Grain Flow in Forgings VI – Preforms and Open-Die Forging

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Grain flow is the orientation of grains and inclusions/particles within the metal caused by plastic deformation. Proper orientation of grain flow can improve component properties that involve a fracture or a crack (e.g., impact resistance, fatigue life and ductility). Previous articles covered how to observe grain flow in forgings, how the forging process can change grain flow, how the grain flow in forgings compares to grain flow produced by other processes, and how forging simulations are instrumental in assessing grain flow during forging processes.

Our primary focus has been on closed-die forging for previous articles in this series. In this one, however, we will consider preforms and large components, which are often produced by open-die forging. Simple preforms can have significantly different grain flow depending on the prior deformation. Open-die forgers have some control in producing a desirable grain flow, even in large components, and it is important to understand grain flow for large open-die forgings to the same extent as for smaller impression-die forgings.

Grain Flow in Simple Preform

Grain flow is accumulated and is additive over all the deformation processes through the process chain. An ingot can be converted to billet using rolling, cogging, drawing or extrusion. Each produces a different grain flow, although it has a dominant longitudinal component. This becomes the starting point for subsequent forging operations. Final forging modifies the prior grain flow, generally to a great extent. On the other hand, early operations can still have a significant influence on the grain flow in the final product. For example, a simple cylindrical preform can have different grain flow depending on the source of the disk and the prior work that has been imparted to the metal.

Figure 1 shows how a simple cylindrical workpiece can be obtained from sources with different processing techniques, each of which will have imparted a different grain flow to the workpiece. Furthermore, this grain flow will be imparted to (and within) the workpiece before the upset process occurs. In the top image of Figure 1 the cylindrical preform is cut from a rolled plate. The middle image shows a cylinder preform cut from an extruded bar. The bottom image shows a cylinder obtained by prior upsetting of a taller cylinder. In all three cases, the final cylindrical preform has essentially the same external shape. The geometry of the final cylinder does not reveal much about the prior deformation. The issue is that this deformation history can be extremely important.

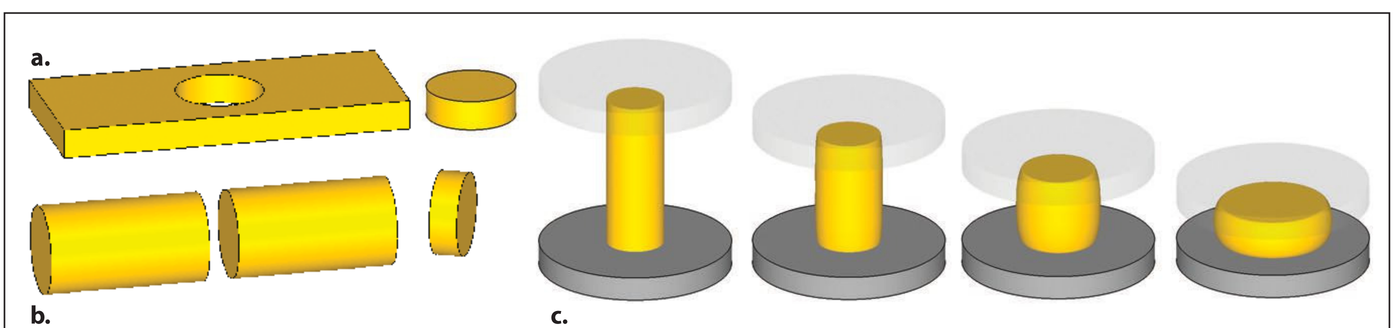

Figure 1. A simple cylindrical workpiece can be cut from a rolled plate (a); cut from an extrusion (b); or produced by the upset of a taller cylinder (c).

Figure 2 shows the primary orientation of the grain flow for cylinders made by the processes shown in Figure 1. The top left image is the cylinder obtained from a rolled plate. The deformation by rolling imparts a grain flow to the plate that is in the direction of rolling. A cylinder extracted from such a plate will have grain flow perpendicular to the center axis of the disk. In contrast, the top right image shows the grain flow present in the cylinder obtained from an extruded bar. The extrusion process produces a part with a grain flow in the direction of the extrusion process (longitudinal). Cutting a cylinder from this material creates a disk with grain flow that is parallel to the center axis of the disk, which is completely different from the disk obtained from a rolled plate.

The lower images in Figure 2 show the evolution of the grain flow in a cylinder produced by upsetting a taller cylinder. The initial tall cylinder will have grain flow from its prior processing, which generally is in the direction of the bar's center axis. During upsetting, metal will flow from the center of the piece radially outward. The top and bottom regions will also flow outward but in a somewhat restricted way due to friction between the tooling and workpiece end faces. Thus, the final grain flow is more complex than in plate or extrusion. This grain flow has more process-induced curvature.

Although these examples appear to be simple, they illustrate the absolute need to understand a billet's prior processing. The examples can be very significant in some applications and forging operations. In most rolled-ring processing, the initial preform is doughnut-shaped and obtained from punching a hole in a cylindrical disk. As can be easily seen in this example, the starting workpiece will have a different starting grain flow depending on the source of the preform disk.

Open-Die Forgings

Open-die forging uses simple tool geometry to forge a workpiece. This is in contrast to closed-die forging, which involves more geometrically complex geometries. Though the fundamentals may appear to be roughly equivalent to a blacksmith with a hammer and anvil, some very complex shapes can be produced for critical applications. There is a much greater dependence on the skill of the operator(s) compared to a closed-die forging, where the shape is dependent on the die cavity and shape control is more dependent on the skill of the die designer.

In spite of the simple tooling, grain flow will continue to develop as the workpiece is deformed. The final grain flow will be the result of that which is inherent to the starting material and the deformation during the open-die forging process.

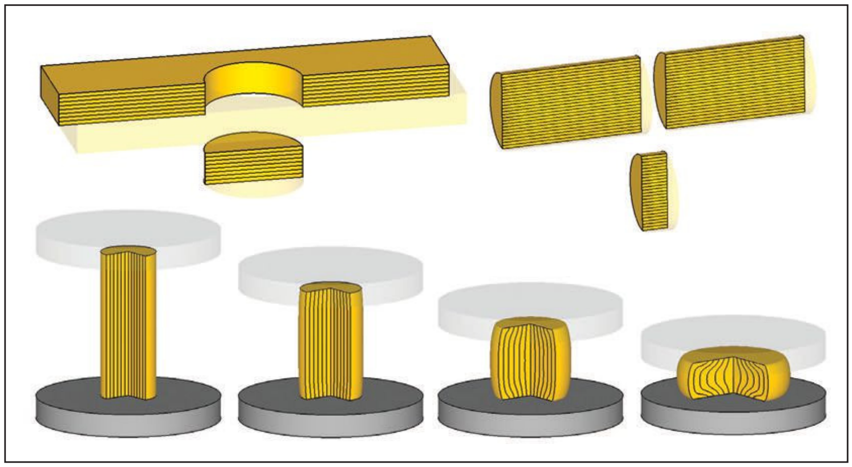

Figure 2. The grain flow in the workpiece is completely different for the three manufacturing methods.

Figure 3. Large crankshafts can be manufactured using several different methods. *Courtesy Ellwood Crankshaft Group*

Figure 4. One method of forging crankshafts is to heat and forge the individual throws of the crankshafts to near-net shape. *Courtesy Ellwood Crankshaft Group*

Open-die forgings can frequently be manufactured using different methods. The directional properties produced by grain flow can be optimized for service due to the flexibility of open-die forging. Collaboration between the OEM designer and forger is necessary for this optimization to occur. The forger needs to understand the final use of the component so that the forging sequence can be designed to optimize the grain flow for the application.

Crankshaft Example

A large forged crankshaft will be used to illustrate this process. The upper image in Figure 3 shows a large crankshaft that can be forged by a "slab" process. The lower image shows the crankshaft made by a "continuous grain-flow" method. The slab process is an open-die procedure, while the continuous grain-flow method is a multi-axis closed-die process. The upper image shows the slab forging with the individual throws machined prior to hot twisting. In contrast, the lower image (Figure 3) shows the crankshaft produced by continuous grain flow or near-net shape. Figure 4 shows this continuous grain-flow crankshaft in production.

To see the forging steps and understand the grain flow, a simulation of the continuous grain-flow forging was used. Figure 5 illustrates several steps in this forging. The throws are produced by compressing the shaft to produce the appropriate offset concurrent with some compression in the axial direction. This simultaneous compression causes a significant difference in the grain flow around the corner regions of the crankshaft, which are most susceptible to fatigue cracking. By using continuous grain-flow forging, this region of potential fatigue cracks will have grain flow perpendicular to the direction that a fatigue crack would propagate, thereby enhancing the fatigue properties of the crankshaft. Figure 6 shows a comparison of the grain flow in a typical slab-forged crankshaft and the grain flow in the near-net-shaped forged (i.e., continuous grain-flow) part. The differences in grain flow are obvious, especially in the critical corner regions.

Figure 7 shows the fatigue curves for the two crankshafts. The continuous grain-flow crankshaft has 6% greater fatigue strength relative to the slab-forged crank. This increase in fatigue strength can be directly attributable to the appropriate grain flow in the near-net-shape forged crank.

Summary

This article examined the effect of prior processing on the grain flow that can occur in preforms. Even a simple disk preform can have significantly different grain flow, depending on the previous manufacturing. We also explored grain flow in the open-die

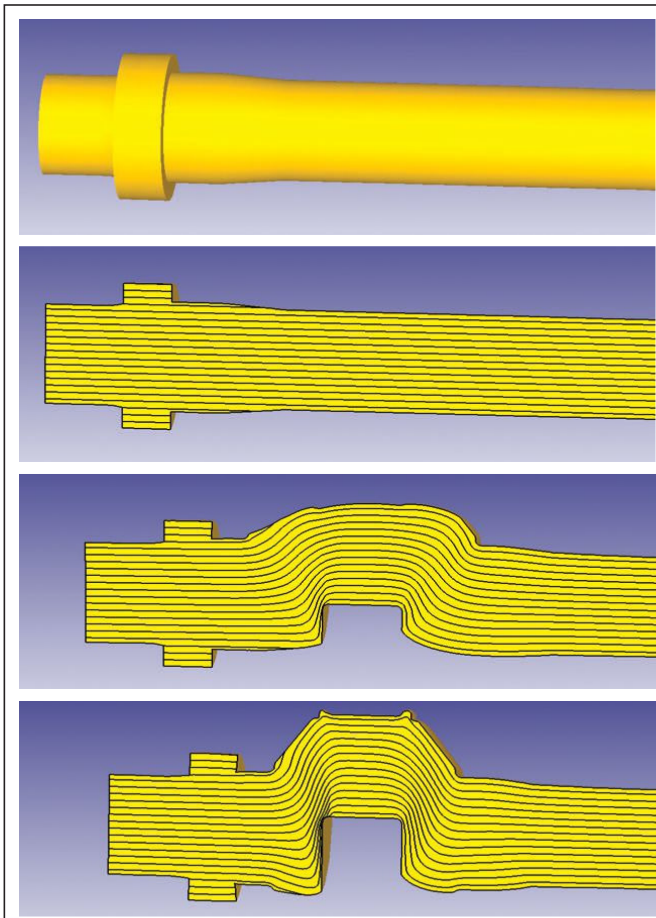

Figure 5. This crankshaft is said to be a continuous grain flow (CGF) forging due to the nature of its deformation steps (as shown)

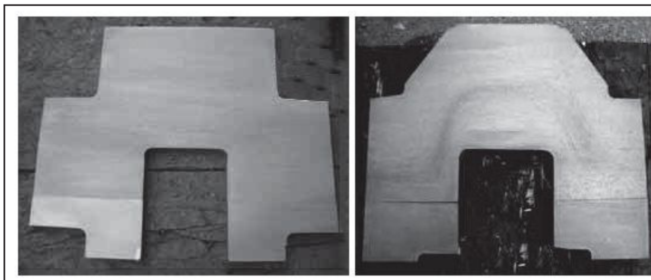

Figure 6. Sliced sections show the horizontal slab forged grain flow and the continuous grain flow of the near-net forged crankshaft.

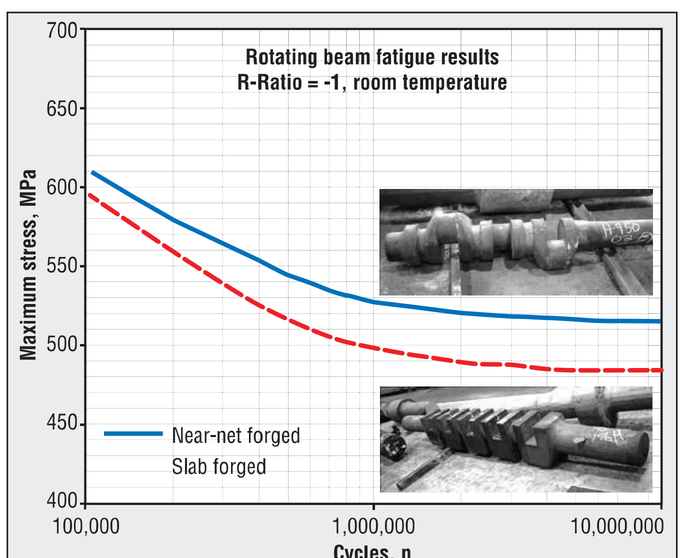

Figure 7. The near-net forged continuous grain-flow crankshaft had a 6% higher fatigue limit than the open-die slab-forged crankshaft.

forging of a large crankshaft. It was found that an increase in fatigue life can be achieved if an appropriate grain flow was obtained in the crankshaft. It again needs to be emphasized that a good level of communication needs to be maintained between the forger and the designer of the final component to achieve this type of increased performance.

This is the final article in our series on grain flow. We hope that you have found these articles of interest and that they have provided some insights on how forgers can provide added benefits to the products they produce.

Acknowledgements

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