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The influence of cold rolling on the pore morphology and flow resistivity of porous aluminum

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THE INFLUENCE OF COLD ROLLING ON THE PORE MORPHOLOGY AND FLOW RESISTIVITY OF POROUS ALUMINUM

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Abstract

Materials with an open porosity are used in many applications, such as filters, acoustic absorbers or heat exchangers. For these applications the pore size and shape as well as the depending flow resistivity are important parameters and need to be adjusted for the specific case. The material parameters are usually defined by the manufacturing process and are therefore signature for different types of porous materials. In this study the porosity, pore shape and the depending flow resistivity of a given material are adjusted using a cold rolling process. The material chosen is a porous aluminum with a porosity of about 50% and relatively large pores, what allows to adjust pore size and porosity on large scale. To characterize the initial porous structure and describe the structural evolution during cold rolling, three dimensional X-ray scans for various degrees of deformation were taken. To analyze pore size and pore shape a line segmentation technique was applied to image stacks extracted from the 3D reconstructions parallel to the three main surfaces of the rolled plate (parallel and perpendicular to the rolled surface). Thus it is possible to examine the formation of an anisotropic porous structure and compare pore shapes and sizes for different degrees of deformation and orientations within the rolled plate. These results are then compared to the evolution of the flow resistivity, which was measured for the three main orientations.

1 Introduction

The porous aluminum used in this study is produced using a salt infiltration technique and was received from "Exxentis"[1]. It is available with various pore sizes and was characterized in a previous work [5]. In order to ensure that the pore size can be adjusted on large scale, the porous aluminum with the largest initial pores was chosen for this study: PA 200-250. A CT image of the material before the cold rolling is shown in Figure 1. To ensure a good deformability a technically pure aluminum was chosen for the porous plates. By deforming the porous aluminum in a rolling mill, the plates are elongated and the thickness is reduced. This causes a reduction of the porosity due to closing pores and an elongation of the pores in the rolling direction along with the material flow.

2 Material characterization

For the structural characterization of the porous aluminum a CT scanner (GE nanotom s) with a minimal voxel size of V=0,5 µm was used. For the scan the sample size was chosen according to the thickness of the rolled plate. This resulted in a voxel size from V≈6 µm to V≈13 µm. The porosity was measured from the 3D reconstructions, whereas the pore size and shape was obtained from 2D images. As can be seen in Figure 1 the porous aluminum has an irregular pore shape that makes it difficult to define a pore size. To describe the pore size and shape a line segmentation technique was applied to the 2D image stacks, extracted from the 3D reconstructions. The line segmentation technique was successfully applied to porous materials to characterize pores and ligaments in size and shape [3, 4, 6]. For this a grid of parallel lines is superimposed to the binarized black and white images and the size of the black and white segments (pores and ligaments respectively) is measured. An example for a binarized image is shown in Figure 2. The superimposed grid is then rotated 180° in steps of 1° giving the pore size for all directions within the analyzed plane. Finally the results are plotted as ellipses showing the mean segment lenght. The mean lenght of the black segements is subsequently called mean pore size. By plotting ellipses for planes oriented parallel to the three main surfaces of the rolled plate it is possible to compare pore sizes and shapes of different orientations in the sample and describe the anisotropy of the porous aluminum. For each orientation 10 images were analyzed and the results avaraged. In all plots the rolling direction is

[1] Exxentis Ltd, Schartenfelsstrasse 6, 5430 Wettingen, Switzerland

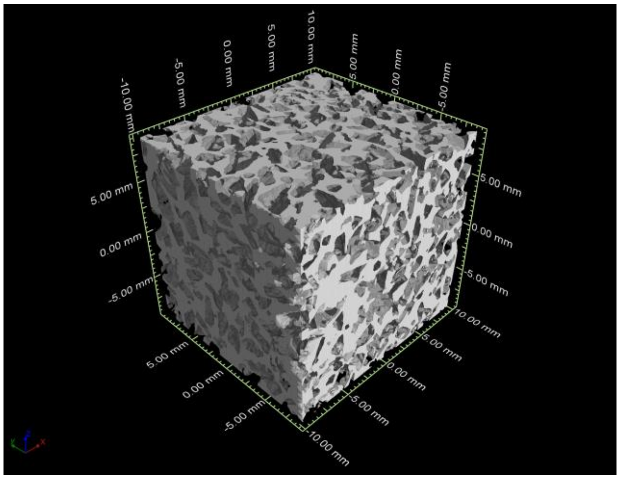

Figure 1 – 3D images of porous aluminum PA 80-110 before rolling

oriented in z-direction and the x-axis is normal to the rolled surface. The rolling direction is indicated by an arrow.
Structural ellipses of the initial plate before cold rolling can be found in Figure 3a. The pore size is similar for all orientations in the initial plate. Within the yz-planes the pores have the same dimensions for every direction, so that the structural ellipse appears as a circle. However, in the xy- and xz-planes the pores are slightly smaller in the x-direction. This slightly anisotropic pore morphology may be caused by the relatively small CT sample and an inhomogeneous pore distribution in the initial plate. This anisotropy in the porous structure is not reflected in the flow resistivities (compare Figure 6).

3 Rolling experiment and structural development

For the rolling experiments a rolling mill with a roll diameter and width of 250 mm and maximum force of 600 kN was used. The rolling speed was 416 mm/sec and the adjustment of the rolling gap was 0,2 mm per rolling pass. The initial thickness of the plates is t_0=20 mm.
During the cold rolling process the porosity and the pore size of the porous aluminum were decreasing with an increasing degree of deformation. Also it was possible to maintain an open porosity even for high degrees of deformation. Porosities for the initial and rolled plates are given in Table 1. All porosities given are open porosities.

Table 1 – porosities ϕ of the initial and rolled plates determined using CT scans

$\Delta t/t_0$ [%]	0	10	20	30	40	50
ϕ [-]	0,56	0,55	0,51	0,43	0,37	0,29

The structural ellipses for the selected degrees of deformation, plotted in Figure 2b to 2d, show a decreasing pore size with an increasing degree of deformation. Also it can be seen, that the reduction in pore size is strongest for the direction perpendicular to the rolled surface (x-direction). This leads to an anisotropic porosity in the rolled plates, with pores that are elongated in the direction of rolling (z-direction). The aspect ratio of the pores is strongest for planes perpendicular to the rolled surface and parallel to the rolling direction (xz-planes). Here the pores were compressed in the rolling gap and elongated with the material flow. Their width corresponds to the width in planes perpendicular to the rolled surface and the rolling direction (xy-planes). In these planes the pores were only compressed but not elongated with the material flow. Therefore their length corresponds to the width of pores in planes parallel to the rolled surface (yz-planes).
To analyze the influence of the decreasing pore size on the flow resistivity the pore width will be regarded as the decisive parameter. The mean pore width in the three planes is plotted in Figure 4. As indicated by the structural ellipses, the pore widths in planes perpendicular to the rolled surface (xy- and xz-planes) are similar, whereas the mean pore width in the planes parallel to the rolled surface (yz-planes), averaged over the whole thickness of the plate, is higher. Striking are also the high standard deviations in these planes, caused by a gradient of the pore size from the

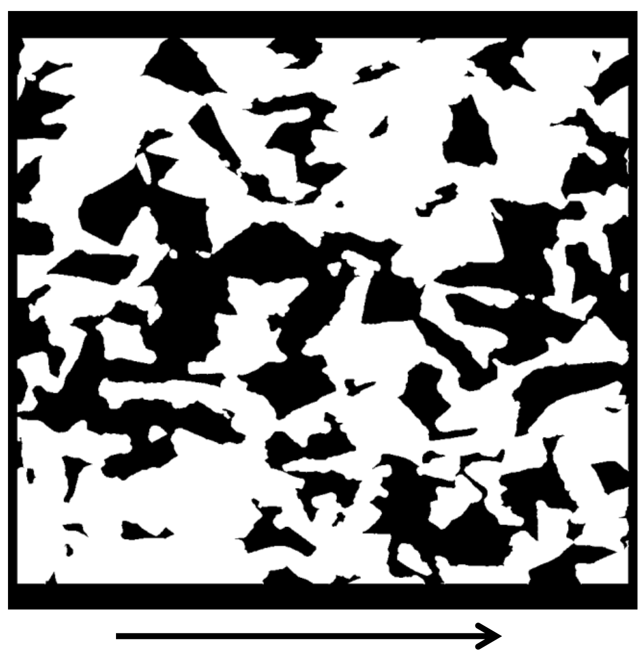

Figure 2 – Binarized image of the xz-plane for $\Delta t/t_0$=30%, rolling direction (z-direction) indicated by the arrow

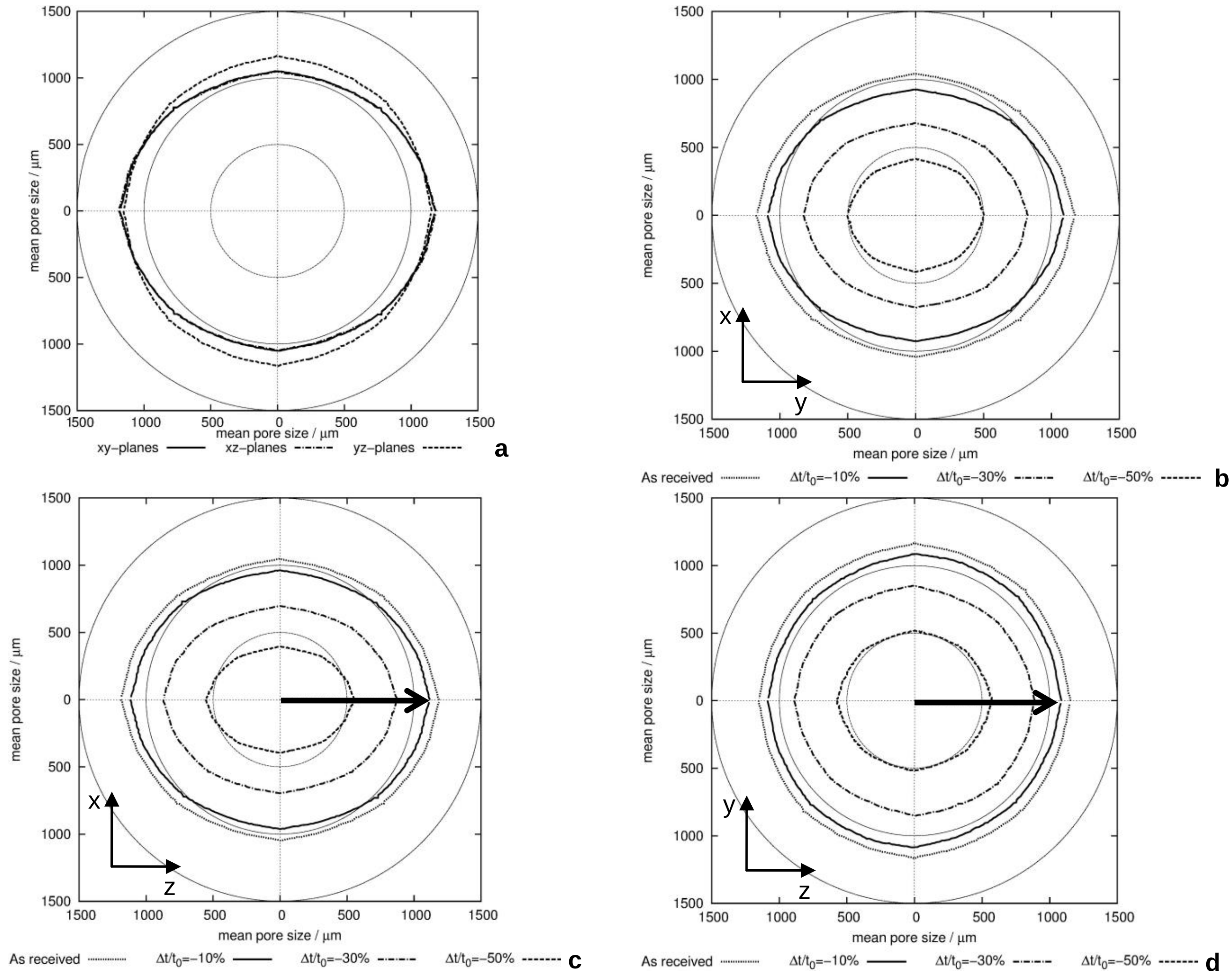

Figure 3 – Structural ellipses of initial and rolled pates. a) as received, b) planes perpendicular to the rolling direction and the rolled surface (xy-planes), c) planes parallel to the rolling direction and perpendicular to the rolled surface (xz-planes), d) planes parallel to the rolling direction and the rolled surface (yz-planes)

rolled surface to the core of the plate.

Figure 2 shows a plane parallel to the rolling direction and perpendicular to the rolled surface (xz-plane) for a degree of deformation of $\Delta t/t_0$=30%. The pores in the inner 30% to 40% of the plate appear significantly larger than the ones close to the surface of the rolled plate. To take that effect into account Figure 4 also shows a mean pore size for the inner 40% of the rolled plate and the regions close to the rolled surface separately. For these two regions the mean pore size diverges up to a degree of deformation of $\Delta t/t_0$=30% and converges again for higher degrees of deformation. This indicates, that the plastic deformation does not reach the core of the porous aluminum for plates thicker than t=12 mm ($\Delta t/t_0$=40%). From that point on the pores over the complete cross section of the plate are deformed. The mean pore width of pores close to the surface is similar to the width of pores in planes perpendicular to the rolled surface (xy- and xz-planes). For $\Delta t/t_0$=40% it reaches the smallest dimension of all three orientations. This is probably due to stochastic scattering, because for $\Delta t/t_0$=50% the pore width is again very similar to the width in planes perpendicular to the rolled surface.

4 Flow resistivity measurements

The flow resistivity was measured at the *Institute for Engineering Design – TU Braunschweig* in three main orientations (normal to the rolled surface (x-direction), transverse to the rolling direction (y-direction) and in rolling direction (z-direction)) for the initial and rolled plates, using the alternative airflow method (Method B DIN EN 29035) with an uncertainty of 14% [2]. The measured values were divided by the material thickness to obtain a specific flow resistivity and compare the values for rolled plates with different thicknesses. For the flow resistivity measurements the initial and rolled plates

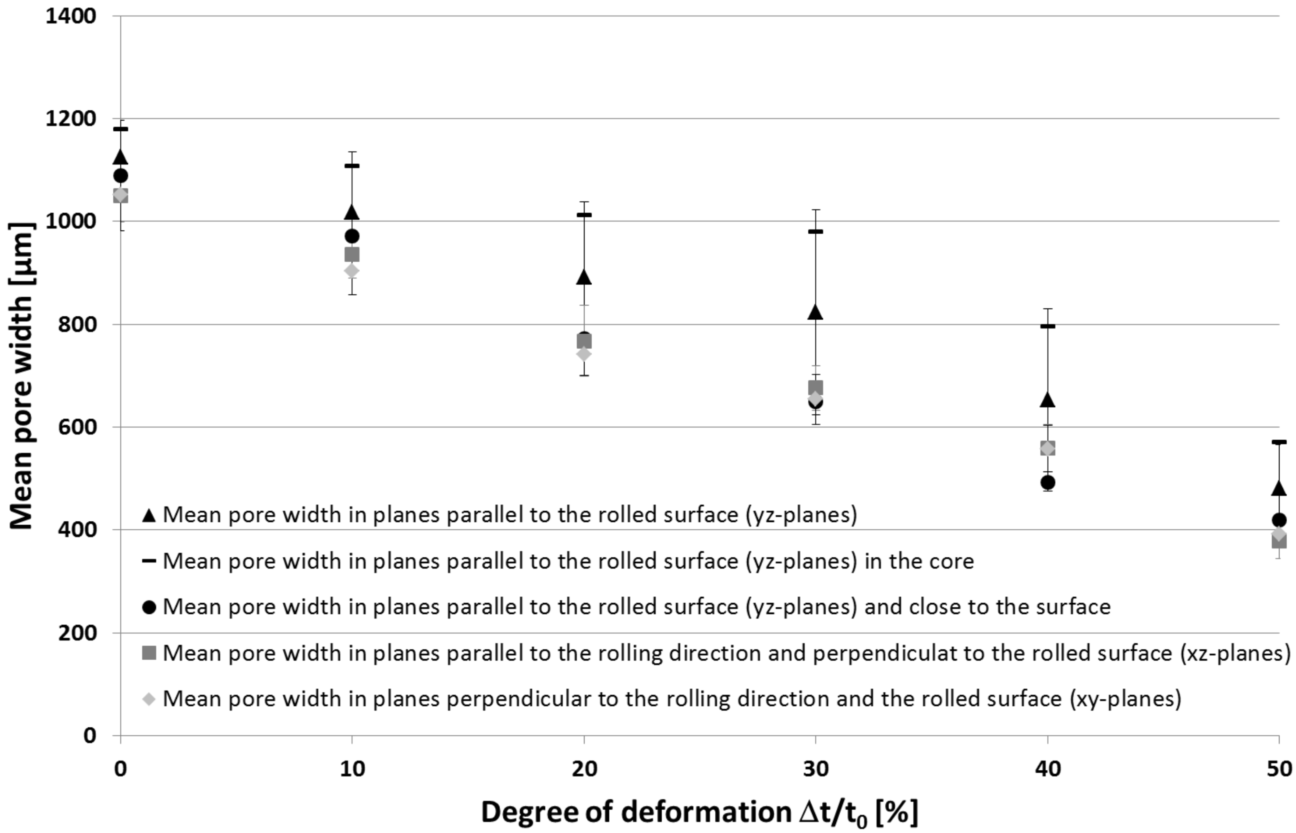

Figure 4 – Mean pore widths for different degrees of deformation and planes in the initial and rolled plate

were divided into four square plates of 60 mm edge length and a thickness according to the degree of deformation using wire-cut EDM to maintain an open porosity. For these four plates the flow resistivity was measured for the three orientations mentioned above. Because the sample shape differs from the one intended for the instrument, an adapter was used to mount the samples (compare Figure 5).

During the measurement the four surfaces parallel to the direction of flow were sealed with tape and gaps between the adapter and the sample were filled with plasticine. The averaged flow resistivity for the different degrees of deformation is shown in Figure 5. For the initial plate the flow resistivity is the same in every orientation. An anisotropic behavior, as could be expected from the structural characterization, was not found. As expected from the pore size analysis, the flow resistivity is increasing with the degree of deformation. Up to $\Delta t/t_0$=30% the flow resistivity is similar for all orientations. For higher degrees of deformation the flow resistivity is highest normal to the rolled surface (x-direction). For $\Delta t/t_0$=40% this corresponds with the smallest pore width close to the surface of planes parallel to the rolled surface (yz-planes). For $\Delta t/t_0$=50% the mean pore width is again very similar to the width in planes perpendicular to the rolled surface and therefore can't explain the difference in the flow resistivity. Besides being inversely proportional to the porosity and the pore diameter in second power, the flow resistivity is proportional to the tortuosity [1]. Due to the material flow during cold rolling and shear

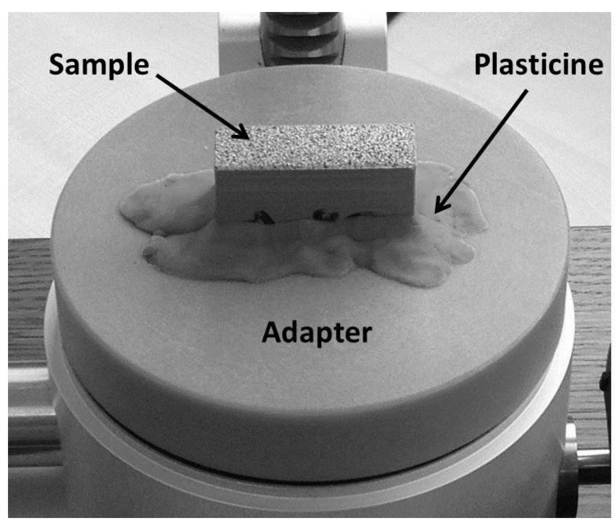

Figure 5 – Sample in adapter for flow resistivity measurement transverse to the rolling direction and transverse to the rolling direction

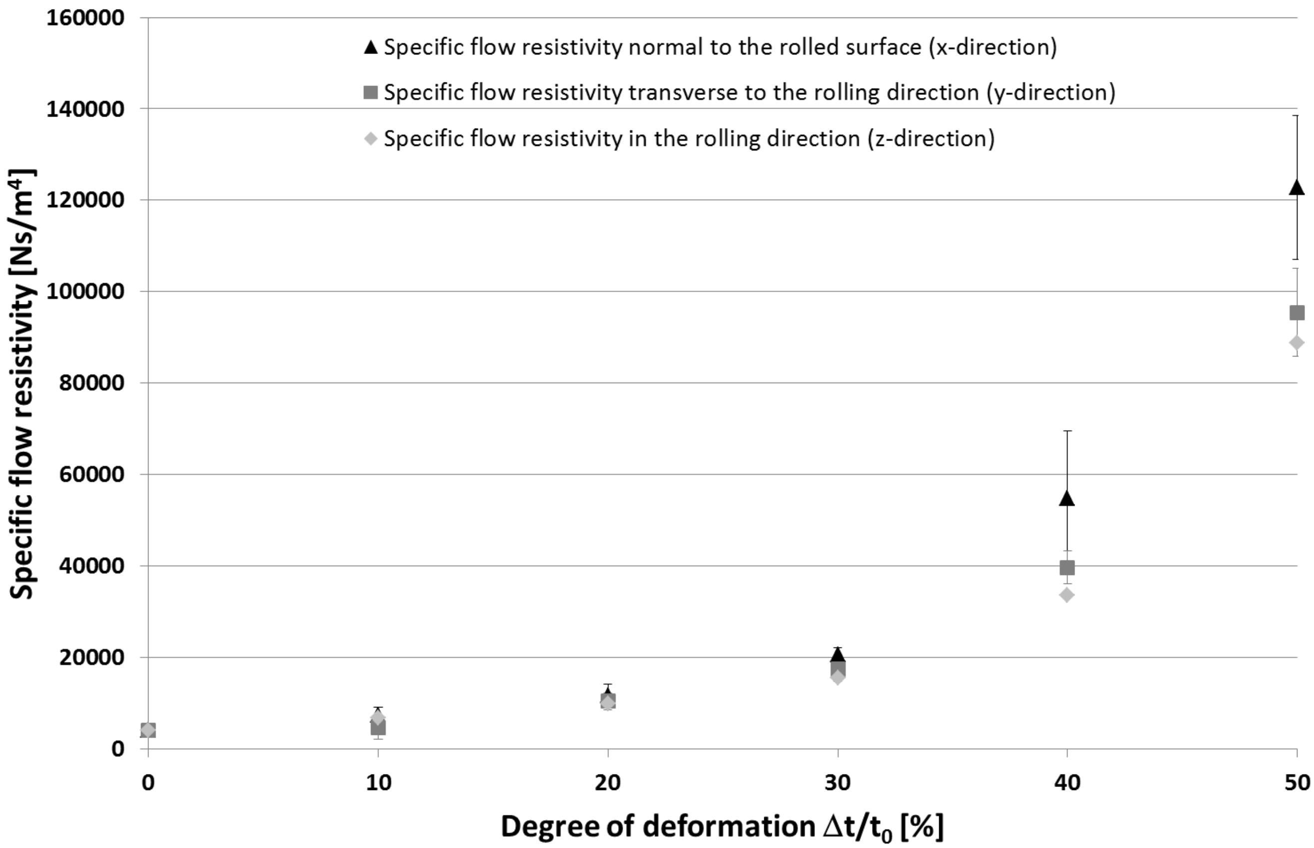

Figure 6 – Flow resistivity of porous aluminum after cold rolling

forces parallel to the rolled surface, channels through the material perpendicular to the rolled surface (x-direction) are twisted. Windows between pores are blocked and shifted in the direction of rolling (z-direction). This increases the tortuosity and as a consequence the flow resistivity normal to the rolled surface (x-direction). Therefore the development of an anisotropic flow resistivity is not so much influenced by the pore size, but by the increasing tortuosity normal to the rolled surface.

5 Conclusion

This study shows that it is possible to adjust pore size, porosity and flow resistivity of porous aluminum using a cold rolling process. It was observed that porosity and pore size in planes parallel to the three main surfaces of the rolled plate are decreasing with an increasing degree of deformation and that the aspect ratio of the pores is increasing. Even though the pores are closing during the rolling process, the X-ray scans show an open porosity even for high degrees of deformation. These results were compared to the evolution of the flow resistivity that confirmed the open porosity observed in the X-ray scans.

The development of the flow resistivity was anisotropic with the highest values measured normal to the rolled surface. This effect cannot be explained by the pore sizes in planes parallel to the three main surfaces but by an increasing tortuosity normal to the rolled surface. The tortuosity appears to be primarily responsible for the development of an anisotropic flow resistivity.

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References

[1] J. F. Allard und N. Atalla (2009) Propagation of Sound in Porous Media: Modelling Sound Absorbing Materials, Second Edition, John Wiley & Sons, Ltd; 67-69.

[2] DIN 29053 (1993) Acoustics; materials for acoustical applications; determination of airflow resistance (ISO 9053:1991); German version EN 29053.

[3] B. Hinze, J. Rösler und N. Lippitz (2012) Noise Reduction Potential of Cellular Metals, Metals, 2: 195-201.

[4] B. Hinze, J. Rösler and F. Schmitz (2011) Production of nanoporous superalloy membranes by load-free coarsening of ’-precipitates, Acta Materialia, 59: 3049-3060.

[5] N. Lippitz und J. Rösler (2015) Mechanical and structural characterization of porous materials, Braunschweig: TU Braunschweig – Niedersächsisches Forschungszentrum für Luftfahrt, 29-40.

[6] J. Rösler and O. Näth (2009) Mechanical behaviour of nanoporous superalloy membranes, Acta Materialia, 58: 1815-1828.