FORGING SOLUTIONS
Design Engineering Information From FIA

OPEN DIE – CASE STUDIES

TABLE OF CONTENTS

Replacing a Cast Hub with a Forged Hub Reduced Downtime
Forged Compressor Cylinders Achieved Longer Life and Isotropy via Optimized Forging Techniques and Inclusion-shape-controlled Steel
Open-die Forged Gear Blank/Hub Delivered Maximum Property Profile with Cost Savings
Forged Tube Support Replaced Bar Stock, Eliminated all Machining and Cuts Cost by 85%
Capability Analysis Brought Process into Control, Boosted Quality of Forged Automotive Parts
Forgings Replaced Castings, Cut Costs, Eliminated All Rework and Rejects for Critical Tank Part
Statistics Confirmed Castings as Downtime Culprit, Replaced with Open-die-forged Cylinders
Forged Aluminum Ejector Cut Cost, Provided Critical Dimensions
CASE STUDY FROM THE FILES:
Replacing a cast hub with a forged hub reduced downtime

Just days short of a catastrophic failure, workers discovered several large cracks in a mining shovel’s cast hub, the central pivot point upon which all shovel functions depend. Apparently, a combination of sub-surface porosity and HAZ (heat affected zone) effects initiated fatigue cracking in the weld area.

Unfortunately, a call to the casting supplier brought the advice that a cast replacement would take a minimum of four weeks (and perhaps as many as six) to make. Shutdown of the mine for such a long period of time would be economically unfeasible.

Fortunately, an enterprising open-die forger got the second call and within four days (two working days) the customer had a forged-steel hub—at the same price as a casting—ready for installation. In addition, freedom from porosity and other internal defects holds promise for a longer service life for the forged version. See figure above.

Of course, it was not a simple case of substituting a forging for a casting. Some creative forging techniques were necessary, especially considering the time constraints involved. With an unusual shape, the hub has a square head, stepping up to a round journal, and incorporates a large, forged inner diameter.
Forged compressor cylinders achieved longer life and isotropy via optimized forging techniques and inclusion-shape-controlled steel

Large internal-engine compressors, where the natural-gas-fueled engine and compressor cylinders operate from the same crankshaft, are used to re-pressurize natural gas for conveyance through cross-country pipelines, or for high-pressure injection into underground storage.

The design of multi-port compressor cylinders is particularly critical, especially when it comes to ensuring good microstructural integrity in the areas between the valve ports. In these areas, there is a tri-axial stress state and fracture would eventually lead to gas escape and a potentially hazardous situation.

Accommodating the stresses in these areas requires the best possible metal soundness and toughness to avoid the possibility of internal cracking of the cylinders in fatigue.

Castings were quickly ruled out because of their lower strength and potential for porosity. Castings rarely show tensile elongations higher than 10% when heat-treated to strength of over 120,000 psi, making desired elongations of at least 10% all testing directions, which was impossible for cast versions.

Initially, conventional open-die forgings were evaluated to determine if the overall property profile was adequate. Standard forging techniques included the normal drawdown procedure from ingot to billet to forging. Here, 45 in. diameter ingots were conditioned, heated to forging temperature, and upset sufficiently to remove scale. They were then drawn down to a billet size of 28 x 36 in., cut and redrawn to the final size of 24 x 36 in.

Although longitudinal mechanical properties were more than adequate, less than desirable ductility and fatigue properties were achieved, especially in the short-transverse properties in large forgings. Consequently, the forging procedure was modified to include a 42% upset reduction prior to the final draw-down procedure. In addition, the Cr-Mo-V steel was further improved by using inclusion-shape-control technology to modify the shapes of normally occurring intermetallics and inclusions. The refinement in steelmaking reduces the likelihood that long stringer-like inclusions, which can seriously reduce transverse properties, would be present after forging. Prototype forgings made by using the modified upset-redrawing procedure on inclusion-shape-controlled steel yielded the desired property profile.
CASE STUDY FROM THE FILES:

Open-die forged gear blank/hub delivered maximum property profile with cost savings

Open-die forging is often the best way to produce an integral gear blank and hub. It is not only a cost-effective process that yields the optimum in performance, but also offers the flexibility of size change. For instance, if it becomes necessary to increase the gear blank diameter or thickness, open-die forging readily accommodates such a change. For 10 or 20 pieces, open-die forging is ideal, achieving the optimum property combination. For 1,000 pieces, closed-die forging would be more practical.

In this case, hot forging consisted of a series of cross-section reductions and then upsetting the gear-blank section to the proper size. A 4,000 lb. steam hammer was used to provide good depth of deformation (to the center of the workpiece) and to eliminate the as-cast grain structure.

Each forging operation was designed to achieve the desired configuration sequentially while imparting the required reduction ratio through five separate forging operations. See figure above. Together, these forming operations aligned the grain-flow orientation with the part configuration, essentially enhancing properties in the longitudinal or axial direction in the hub and in the radial direction of the gear blank. This resulted in the optimum combination of tensile and yield strengths, impact toughness, and fatigue life.

Hot forging refined and densified the characteristic cast structure of the starting stock, thereby eliminating inherent
cast porosity, redistributing segregation more evenly via metal flow, and reducing the size of as-cast large inclusions. By controlling the reduction ratio throughout the forging process, the extensive working or deformation imparted achieved structural integrity, a uniform microstructure, and much improved mechanical properties, as compared with the properties of the starting stock. Overall, resultant properties surpassed those that can be obtained with a cast, machined, or welded component.

The steel of choice was 4140, selected for its excellent combination of strength, ductility, toughness, and fatigue properties. It is a modification of 4130 steel that provides a greater depth of hardenability (due to its higher carbon content). It is also suitable for surface hardening. After machining, the customer may elect to normalize, temper, and then either induction-harden or nitride the forging, depending on the particular gear application.
CASE STUDY FROM THE FILES:

Forged tube support replaced bar stock, eliminated all machining and cuts cost by 85%

In a concerted effort to reduce costs of its metal components, a major manufacturer of medium- and heavy-duty industrial and agricultural equipment worked closely with a local forging company to redesign a machined bar stock component as a more cost-effective forging. After conversion, the results were better than expected, for a simply configured, volume-sensitive component. The steel forging cost less than one-sixth that of machined bar stock.

Previously, four different operations were required to produce the part. First, a long piece of 1020 hot-rolled bar was cut in two, then flame cut, ground, and was finally placed into a lathe fixture where the bottom was turned. By making it a forging, the company was able to produce it close enough to net shape to eliminate all machining operations—a reduction from four in-plant operations down to none. See top figure. As received from the forger, the components were directly installed on the equipment. See bottom figure.

The as forged steel tube support was ready for assembly, as compared to the bar stock version, which required extensive machining.

COST ANALYSIS FOR STEEL TUBE SUPPORT

<table>
<thead>
<tr>
<th>Operation</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL COST OF MACHINED BAR STOCK</td>
<td>100%</td>
</tr>
<tr>
<td>RAW MATERIAL COST</td>
<td>7%</td>
</tr>
<tr>
<td>SAW, FLAME CUT, SHOT BLAST</td>
<td>10%</td>
</tr>
<tr>
<td>BORE OPERATION, DEBurr</td>
<td>83%</td>
</tr>
<tr>
<td>TOTAL COST OF FORGING</td>
<td>15%</td>
</tr>
</tbody>
</table>
CASE STUDY FROM THE FILES:

Capability analysis brought process into control, boosted quality of forged automotive parts

Capability studies are powerful tools in controlling the forging process. In this example (relatively high volume aluminum die forgings), too many automotive parts were being produced outside the specification range. Although practically all parts could be reworked to bring them within the blueprint tolerance range, adjusting the process should theoretically produce all parts to specification.

To analyze the situation, engineers conducted a capability study using the die closure dimension (thickness), which is normally the dimension of interest for evaluating how well the process is “in control.” If this dimension is correct, so are all other dimensions.

Initial capability analysis showed that the spread was too wide for the specification, and that the process was off center, as indicated by a low process capability index or Cpk. By definition, Cpk = specification tolerance range divided by ±3σ of the process capability range. A process capability index, Cpk, of greater than 1.33 means that more than 99.94% of the forged products are within the specified blueprint tolerance.

Adjusting specific process variables brought the process back into control, achieving a Cpk of 1.3820 versus the initial value of 0.0123. See table. The adjustments also brought the mean value much closer to center. See figure above. Consequently, all parts produced after process adjustment fell within the specification limits. Rework dropped from 49% to 0.

Other benefits included not only reduced inspection, but also the elimination of part sorting and restriking or oth-
erwise reworking parts to make them acceptable. Correspondingly, productivity and cost effectiveness also increased.

Finally, once the process was centered with a relatively high $C^*_p$, it was relatively simple to maintain. Only statistical sampling and plotting of control chart points were necessary to monitor production. Once a process is adjusted, it tends to stay "in control."

### PROCESS CAPABILITY PARAMETERS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Before</th>
<th>After</th>
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<tbody>
<tr>
<td>Mean</td>
<td>2.9543</td>
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<tr>
<td>Std. dev.</td>
<td>0.0281</td>
<td>0.0081</td>
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<tr>
<td>% &lt; L.S.L.</td>
<td>0.89</td>
<td>0.0000</td>
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<tr>
<td>% &gt; U.S.L.</td>
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<td>0.0000</td>
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<tr>
<td>$C^*_p$</td>
<td>0.0123</td>
<td>1.3820</td>
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<tr>
<td>Process capability, % of blueprint tolerance:</td>
<td>187.3</td>
<td>54.2</td>
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<tr>
<td>Specification limits (L.S.L - U.S.L.)</td>
<td>2.870-2.960</td>
<td>2.870-2.933</td>
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<tr>
<td>3σ limits (Before)</td>
<td>2.870-3.039</td>
<td>2.884-2.933</td>
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<td>3σ limits (After)</td>
<td>2.842-3.067</td>
<td>2.876-2.941</td>
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<tr>
<td>4σ limits (Before)</td>
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<td></td>
</tr>
<tr>
<td>4σ limits (After)</td>
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</tbody>
</table>
CASE STUDY FROM THE FILES:
Forgings replaced castings, cut costs, eliminated all rework and rejects for critical tank part

A critical component for the 105-mm cannon on a tank, the recoil piston, was originally made as a centrifugal casting. Unfortunately, the cast steel part was plagued by extensive rework and rejects, wreaking havoc with production and making it impossible to ship gun mount assemblies on a timely basis.

Designers of the large hollow part initially specified the component as a centrifugal casting, allowing a forging to be considered as an alternate. Although conventional forging methods could be used to manufacture the part, this approach would be more costly. To offset such a cost increase, an open-die forging company began cooperative engineering efforts, developing an unconventional forging technique that not only saved money but also proved to be a production savior.

During the various machining, plating and cladding operations, microporosity in the internal diameters was detected in a high percentage of the cast parts, which were already processed to near finish-machined condition. The only way to reclaim the castings involved welding, then remachining—an expensive proposition at best. Even with rework, the average rejection rate was about 10% for cast parts. Not surprisingly, scheduling and production quotas were in disarray.

While total quality costs due to cast products continued to skyrocket, the manufacturer worked closely with the open-die forger who came up with the ultimate solution for this critical component: innovative hollow forging techniques. The result of these efforts delivered initial cost savings of $125 per part over centrifugal castings and conventionally forged components. But the savings did not stop there.

Success of the switch to forging was reflected in the attainment of zero rejections. Out of thousands of shipped forgings, not a single part was rejected. The manufacturer reported consistent hardness and improved machining rates. Cladding and baking distortion proved predictable, component after component. And, rework that included dreaded salvage welding of castings and related NDT (nondestructive testing) of the salvaged parts was completely eliminated.

More than just innovative hollow forging contributed to this success story. The full-service forge shop also heat treats and rough machines, then provides full destructive and nondestructive testing, shipping a CNC-ready part on time.
CASE STUDY FROM THE FILES:

Statistics confirmed castings as downtime culprit, replaced with open-die-forged cylinders

As part of a comprehensive statistical study performed in a major forging plant, a Pareto analysis identified cast steel cylinders as a major cause of downtime. See the figure on the right. Installed on a 10,000 ton hydraulic forging press, the cast cylinders were not doing the job. They did not hold up under pressure.

Four cylinders, in which pistons ride to drive the top of the press down against the forging, are used in each press.

After an unexpectedly short time in service, the castings developed fatigue cracks, followed by small leaks, and finally, total functional failure. Although weld repair was routinely used as a stop-gap measure, the amount of downtime and labor from frequent repair (and corresponding lost production) became expensive. Consequently, the forging company decided to use open-die-forged cylinders.

The company also opted to upgrade the material to vacuum-degassed 4130 normalized steel versus 1030, and they redesigned the cylinders for periodic ultrasonic inspection.

The forged cylinder, with much improved internal soundness and microstructure (no as-cast porosity or large inclusions), as well as greater strength and fatigue resistance, was selected over troublesome cast replacements, even though the forgings cost about $15,000 more. Although some of this additional cost was due to additional machining for ultrasonic examination, the company projected that the forging would more than make up for the cost differential in terms of longer life and increased production time (significantly less downtime). An additional advantage of going to forged cylinders is simpler ultrasonic inspection because of the absence of porosity.
CASE STUDY FROM THE FILES:

Forced aluminum ejector cut cost, provided critical dimensions

Forged from 2014 aluminum alloy, an ice-cube ejector for refrigerators held up where cast, powder metal, and plastic components just could not perform. The 1 oz. forging provided the required strength and critical dimensions needed to mesh with mating parts and function without water leaking, which would stop the icemaker from operating.

Approximately 5.5 in. long, the impression die forge aluminum ejector has performed well in refrigerators.

In the interest of cost savings, the manufacturer explored non-forging options. If water leaked and froze, the casting snapped in half under pressure when trying to push down and eject the ice cubes. It was the same result with both the powder metal (PM) and plastic versions. Although plastic and PM parts cost less initially, continual replacement of parts in the field was an extremely costly option and a short-lived one. The OEM certainly did not want its reputation tarnished. Forgings provided superior strength and unmatched service life. According to the forger, life cycle cost savings were significant.

Conventionally forged from 6 in. sections cut from 1 in. diameter 12 ft. long rods, the aluminum ejector was forged two at a time to maintain size and maximize die life. See figure. Flash was removed by clipping and, at the same time, a shaving operation was performed on the web thickness. The parts were then solution heat treated and aged to provide the required in-service strength and proper hardness for machining. Next, the forging went into an automatically fed saw that made two parts from one forging. Prior to vibratory deburring, parts were gauged to ensure straightness and thickness from one end of the part to another. After drilling and counter-boring of the center hole, the parts were clear anodized for additional corrosion resistance.

For proper function, the ejector had to meet stringent engineering specification, including a number of critical dimensions. For example, the pad diameters had to be accurate to prevent leading water and restriction of ejector movement. For the center pad, diameter was held to 0.798 to 0.810 in.

Web thickness also was critical in meeting assembly tolerances for mating parts. Essentially, the draft was shaved off, creating a straight wall. Excess thickness (0.095 to 0.085 in., as forged) was reduced to 0.085 in.

Even though dimensional tolerance of the forge was considered minimal for this part, secondary operations like shaving and automatic sawing hold critical dimensions to the close tolerances required.

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