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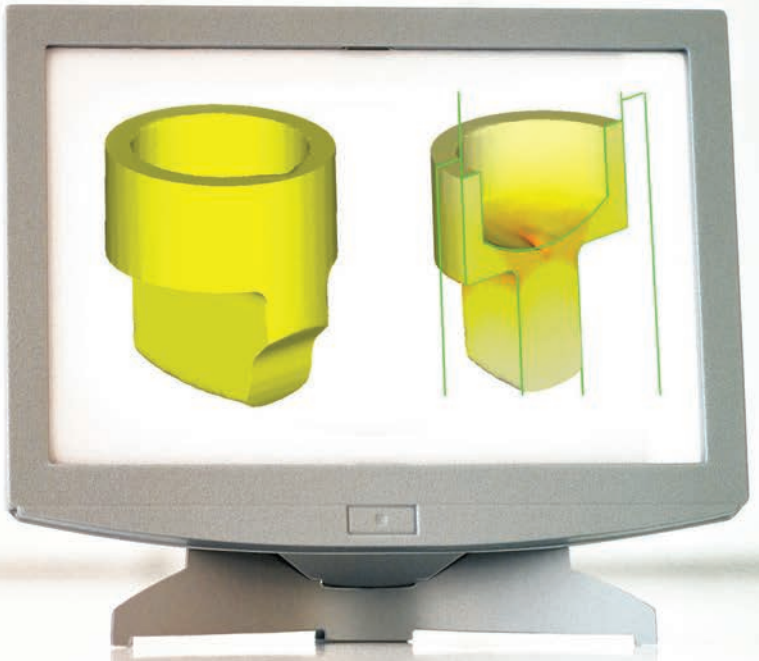

Understanding Geometrical Forging Defects

In this first of two articles, authors Van Tyne and Walters examine possible causes and remedies of geometrical foging defects, which are generally related to pocess design. In the second and final article – in a subsequent issue of FORGE – the authors will examine the subject of material-related defects.

The forging process, by its nature, produces a superior product, especially in comparison with castings and machined components. Defects can occasionally occur during the forging process, but it should be understood that forging defects are not inherent to the process itself. By analogy, a world-class athlete will occasionally suffer an injury. How does the athlete respond to this setback? He or she will determine the cause of the injury, take corrective actions to repair any damage and try to prevent the re-occurrence of the injury in the future. Similarly, if a forge shop begins to experience defects in their process, they should try to find the root cause of the problem, initiate corrective action and implement procedures to prevent its recurrence.

In this two-part article we plan to cover a number of possible forging defects and provide some insight into their cause as well as recommendations for corrective action. In this first part we will cover geometrical defects. In the second we plan to discuss material-related defects due to microstructure and ductile failure.

Remember that in an optimum environment, many defects could be avoided. Cost pressures and lead-time reduction efforts result in pushing the forging process to its limits. Although some phenomena require additional research, there are many defects that have been characterized and studied. Many of these can be corrected. Economically, as well as from a quality perspective, it is better to understand and control your process so as to avoid defects rather than scrapping defective parts during a final inspection.

Defects can result from a less-than-optimum process design or poor execution of the design in manufacturing or material-related problems. It should be noted that a robust process would be designed so as to allow some variation in material without causing a defect. This article addresses the defects generally related to process design – usually described as geometrical defects.

There are a number of different geometrical defects that can occur during forging. These include:

- Laps and folds
- Underfills
- Piping
- Forging shape does not match design
- Die deflection, yielding or wear
- Eccentricity or buckling

Less-than-optimum process and preform design is the principal cause of most geometrical defects. By understanding the process issues, the forge is better able to design its processes to minimize the occurrence of such defects.

When the press or hammer dies close, the workpiece will move in

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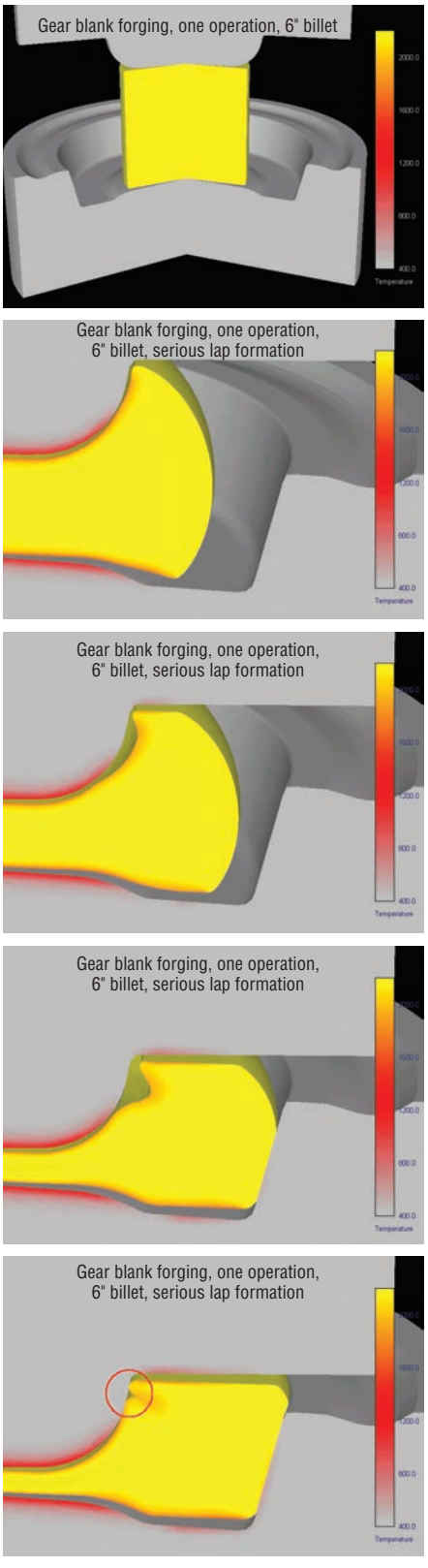

Figure 1. The formation of a "flow-by" lap is shown in a gear blank forging. Redesign of the punch nose or preform geometry can prevent this type of geometrical defect.

a path of least resistance. It is imperative that the die and preform design create this least resistant path so that the net result is a sound forging. On occasion, the die design may create a situation in which the path of least resistance is the one that results in a defect during forging. By examining the various types of geometrical defects, the fundamental cause can be understood and the die designer can produce a die that creates a sound, defect-free product.

LAPS AND FOLDS

The most common type of geometrical defect is a lap. Laps are the result of:

- A section of the workpiece flowing into itself
- A "flow-by" in which the workpiece surface is in contact with a die and is subsequently pulled away by a tensile stress component and closes on itself
- "Peeling" that can form when the surface of a billet or preform is sheared by a die, resulting in an area of localized folding. A die corner is frequently involved, as it forces material ahead of a moving contact region, without significant subsurface deformation. This defect can be the result of a poor design or inadequate process control.
- Flow localization that can also show up as a forging lap in alloys where flow softening exists. (These will be discussed in more detail in part 2).

Most laps are resolved by changing the forging preform, forged shape or process. The prevention of laps is primarily a process-design issue due to improper preform geometry or improper impression geometry. The use of simulation tools is a very effective way to evaluate several preform shapes and avoid forging laps.

Figure 1 shows several frames of a simulation for the forging of a gear blank in which the die design produces a "flow-by" lap. As the upper die descends and the workpiece is compressed, the material "flows by" – does not maintain continuous contact with – the side surface of the punch. The material hits the outer bottom surface of the punch and folds back onto itself, creating the lap defect as indicated. The preform shape in conjunction with the punch design causes the defect.

Figure 2 illustrates the formation of a "peeling" lap for the forging of an aluminum rib. The shape of the preform, together with the shape of the upper die, causes this defect to occur. As the upper die compresses the workpiece material, it begins to shear, or "peel," the surface of the rib region. In the finished component the defects appear on the part's top surface in spite of the fact that they were generated on the side surface of the rib. The use

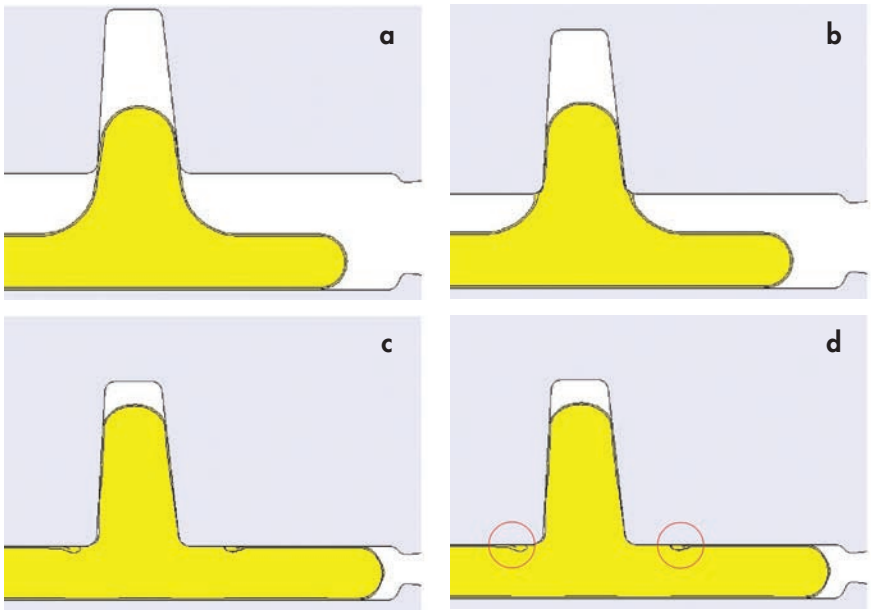

Figure 2. A "peeling" lap forms in an aluminum rib-web forging as the corner of the die forces surface material ahead of the contact region. With a redesign of the upper die or preform, this type of defect can be prevented.

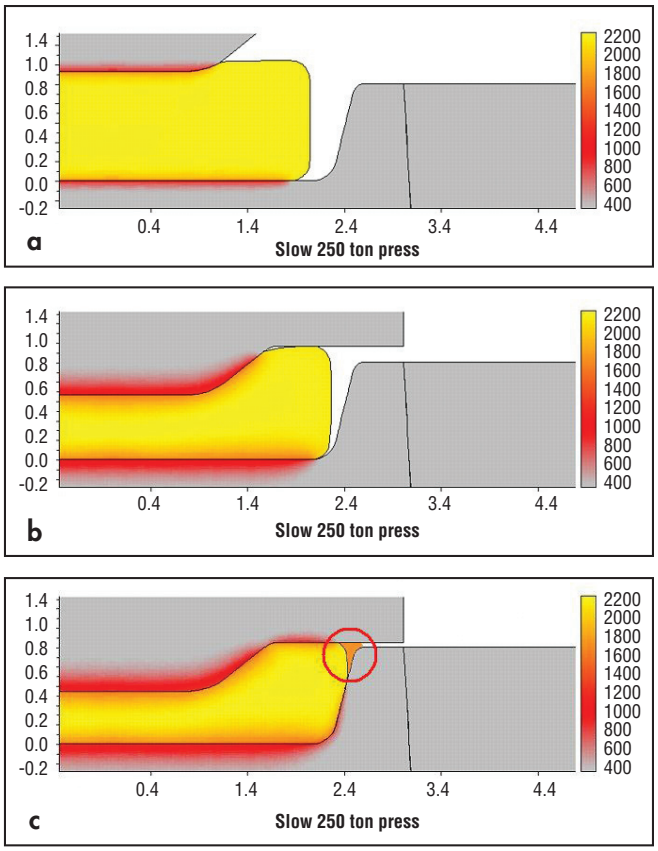

Figure 3. A steel forging with an underfill (orange) is the result of using an undersized hydraulic press with inadequate power and force to completely fill the die cavity.

of the simulation program to study this defect provides insight into how it was generated and where remedial changes should be made to the die design. To correct this defect, a redesign of the rib region in the preform shape would be advisable.

UNDERFILLS

Underfills are another geometrical defect commonly caused by inadequate press force, energy and/or power. These may be symptomatic of the use of undersized equipment on jobs that are too big for it. Also, the improper control of lubricant vapors can cause this type of defect.

Underfilling is typically a problem when a large part is manufactured on a small press with a less-than-optimum preform geometry. Smaller equipment does not provide the option of overpowering a less-than-optimum design or leave much margin for process variation. Depending on the equipment, force, power, speed or energy can be the culprit for an underfill.

Figure 3 shows a steel forging being produced on an undersized hydraulic press. Because the press is slow, there is significant chilling of the workpiece, as indicated by the temperature profiles in the figure. This causes the flow strength of the steel to increase and require more force to deform it. Because of its small size, the press will stall before the component is completely forged, leaving an underfilled region. To avoid this, equipment of the right capacity must be used.

Underfills can also result from air, gas or lubricant being trapped in a corner feature of a forging. These can be eliminated by a redesigned preform, which provides a vent for gas, or by adding corner closure to the final forging. The ideal gas law can be used to describe the behavior of gas being compressed in a die corner:

$$PV = nRT$$

where P is the pressure, V is the volume, n is the number of gas molecules, R is the ideal gas constant and T is temperature. For a fixed amount of gas at a constant temperature, the right side of the equation is constant. However, when gas is trapped inside the die cavity and compressed (i.e. volume decreases), the gas pressure increases. When the pressure of the trapped gas is equal to the surface pressure on the forging, no further reduction in volume occurs, resulting in an underfill.

High temperatures compound this effect by heating the trapped gas first with a resulting increase in pressure and subsequently larger underfill. Finally, trapping lubricant, glass or water vapor may change the dynamics of the compression process since these materials may not precisely follow the compressibility of the ideal gas law. Glass coatings used when forging titanium alloys are virtually incompressible.

Figure 4 shows an underfill created by trapped gas in a rib corner. As the dies close, a fixed amount of gas is trapped. As the volume available for the gas decreases, the pressure of the gas increases (via the ideal gas law). Eventually, the gas pressure gets so high it reaches the same level as the surface pressure on the forging and further compression cannot occur. At this point, some volume of the die cavity will remain unfilled.

At times, underfills can result from blockers with less-than-optimum volume distribution. Blockers are designed to approximate the volume distribution of the final forging with less detail. With a perfect preform, the cavity is finished filling as the flash starts to form. The flash formation increases die-cavity pressure and is used to ensure complete die filling. With an incorrect volume distribution, the flash can form prematurely, resulting in an underfill.

Figure 5 shows a forging simulation using an improperly designed preform, which causes an underfill. In this web-rib forging the

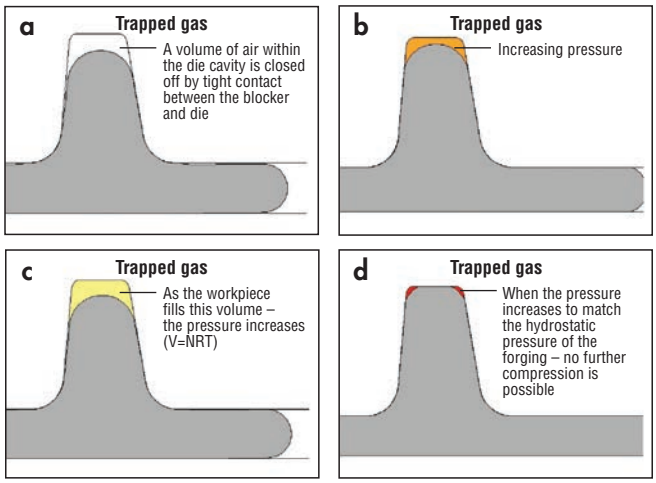

Figure 4. Underfilled corners are the result of trapped gas during the forging process. This type of underfill can be prevented by redesign of the preform, by providing a vent (or relief gutter) for gas or by adding corner closure to the final forging.

volume distribution of the preform is incorrect. Note that the flash begins to form (Figure 5c) well before the web cavity is filled. To correct this problem the blocker must leave more material in the web region so that the cavity can be filled at the time the flash begins to form. In this case the simulation aids the die design to see how the distribution of material affects the final shape.

During extrusion, die forging or other processes with significant changes in section sizes, it is possible for a feature to be starved for volume. This starvation can result in defects ranging from a shallow underfill to a severe seam. These defects are commonly referred to as pipes.

Piping defects are closed underfills. Piping, or "flow-through," defects are resolved by changes in the die impression or the preform geometry. Figure 6 shows a piping or suck-in defect in an aluminum impact extrusion. The pipe occurs at the end of the stroke when there is an insufficient volume of material in that location.

GEOMETRICAL DISCREPANCIES

During open-die forging or forging without any die contact, the workpiece may flow in a manner that is different from the design plan. Even though we would like the material to flow in a prescribed manner, if it is unconstrained it may move in an undesirable fashion, leaving a part that does not meet the customer's specifications. This type of material movement is not random or arbitrary and will take the path of least resistance in determining its flow. Simulation programs can aid the forger in understanding actual material flow. These packages incorporate the flow along the path of least resistance within their calculations and provide a detailed view of the actual geometry that a part would take when the dies do not provide constraint.

SIMULATION PROGRAMS

Simulation programs can be effectively used to see the formation of defects. These tools allow the forger to "see" inside the die and the workpiece during deformation. The simulation tool can also provide a serial view of the process dynamics in both forward and backward directions. These can provide the forger with significant insights into the origin and evolution of the geometrical defects that are described in this paper.

Simulation has allowed us to clearly illustrate die designs that contribute to geometrical defects of laps and underfills. The programs also allow the forging engineer to test a number of "what if" scenarios without having to actually sink a die and run tests in the forge shop.

FINAL COMMENTS

During the forging process, workpiece material follows the path of least resistance rather than the forging print. Improper die design or improper preform design can cause the workpiece to flow in an undesirable fashion, resulting in a geometrical defect. The main types of geometrical defects are laps and underfills. If such defects are encountered in your forgings, corrective action needs to be taken. The use of simulation tools can provide insight into the fundamental cause and the appropriate adjustment.

Part 2 of this article will address the problems and solutions associated with the second major class of forging defects – material induced defects.

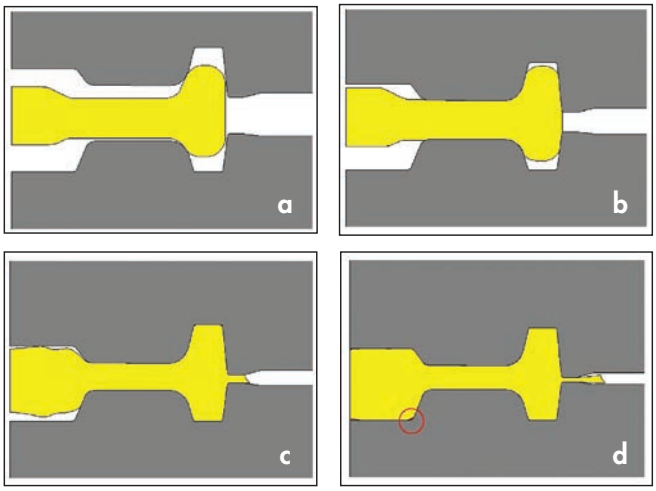

Figure 5. Underfill due to incorrect volume distribution in the blocker for a rib-web forging. The underfill is shown in d. The preform must be redesigned to prevent this type of underfill.

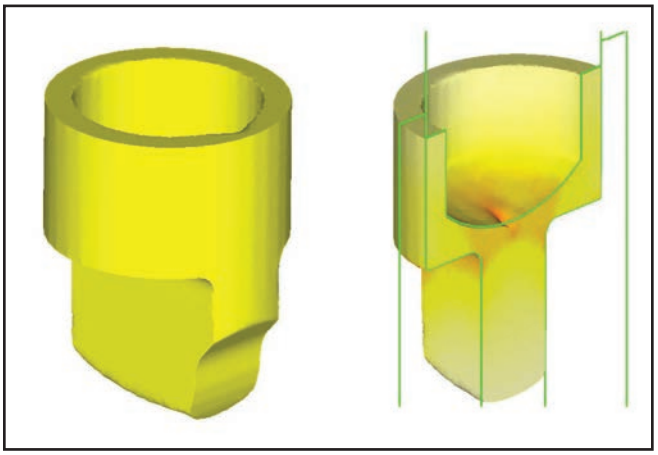

Figure 6. An aluminum impact extrusion – note the piping defect (i.e. suck-in defect) at the end of the die stroke. The forging has been starved for material in this region. A redesign of the die or preform is needed in order to correct this.

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