Cold Forging of Steel: Prerequisite Optimizations and Process Study

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Abstract— A detailed analysis of the cold forging process of steel including the material used, processes involved, advantages, disadvantages, effective optimization for improvement, process flow and a schematic comparison with the conventionally followed hot forging process was carried out. The processes of improvement for the possible limitations of cold forging were analyzed. Preference of cold forging over hot forging was concluded for its economics, energy savings and eco-friendliness.

Index Terms—Forging, Cold Forging, Prerequisite Optimizations, Advantages of Cold Forging, Limitations of Cold Forging.

1. INTRODUCTION

Forging is a process of manufacturing which involves shaping of metal with the help of localized compressive forces. It is often classified based on the temperature at which it is performed: cold forging (a type of cold working), warm forging, or hot forging (a type of hot working). The largest area of application of cold and warm forging is the automobile industry. Among all manufacturing processes, forging technology has a special place as it helps to produce parts of superior mechanical properties with minimum waste of material [1]. In forging, the starting material has a relatively simple geometry; this material is plastically deformed in one or more operations into a product of relatively complex configuration. Forging to net or to net shape dimensions drastically reduces metal removal requirements, resulting in significant material and energy savings. Since forging usually requires relatively expensive tooling, the process is economically attractive when a large number of parts are to be produced and/or when the mechanical properties required in the finished product can be obtained only by a forging process.

Hot Forging

Forging can be done at different temperatures. When the temperature is above the recrystallization temperature of the material it is known as hot forging. If the temperature is below the recrystallization temperature of the material but above 30% of the recrystallization temperature it is called warm forging; but if it is below 30% of the recrystallization temperature it is known as cold forging. In hot forging, the billet is heated to temperatures below the recrystallization temperature, for example, up to 1290 to 1470 °F (700 to 800 °C) for steels, in order to lower the flow stress and the forging pressures. The main advantage of hot forging is that as the metal is deformed work hardening effects are negated by the recrystallization process.

Cold Forging

Cold forging is a precision category of forging, included in as a metal shaping process in which a malleable metal part, known as a blank, billet or work-piece, is worked to a predetermined shape by one or more processes such as hammering, upsetting, pressing, rolling etc, heating of the material (room temperature), or removal of material. Cold forged parts are also used in manufacturing bicycles, motorcycles, farm machinery, off-highway equipment, and nuts and bolts. Cold forging processes do not cause any structural changes to the metal, and hence maintains all its original mechanical and tensile characteristics.

In cold forging, the billet or the slug is at room temperature when deformation starts. In cold forging of parts with relatively complex geometries from high-carbon and alloy steels, forging pressures are extremely high and the ductility of the material is low. As a result, short tool life and defects formed during forging limit the economic use of the cold forging processes. Consequently, in many cases, warm forging is commonly used. For warm forging, steels are usually heated between room temperature and usual hot forging temperature. The normal temperature range is considered to be 1110 to 1650 °F (600 to 900 °C). An exception is the warm forging of austentic stainless steels, which usually are forged between 390 and 570 °F (200 and 300 °C).

Processes involved in Cold Forging

- Extrusion
- Bending
- Coining
Cold forging the shaft produces a part with a far superior grain structure as shown by the lines below. The shaft on the lower half of the above figure is machined out of bar stock and results in approximately 64% loss of material [3]. The shaft on the upper half of the figure, is formed and extruded to form a head and nose. Cold forged parts require 40% less material.

III. LIMITATIONS OF COLD FORGING

Depending on the manufacturer’s requirements, some of the cold forging characteristics may turn out to be disadvantages [4]. Only simple shapes in high volumes can be shaped. Therefore, if the customer is searching for a specific customized component, cold forging won’t be the best alternative. A second more significant disadvantage is that cold forged metals are less ductile, which makes them inappropriate for certain configurations. Also, because of the grain structure that gives the material its strength, residual stress may occur. Heavier and more powerful equipment is needed and stronger tooling is required. It also leads to increased Die Wear (lesser tool life).

Residual Stress

Residual stresses are stresses that remain in a component after any external loading or forces are removed. They can be viewed as a form of potential energy, and the stress relieving, whether by thermal, peening, vibratory, long term storage (aging), or even by unintentional “bumpy” transport, act as a means of release of this potential energy. Residual stresses in metal structures occur for many reasons during the manufacturing processes such as hot and cold working, rolling, bending, forging, casting machining operations and the various welding processes.

Decrease in Ductility

Material grains are so deformed that they have very little freedom to move, and instead of absorbing energy in the deformation, the material becomes brittle and fractures occur. The lateral expansion is reduced when the percentage of cold forging is increased.

The figure given above shows that the energy absorption capacity of the material to deform plastically, before the...
occurrence of fracture, increases strength and hardness, and decreases the toughness of steel.

**Die Failures**

The most common cause of die failure is wear. Die wear occurs as a result of sliding of die and the work-piece relative to one another while in contact [5]. Typically, die wear is thought of as removal of material from the die surface, but it also may include build-up of material on the die surface or damage to the die surface. Die wear results in the gradual loss of part tolerances. Eventually, the part tolerances will not meet the customer’s specifications, and a new die or die insert will need to be manufactured.

The second most common cause of die failure is fatigue fracture. Fatigue occurs as the result of the continual stress cycles that the dies are subjected to. The stress cycles are attributed to both mechanical and thermal loading and unloading of the dies. Fatigue is accelerated in the vicinity of stress concentrations, such as small radii. The third cause of die failure is plastic deformation. Plastic deformation results from forming pressures that exceed the yield strength of the die material.

**IV. IMPROVEMENTS IN COLD FORGING**

**Surface Finishing:** Pickling and abrasive blasting are generally used for better surface finishes.

- **Pickling** is a metal surface treatment used to remove impurities, such as stains, inorganic contaminants, rust or scale from ferrous metals, copper, precious metals and aluminium alloys. A solution called *pickle liquor*, which contains strong acids, is used to remove the surface impurities. It is commonly used to descale or clean steel in various steelmaking processes.

- **Disadvantages**
  - Acid cleaning has limitations in that it is difficult to handle because of its corrosiveness, and it is not applicable to all steels. Hydrogen embrittlement becomes a problem for some alloys and high-carbon steels.

- **Alternatives**
  - Smooth clean surface (SCS) and Eco pickled surface (EPS) are more recent alternatives. In the SCS process, surface oxidation is removed using an engineered abrasive, and the process leaves the surface resistant to subsequent oxidation without the need for oil film or other protective coating. EPS, on the other hand, is a more direct replacement for acid pickling. Acid pickling relies on chemical reactions while EPS uses mechanical means. The EPS process is considered "environmentally friendly" compared with acid pickling, and it imparts to carbon steel a high degree of rust resistance, eliminating the need to apply oil coating that serves as a barrier to oxidation for acid-pickled carbon steel.

- **Abrasive blasting** is the operation of forcibly propelling a stream of abrasive material against a surface under high pressure to smoothen a rough surface, roughen a smooth surface, shape a surface, or remove surface contaminants. A pressurized fluid, typically air, or a centrifugal wheel is used to propel the blasting material (often called the *media*).

<table>
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<th>Types</th>
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<tbody>
<tr>
<td>Wet abrasive blasting</td>
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<td>Bead blasting</td>
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<td>Wheel blasting</td>
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<td>Hydro-blasting</td>
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<td>Micro-abrasive blasting</td>
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<td>Automated blasting</td>
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<td>Dry ice blasting</td>
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<td>Bristle blasting</td>
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**Simulation Study**

A complete virtual simulation study of the cold forging process can save companies a lot of time and money, as the entire process can be optimized eliminating the costly trial and error phase altogether [6]. The numerical simulation of cold forging needs to account for some characteristics that are peculiar to cold steel forging:

Both, the material to be forged and the dies are made of steel. The software model, therefore, should make use of a deformable die rather than a rigid die. Carbides such as tungsten carbide and titanium carbide are often the material of choice for the inserts in order to improve the finishing of the part. They provide pre-stress to the tool stack and improve the total life of the tools. It is, therefore, important that the software package used, is able to accurately simulate different materials with the same tool as well as the methods by which these inserts are mounted in the tool stack (via press-fitting or shrink-fitting).
The figures above shows a simulation study of stress analysis of the die (left panel), and the resulting shafts (right panel) manufactured after the cold forging from the respective simulated die.

Residual Stress Reduction

Different ways of reducing Residual Stress within the workpiece are as follows:

Heat Treatment (furnace methods)

Thermal stress relieving involves heating a component to a temperature at which the material yield strength has fallen, allowing creep to take effect [7]. Large residual stresses are no longer supported and, if the temperatures are high enough, the stress redistribution will become more uniform across the component.

Localized Heat Treatment

There are frequent occasions when the item requiring thermal treatment is part of a larger fabrication, which is either too large, or inconvenient, to heat as a whole for financial or technical reasons. In such circumstances local heat treatment is preferred. This is done using ceramic elements surrounding the resistance heating wire.

Radiant Heating

This exploits the heating properties of infrared radiation, which may be generated either by firing ceramic elements with gas, or from a tungsten quartz lamp. The efficiency of the method depends on the absorptivity / emissivity of the item which is dependant both on the material being treated and on its surface condition.

Monotonic Overloading

Overloading techniques involve relaxation of stresses by permanent yielding via the hydrostatic test or the warm pressure test. Overloading techniques combine loading generated by external pressure together with the presence of residual stresses. A single overloading above the yield stress results in a decrease of any residual stresses

Shot Peening

A local form of overload can be applied in the form of peening. This can be employed to reduce general residual stress levels in welded joints or to control distortion, but is used principally to improve the fatigue strength of welded joints by the introduction of a local compressive stress field close to the weld toes.

Vibratory Stress Relieving

Effective vibratory stress relieving treatment can be carried out on a production basis provided that the changes in the work piece's resonance pattern are carefully monitored. Stability of the new resonant pattern is indicative of completion of the vibration treatment. These changes are consistent with the work piece's increased mechanical response to dynamic loading.

Ductility Improvement

The lateral expansion is reduced when the percentage of cold forging is increased. As a consequence the ductility of the cold forged material declines. Following are the ways for ductility improvement:

High Temperature Annealing

High-temperature annealing is effective in reducing the degree of the texture anisotropy of the specimen, and the forging limit of the annealed specimen gets improved during cold forging [8]. On the other hand, in cold forging of the annealed specimen application of counter pressure upto 100-200 MPa, the critical punch stroke for forging limit of the specimen without crack improves by 25% in punch stroke.

Manganese Content:

Increase in the Manganese content increases strength at high temperatures by eliminating the formation of iron sulphides. Manganese also improves hardenability, ductility and wear resistance.

Incorporating tempering in the manufacturing processes of Steel:

Tempering is a heat treatment technique applied to ferrous alloys, such as steel or cast iron, to achieve greater toughness by decreasing the hardness of the alloy [9]. The reduction in hardness is usually accompanied by an increase in ductility, thereby decreasing the brittleness of the metal.

Optimization in Dies:

Die Assembly

To prevent premature die fracture and its excessive deformation, pre-stressed dies are used. Main reasons for use of die assembly than solid dies are to reduce intensive abrasive wear, increase tool life by die design using insert and pegs and using much harder and wear resistant material, to avoid low cycle fatigue due to local plastic deformation, to eliminate stress concentration in the die areas that are not in
contact and to compensate excessive elastic deformation of the die.

**Optimal Die Design on FEM program, Qform Software**

The Finite Element Method (FEM) is widely used in metal forming analysis due to its capabilities to model the complicated geometries of tools and parts in forming processes [10]. It can provide detailed information for forming designers such as forming force, defects predictions, flow pattern, and stress concentration in the dies. The strain output, for instance, can display strain concentration areas to identify the possible early failures in the tools or to predict formability problems. Therefore, part fabrication design can modified to improve tool’s life or to enhance the formability conditions, and the new designs can be checked with repeated finite element simulations before experimental tests.

V. **PROCESS FLOW DIAGRAM**

- **Tempered Raw Material (Steel)**, includes the raw material steel for the process of Forging. That had been subjected to tempering during the manufacturing.
- **Inspection**, includes the testing of the material for checking its forgeability.
- **Simulation**, it is done of both the die as well as the forging process for the shaft. Entire process can be optimized eliminating the costly trial and error phase altogether.
- **Die Design**, it is performed by following all the desired precautions and possible ways of optimization.
- **High temperature Annealing** should be done under Hydrostatic Pressure for enhancement of the ductility (Reduced during Cold Forging).
- **Surface Finishing**, operations such as Pickling and Abrasive Blasting are performed to provide a good surface finish prior to the Cold Forging.
- **Cold Forging**, the process of cold forging is now performed for the desired shape of the product to be produced.
- The product is now subjected to **Hardening**. The material is strained past its yield point. The plastic straining generates new dislocations. As the dislocation density increases, further dislocation movement becomes more difficult since they hinder each other, which means the material hardness increases.

VI. **COMPARISON OF COLD FORGING WITH HOT FORGING**

**Advantages**

- **Finished Product** is obtained as per the requirements and is sent for analysis to ensure its ‘ok’ to be shipped.
- **Shipment** of the product done after successful evaluation of the finished product.

Traditionally, manufacturers choose hot forging for the fabrication of parts that have a greater influence in the technical arena. Hot forging is also recommended for the deformation of metal that features a high formability ratio.

However, manufacturers must choose cold forging over hot forging for a number of reasons. Since cold forged parts require very little or no finishing work, that step of the fabrication process is often dispensable, which saves money. Cold forging is also less susceptible to contamination problems.

**Disadvantages**

- **Hot Forging**: Varying metal grain structure, Possible reactions between the surrounding atmosphere and the metal
- **Cold Forging**: Stronger tensile is required, Harder and more powerful equipment is needed, Residual stress may occur, The metal is less ductile
VII. CONCLUSION

Hot Forging is conventionally used in the field of forging. But, this process suffers from some limitations which include the loss of material, several steps of finishing processes, use of high energy for the heating of the specimen before the forging etc. To overcome the limitations of hot forging, cold forging may be used as cold forged parts require very little or no finishing work resulting is cost saving. Material saving is achieved through precision shapes. Cold forging does not need extra energy for the heating up of the specimen before forging. Thus, it is an energy saving, cost saving as well as eco-friendly process. However, cold forging also suffers from a few drawbacks. For example, the material surfaces need to be cleaned and made free of scale before cold forging, ductility of the metal reduces, residual stress increases. Cold forging requires heavier and more powerful equipment and stronger tooling. These limitations of cold forging can be overcome in following ways,

☐ Pickling and abrasive blasting for better surface finishes.
☐ High temperature annealing, increase in Manganese content and incorporation of tempering process in the manufacturing of steel for the enhancement of ductility in the alloy steel.
☐ Residual stress reduction through heat treatment, radiant heating, monotonic overloading, shot peening and vibratory stress relieving.
☐ Use of Die assembly, and research and development of new materials (more susceptible to Wear, Plastic deformation and fatigue) for the design of suitable dies for the operation of Cold Forging Process.
☐ New materials and material characterization, surface polishing, coatings and selective surface treatment (Hard roller burnishing and surface heat treatment by LASER).

The economic advantages combined with high productivity thus suggest that cold forging is a better option for a manufacturing company.

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