the need for greater flexibility in the wall thickness variation of semi-finished parts compared with present manufacturing processes. In the so-called Internal Flow-Turning (IFT) process, the wall thickness contour of regular tubes with a uniform wall thickness is adjusted by means of a rolling process employing an innovative roller tool on the inside of the tube and a die on the outside of the tube. The gap between the roller element and the die can be adjusted through the axial infeed of the roller tool. The gap defines the current wall thickness of the tube during the manufacturing process. In this way, the wall thickness contour can be set in a precise manner by varying the gap distance as the tube is being pulled through the die. Besides the possibility of locally adjusting the wall thickness, IFT can also be used to form geometrical rib elements in the radial tube direction by using a radially shaped die. As the material flow in the IFT-process is mainly caused by compressive stress, the grooves of the die can be “filled up” by radial material displacement.

Keyword: Manufacturing process, Metal forming, Rolling

1 Introduction

The efficient use of material in present-day manufacturing is driven by the demand for sparing use of resources and the need for lightweight structures at a reasonable cost. One way to improve lightweight design is to adapt the wall thickness of the work pieces to match the expected loads, and hence to manufacture tailored semi-finished parts. By comparison with present manufacturing processes, the Internal Flow-Turning has a greater flexibility regarding the wall thickness variation in the production of semi-finished parts, which holds great potential for the manufacturing of tailored tubes. In the IFT-process regular tubes with a uniform wall thickness are formed to tubes with a tailored wall thickness contour by means of a rolling process using an innovating roller tool on the inside and a die on the outside of the tube. By axially adjustment of the tool the gap between the rolling elements and the die can be set. The gap defines the current wall thickness of the tube during the manufacturing process. By simultaneous movement of the tube relative to the die and the adjustment of the rolling cycle diameter a given wall thickness contour can be formed in a precise manner. As in conventional flow forming, the plastic deformation in the Internal Flow-Turning process is caused mainly by compressive stress, which means that quite a large number of materials can be formed. In experimental investigations, aluminium alloys like EN AW 6060 and several steels (from mild steel (1.0308) through to high-

strength steel (1.3548)) were successfully formed using the IFT process [3]. Internal Flow-Turning makes it possible to extend the wall thickness reduction range as well as to increase the freedom of design in terms of the wall thickness distribution or contour when manufacturing wall-thickness-contoured tubes. Local reductions of up to 90% of the initial wall thickness are possible. The transition between the different wall thicknesses can vary from almost “rectangular” transitions to very smooth (conical) transitions of just a few degrees. The varying wall thickness contour in the axial tube direction is only implemented on the inside of the tube wall, and the outer diameter stays constant in the axial direction. In addition, the IFT process can also be used to form geometrical rib elements in the radial tube direction by using a radially shaped die. As the material flow in the IFT process is mainly caused by compressive stress, the grooves of the die can be “filled up” by the radial material flow. In addition the geometrical forming of the tube cross-section, Internal Flow-Turning also improves the mechanical properties and geometrical accuracy of the rolled tube section. The hardness and strength improvement as a function of the wall thickness reduction, generates an increase of up to 70% [1]. Moreover, the surface roughness can be reduced significantly, depending on the related feed rate [mm/rev] of the rolling tool and the wall thickness reduction. IFT could be used to advantage not only for the production of work pieces but also for the production of preforms or semi-finished parts in a highly efficient manner. As a demonstrator for potential applications for

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internal flow-turned tubes, a preform for an automotive exhaust manifold in high temperature stainless steel was optimised in terms of weight and material cost. The hydroformed demonstrator has a greatly reduced wall thickness over its area, apart from in the main forming zone, which gives a weight and material reduction of 20% compared to the original part [2, 3].

2 Process principles

The IFT process is based on an internal rolling process with an innovative roller tool, whereby the contour in the axial direction is only implemented on the inner side of the tube. The driven roller tool positioned inside of the tube forms the wall thickness contour in a large number of small local forming steps. Due to the incremental character of the forming process the forces are quite low, thus allowing a far higher wall thickness reduction compared to flexible tube drawing for example. Additionally, the transitions between different wall thickness sections are more flexible, even enabling steep transitions.

The rolling takes place while the tube has an axial movement relative to the rolling elements. The wall thickness is determined by the gap between the roller elements on the inside of the tube and the die on the outer surface of the tube. The die and the roller tool are mounted on two separate sliding supports, which can be moved in an axially synchronized manner at the same speed in relation to the static tube. In addition the tool support can be moved with a superimposed translational displacement. In doing this, the gap can be adjusted while the die is moving over the tube, whereby two different tool concepts can be used. The two process concepts differ in respect of internal flow-turning with integrated tube drawing and a rigid turning circle diameter (Fig. 1a)). Here the relative movement between the die and the tube is a necessary process element for the ability to adjust the gap or wall thickness reduction respectively. In the process version without tube drawing the relative movement between the die and the tube is not necessary because the tool has a radially adjustable rolling circle diameter and the drawing process element is not required for the adjustment of the gap (Fig. 1b)).

2.1 IFT with tube drawing

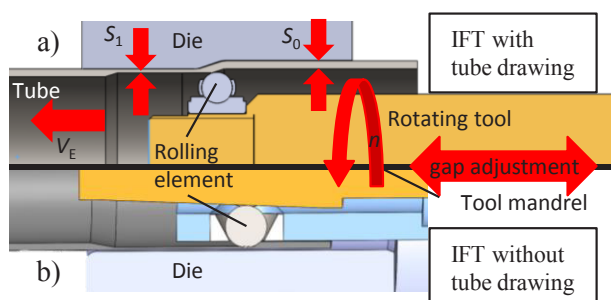


Fig. 1. Process principle of Internal Flow-Turning (IFT) with tube drawing a); and without tube drawing b)

In the version of the process with tube drawing, the roller gap adjustment takes place as a result of the axial movement of the roller tool into the tapered section of the die (see detail a)1 & a)2 in Fig.2). The axial displacement of the roller tool is quite small and depends on the tapering angle of the die and the desired wall thickness reduction Δs . The main component of the tool is a standard groove ball bearing where the external ring is removed. A schematic diagram of the tool is shown as a segment of the cross-section in Fig. 1a). The tube drawing forms part of this process, since it is necessary for the roller gap adjustment. In this process version, therefore, the forming of the wall thickness contour to achieve the desired external diameter has to be performed in a single overrun step.

2.2 IFT without tube drawing

In the version of the process without tube drawing, the tool has a radially adjustable rolling circle diameter, whereby the infeed is achieved through the axial displacement of the conical driving shaft surface. Due to the quite small angle of the conical driving shaft, the axial displacement is higher compared to the process version with tube drawing. The tool design is shown in Fig. 1b) and a detail of the gap adjustment in Fig. 2b). Because the processed tube keeps its initial external diameter, the forming process of the wall thickness contour can be divided into several overrun steps. Due to the absence of tube drawing, the axial tension forces on the tube are reduced. This leads to a higher potential wall thickness reduction of almost 90 % of the initial wall thickness. Furthermore, this IFT version allows backward and forward flow-turning by contrast to the IFT version with tube drawing, where only forward flow-turning is possible. This option depends however, on the geometry of the rolling elements employed. Due to the modular setup of the radial adjustable tool, it is possible to use balls or various cone geometries as rolling elements. If cones are used as rolling elements, the conical driving shaft must have the same angle as the attack angle of the rolling element.

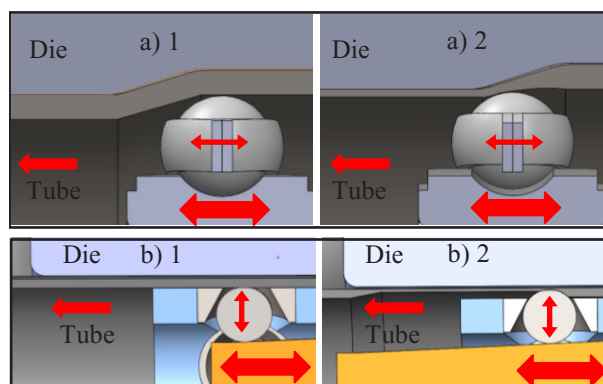


Fig. 2. Details of the gap adjustment principle for the IFT process with tube drawing a) 1&2 and the IFT process without tube drawing and a radially adjustable roller tool with balls as rolling elements b) 1&2

2.3 Effects on the processed tube properties

The IFT process has various impacts on the geometrical and mechanical properties of the processed tube. With the mentioned increase of the hardness and strength of the rolled tube section the remaining formability decreases as a function of the wall thickness reduction Δs due to work hardening. As the strength increase only takes place within the rolled tube section for the IFT process without tube drawing, the cold work hardening impacts the whole tube for the process with tube drawing and has a greater impact in rolled sections in relation to the wall thickness reduction Δs . The tube drawing itself also leads to a reduction of the remaining formability of the tube. The choice of IFT version (with/without tube drawing) thus depends on the downstream manufacturing process in addition to other factors. If further forming processes are needed, the IFT version without tube drawing is suitable, due to the greater remaining formability properties. If a high strength is needed, the IFT process with tube drawing is advantageous [2].

The rolling process also leads to an improved surface, whereby the processed surface depends mainly on the related feed rate f (millimetres per revolution) and the wall thickness reduction Δs . In addition, the geometry of the rolling element affects the surface roughness. The IFT process also improves the roundness of the tube, irrespective of the wall thickness reduction Δs [1].

3 Manufacturing of contoured outer surfaces with the IFT process

Internal Flow-Turning is in various ways comparable and related to flow forming. In both processes, the material flow is based mainly on compressive stress, and very high wall thickness reductions of up to 90 % of the initial state are possible [4,5]. The concept of using flow forming to create tubular parts with internal gearing elements was developed decades ago [6,7] and is applied today in the series production of plate carriers with internal gears for gearboxes in the automotive industry for example [8,9]. In the flow forming of tubes with inner ribs it is also common to use balls as rolling elements [10-14].

Experimental investigations relating to the manufacture of contoured outer surfaces using the IFT process with tube drawing revealed that the rib element shaping results mostly from a bending process during tube drawing. With an increasing wall thickness reduction Δs , the level of groove filling even decreases. Moreover, the cross section on the inner side of the tube is not circular, but has a local deviation from circularity in the rib area (see Fig.3) which increases with the size of the groove. The deviation decreases with an increasing wall thickness reduction Δs . The height of the groove has to be quite small to achieve a high enough wall thickness reduction Δs to create a cylindrical inner cross section before any tearing of the tube occurs. Fig. 3 shows an example with a circular inner cross section (top

right). Here the outer contour is an oval with wall thickness differences of 0.4 mm in 90-degree shifts. The remaining pictures in Fig 3 show the forming behaviour of higher rib elements with a non-circular cross-section in the rib area [15].

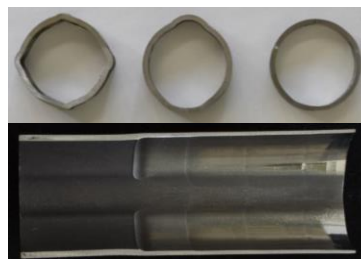


Fig. 3. Specimens with rib elements on the outer contour processed by IFT with tube drawing [15]

The risk of non-circular inner cross-sections developing could be avoided using the IFT process without tube drawing. For the experimental investigation of this variant, a die with three different-shaped grooves was designed. The grooves differ in width from 3 mm to 20 mm and have various edge geometries. The maximum height of each groove, at 1.5 mm, is the same for all geometries. The different-shaped grooves ought to show the influence of the edge geometry and the length or volume, respectively, of the groove on the material flow and the filling ability by IFT. Fig. 4 shows the inner contour of the die ring. The tubes used in the experimental investigations were seamless tubes with a 48 mm external diameter an initial wall thickness of 4 mm. The material of the tubes was either mild steel (E235 (1.0308), seamless drawn precision tube) or extruded aluminium (EN AW 6060 T4).

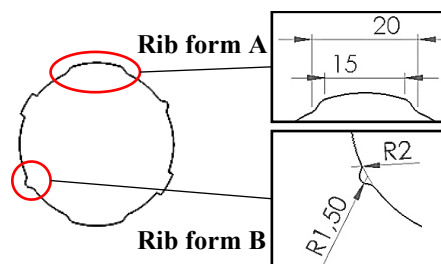


Fig. 4. Inner contour of the die ring; measurements in [mm]

Initially the experiments were carried out with balls as rolling elements that had a diameter of 11.9 mm. The results showed that the increase in the wall thickness reduction Δs and the increase in the related feed f has a positive impact on the filling of the grooves. An even bigger impact than the overall wall thickness reduction comes from the wall thickness reduction in each individual overrun step. Here a maximum wall thickness reduction of $\Delta s_{max} = 0.8$ mm was achieved in each overrun step.

Fig. 5 shows, by way of example, the result of rib form A with the maximum wall thickness reduction (overall and in each overrun) with balls. Complete filling of the groove could not be achieved for all the rib geometries examined, only rib form B displayed almost full filling.

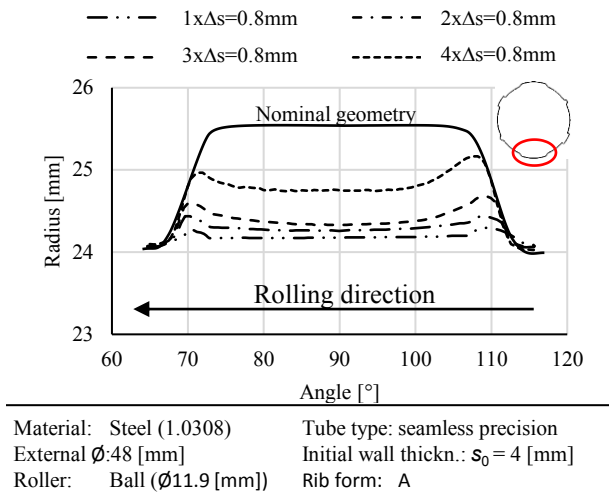


Fig. 5. Influence of the overrun number on the contour accuracy

Due to the fact that conical roller elements enable a bigger wall thickness reduction Δs in a single overrun step, further investigations were carried out using cone elements with an attack angle of $\alpha = 8^\circ$ and a transition radius r_{trans} of 12 mm. The attack angle α of a ball can be approximated as the connecting line of the two endpoints of the contact surface between the ball and the tube [7] (see Fig. 6).

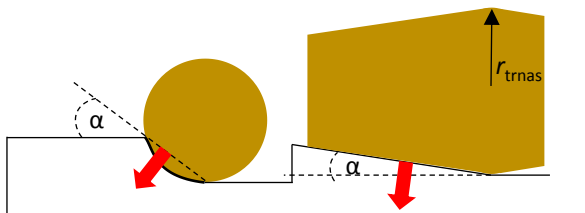


Fig. 6. Entry / Attack angle α of ball and cone roller element and resulting compressive force

According to this definition, the attack angle α of the ball increases with an increasing wall thickness reduction and leads to a resulting compression force with a similarly increasing axial component. This is counterproductive for the radial material flow, which normally allows good filling of the radial grooves. For the wall thickness reduction of $\Delta s = 0.8$ mm, the attack angle α for the balls used is $\alpha = 15^\circ$. A comparison of groove filling for an equal wall thickness reduction of $\Delta s = 0.8$ mm after a single overrun with balls and cones confirms the assumption of the resulting compression force. Irrespective of the groove geometry the filling using cone-rolling elements is significantly higher than that using balls. Fig. 7 shows, by way of example, a comparison for filling in the rib form A.

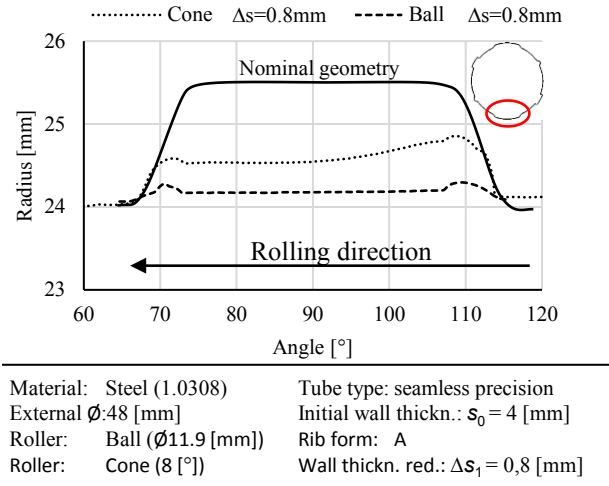


Fig. 7. Influence of the rolling element geometry

These results could be confirmed by a look at the cross section of the specimens shown in the picture in Fig. 8. It was observed that a wall thickness reduction of $\Delta s = 1.5$ mm through conical rolling elements in a single overrun leads to almost complete filling of the groove geometries. A wall thickness reduction that was twice as high, of $\Delta s = 3.0$ mm, achieved with ball rolling elements in four overrun steps, leads to clearly inferior groove filling. Both specimens are made of the same seamless steel tube with an initial geometry of 48 mm external diameter and a wall thickness of 4 mm.

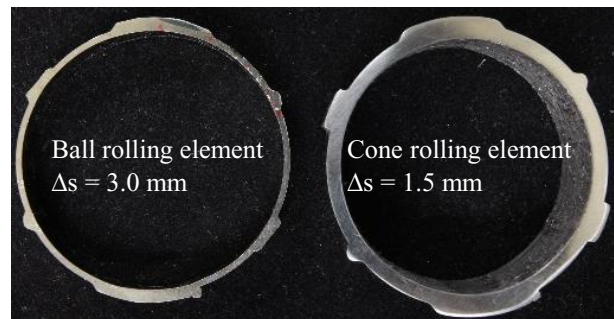


Fig. 8. Comparison of rib forming by IFT with balls (left) and cones (right) as rolling elements

Beside the tactile measurement of the cross section with a coordinate measuring machine (Model Carl Zeiss Contura G2), the complete filling of the groove was also determined by visual testing.

Figs. 9 and 10 show, by way of example, the influence of the wall thickness reduction Δs on the contour accuracy and groove filling for rib form A and B. The results reveal that a bigger volume / length of the rib cross section at the same maximum height requires a greater wall thickness reduction Δs for complete groove filling. For small rib elements (form B) the wall thickness reduction has to be only slightly higher than the rib height itself.

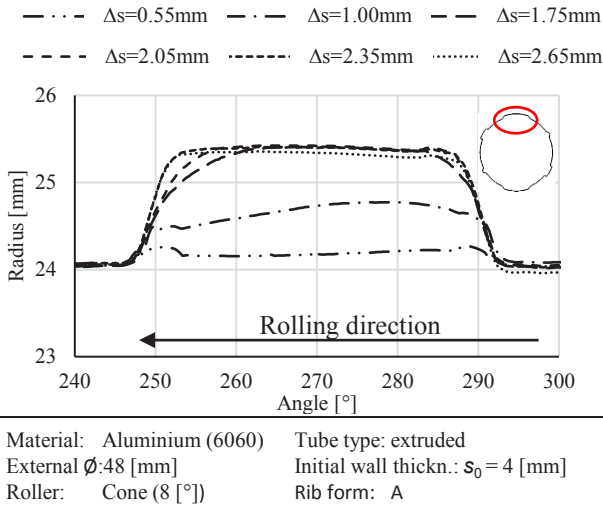


Fig. 9. Influence of the wall thickness reduction Δs on the contour accuracy; The curve with a wall thickness reduction $\Delta s = 2.65$ [mm] is the nominal rib contour

With small wall thickness reduction stages in all groove geometries the corner region starts to build up first. With a further wall thickness reduction, the centre of the rib starts to rise faster than the corners. By increasing the overall wall thickness reduction in a number of overrun steps, the shape with the bulging edges continues to exist even with very high overall wall thickness reductions (compare Fig. 5). With an increasing wall thickness reduction in a single overrun step, the chronologically first over-rolled corner of the groove “fills up” first for longer ribs (see e.g. form A in Fig. 9). For small grooves (form B in Fig. 11) the chronologically second over-rolled edge “fills up” first. This corresponds to investigations conducted for internal gear forming by flow forming [6].

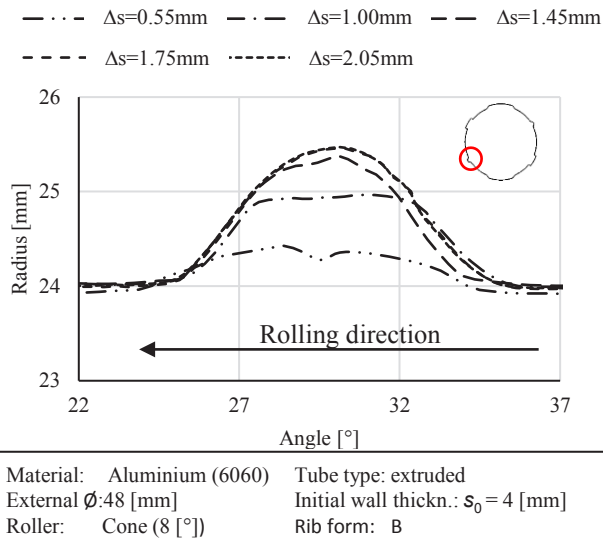


Fig. 10. Influence of the wall thickness reduction Δs on the contour accuracy; The curve with a wall thickness reduction $\Delta s = 2.05$ [mm] equals the nominal rib

Due to the rolling process, there is a varying wall thickness distribution inside the groove elements in the

circumferential direction. The different groove filling is demonstrated in Fig. 11 on the basis of a tactile measured cross-section of a tube section with semi-filled grooves. For a better understanding, the tool and the rotation of the tool elements is illustrated as well as the compression direction and the direction of the tangential material flow.

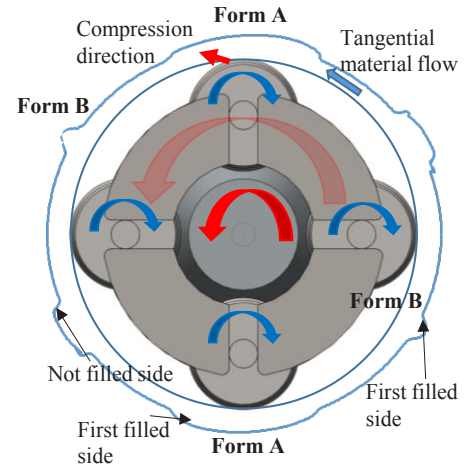


Fig. 11. Effect of the tangential material flow on the contour

Tests that were conducted with an increase in the wall thickness reduction up to the tearing of the aluminium tube (EN AW6060 T4) at $\Delta s = 3.7$ mm (92.5 % of the initial wall thickness) revealed that there is an optimum wall thickness reduction Δs beyond which any further wall thickness reduction causes a deterioration in the filling quality of the groove. This is most noticeable with the widest rib (rib form A). By increasing the wall thickness reduction to above a certain point, the corners and flanks of the rib will no longer be completely filled. The reason for this phenomenon is presumed to be the increasing tangential material flow.

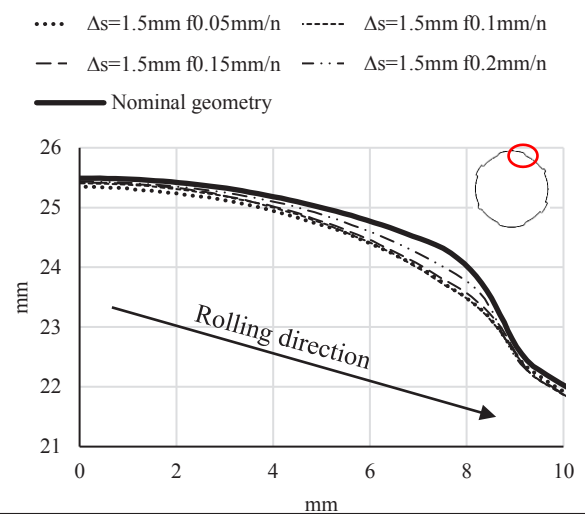


Fig. 12. Improvement of corner filling by increasing related feed f with a constant wall thickness reduction $\Delta s = 1.5$ [mm]

With an increasing related feed f the “filling level” of the grooves improves to the extent previously mentioned for the tool version with balls. Fig. 12 shows the improvement of the corner filling for rib form A with a constant wall thickness reduction of $\Delta s = 1.5$ mm. The wall thickness reduction in this investigation is deliberately set to a not complete “filling level”, to show the improvement achieved by increasing the related feed f from 0.05 mm/rev to 0.2 mm/rev.

To identify the influence of the IFT process on the grain texture, microsections of the three different rib elements were made. The enlargements shown have an optical magnification of 600 times and are taken from each chronologically second-over rolled corner of the rib elements (Fig. 13). For a better comparison, the initial state of the steel tube, which has a ferritic pearlitic microstructure, is shown too. Because the initial tube is a drawn precision tube, the mostly isometric grain structure already shows a slight grain refinement towards the outer tube surface in the initial state.

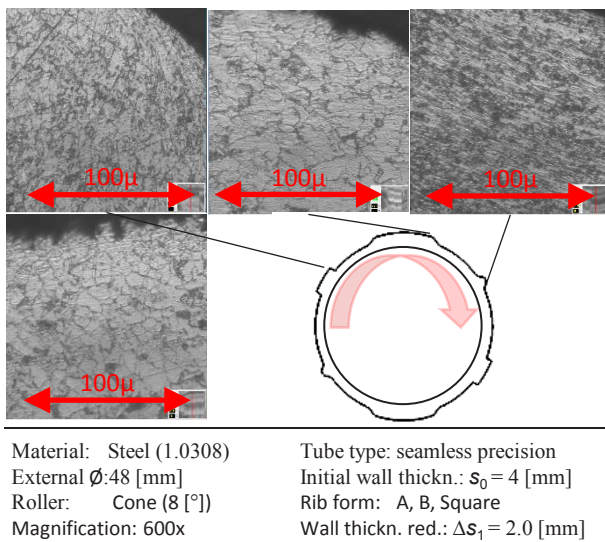


Fig. 13. Grain structure in the rib element corners at $\Delta s = 2.0$ mm of the steel tube (top) and the outer edge of the initial steel tube (bottom)

The grain deformation shows an increase with a decreasing rib volume at the wall thickness reduction stage of $\Delta s = 2.0$ mm. This is the consequence of greater compression at the smaller grooves after these grooves achieve complete filling first. The appearance of the grain structure also confirms the contrary filling order of grooves of different lengths by showing a higher deformation at each first-filled corner. In addition, the “transition sharpness” at the edges of the grooves also has an influence on the grain deformation. The wide rib element (form A) has a very smooth splined transition that merges tangentially between the outer tube surface and the groove surface. Therefore, the material flows into the groove without any significant deformation of the grain structure. The sharp edges (square rib) show severe elongation and bending of the grains in the transition area. Here, the grain deformation on the chronologically second-rolled edge is far more distinct than the first. This results due to the compression direction of the material flow against the groove edge.

The edge hardness of the formed element rib is measured with a minimum distance of 0.1 mm from the outer surface. The test specimen is taken from an steel tube with a wall thickness reduction of $\Delta s = 2.55$ mm which showed the best filling for all the groove geometries. The findings of the filling pattern and the studies of the grain structure reflect the hardness distribution on the edge of the formed rib elements. The smallest rib shows the highest hardness with 270 HV0.1 at the first filled edge, which is the chronologically second-over rolled corner of the rib element. The hardness distribution also shows that the first-filled edge of the rib is subject to the highest compression and therefore has the highest hardness. This also applies to the diagram of the wide rib element form A, shown by way of example, where the first-rolled side is filled first and has a slightly higher hardness (see Fig. 14). For all rib elements, the lowest hardness is seen in the centre of the rib outer surface.

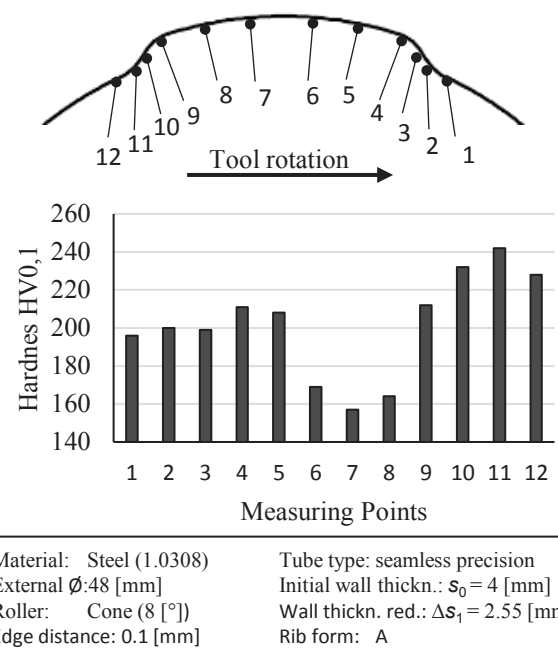


Fig. 14. Edge hardness for rib element form A of an IFT formed steel tube (1.0308) at a wall thickness reduction $\Delta s = 2.55$ mm

4 Conclusions

The internal flow-turning process is not only suitable for manufacturing tailored tubes that have a contoured wall thickness in the longitudinal direction and improved mechanical and geometrical properties but is also suitable for producing tubes with a contoured outer surface e.g. with longitudinal ribs.

Experimental results showed that the production of ribs by the IFT process is greatly influenced by the relative feed f , the roller geometry and the wall thickness reduction Δs . Here, the wall thickness reduction Δs in a single overrun step gives better groove filling than a big overall wall thickness reduction Δs in several overrun steps. A low attack angle increases the radial material

flow which, in addition to an increasing relative feed f , ensures a better filling level.

The influence of the element geometry can be divided up into the edge form and the length of the groove effect. A smooth transition facilitates good formability and precise shaping of the groove corners. As the length of the element cross-section increases, a bigger wall thickness reduction Δs is required to achieve complete groove filling, even though the maximum groove height is the same.

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