An Overview of Forging Processes with Their Defects

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Abstract- The objective of this paper is to identify and understand the various forging processes and to investigate the various forging defects. Initially, some important forging terms that are widely used in this field are discussed. A brief description about classification of forging process on the basis of temperature of work piece (hot, cold, and warm forging) and on the basis of arrangement of dies (open, impression and closed-die forging) is given. Die design parameters, die material requirements and selection of proper die materials are briefly discussed. Also, briefly described the forging equipments (hammer and press). Factors for selection of forging machine, characteristics and common applications of forging are given. Forging defects those are repeatedly occurring are discussed along with their causes and remedies. Then the fish-bone diagram is used to explore the possible causes of defects like unfilling, mismatch and scale pits through a brainstorming session and to determine the causes, which may has the greatest effect. Finally, it is concluded that the forging process gives better quality product than the part produced by any other processes with implementation of preventive actions to reduce the rejection rate.

Index Terms- Forging, Billet, Flash, Forging defects, Unfilling, Fish-bone diagram

I. Introduction

Forging is defined as a metal working process in which the useful shape of work piece is obtained in solid state by compressive forces applied through the use of dies and tools. Forging process is accomplished by hammering or pressing the metal. It is one of the oldest known metalworking processes with its origin about some thousands of years back. Traditionally, forging was performed by a smith using hammer and anvil. Using hammer and anvil is a crude form of forging. The smithy or forge has evolved over centuries to become a facility with engineered processes, production equipment, tooling, raw materials and products to meet the demands of modern industry.

In modern times, industrial forging is done either with presses or with hammers powered by compressed air, electricity, hydraulics or steam. Some examples of shapes obtained now-a-days by forging process are- Crane hook, connecting rod of an IC engine, spanner, gear blanks, crown wheel, pinion etc.

Forging process produces parts of superior mechanical properties with minimum waste of material. In this process, 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 usually requires relatively expensive tooling. Thus, the process is economically attractive when a large number of parts must be produced and/or when the mechanical properties required in the finished product can be obtained only by a forging process.

Though forging process gives superior quality product compared to other manufacturing processes, there are some defects that are lightly to come if a proper care is not taken in forging process design. Defects can be defined as the imperfections that exceed certain limits. There are many imperfections that can be considered as being defects, ranging from those traceable to the starting materials to those caused by one of the forging processes or by post forging operations.

II. Discussion

A. Some Important Forging Terms

1) Forging die: It may be defined as a complete tool consists of a pair of mating members for producing work by hammer or press. Die pair consists of upper and lower die halves having cavities.
2) Billet: A slug cut from rod to be heated and forged.
3) Blocker: Preform die or impression, used when part cannot be made in a single operation.
4) Cavity: The impression in upper and lower die.
5) Draft Angle: The taper on a vertical surface to facilitate the easy removal of the forging from the die or punch. Internal draft angles are larger (7^0-10^0), whereas external draft angles are smaller (3^0-5^0).
6) Fillet: It is a small radius provided at corners of die cavity to ensure proper and smooth flow of material into die cavity. It helps to improve die life by reducing rapid die wear.
7) Flash: The excess metal that flows out between the upper and lower dies which is required to accomplish a desired forging shape.
8) Gutter: A slight depression surrounding the cavity in the die to relieve pressure and control flash flow.
9) Parting Line: The location on the forging where excess material in the form of flash is allowed to exit from the forging during the forging operation.
10) Shrinkage: The contraction that occurs when a forging cools.
11) Sink: To cut an impression in a die.
12) Web: The thin section of metal remaining at bottom of a cavity or depression in a forging. The web may be removed by piercing or machining.
13) Die Closure: Refers to the function of closing together the upper and lower members of a forge die during the process of actually producing a forging.

B. Classification of Forging Processes

In forging, an initially simple part- a billet, is plastically deformed between two dies to obtain the desired final configuration. For understanding and optimization of forging operations, it is useful to classify this process in a systematic way. There are a large number of forging processes that can be classified as follows:

1) Classification based on Temperature of the work piece

a) Hot forging (most widely used): Forging is carried out at a temperature above the recrystallization temperature of the metal. The recrystallization temperature is defined as the temperature at which the new grains are formed in the metal. This kind of extreme heat is necessary in avoiding strain hardening of the metal during deformation.

Advantages: High strain rates and hence easy flow of the metal, Recrystallization and recovery are possible, Forces required are less.

Disadvantages: Lubrication is difficult at high temperatures, Oxidation and scaling occur on the work piece, Poor surface finish, Less precise tolerances, Possible warping of the material during the cooling process.

Table- 1: Hot forging temperature range for different metals and alloys [1].

Metal or alloy	Temperature Range (^{0}C)
Aluminum alloys	400 – 550
Magnesium alloys	250 – 350
Copper alloys	600 – 900
Carbon and Low-alloy steels	850 – 1150
Martensitic stainless steels	1100 – 1250
Austenitic stainless steels	1100 – 1250
Titanium alloys	700 – 950
Iron-base superalloys	1050 – 1180
Cobalt-base superalloys	1180 – 1250
Tantalum alloys	1050 – 1350
Molybdenum alloys	1150 – 1350
Nickel-base superalloys	1050 – 1200
Tungsten alloys	1200 – 1300

b) Cold forging: Forging is carried out at or near room temperature (below the recrystallization temp.) of the metal. Carbon and standard alloy steels are most commonly cold-forged. Cold forging is generally preferred when the metal is already a soft, like aluminum. This process is usually less expensive than hot forging and the end product requires little or no finishing work. Cold forging is also less susceptible to contamination problems, and the final component features a better overall surface finish.

Advantages: Production rates are very high with exceptional die life, Improves mechanical properties, Less friction between die surface and work piece, Lubrication is easy, No oxidation or scaling on the work.

Disadvantages: Residual stress may occur, Heavier and more powerful equipment is needed, Stronger tooling is required, Tool design and manufacturing are critical.

c) Warm forging: The temperature range for the warm forging of steel runs from above room temperature to below the recrystallization temperature. Compared with cold forging, warm forging has the potential advantages of: Reduced tooling loads, reduced press loads, increased steel ductility, elimination of need to anneal prior to forging, and favorable as-forged properties that can eliminate heat treatment. In warm forging, the billet is heated below the recrystallization temperature, up to 700 to 800 ^{0}C for steels, in order to lower the flow stress and the forging pressures.

Advantages: High production rates, Excellent dimensional tolerances and surface finish for forged parts, Significant savings in material and machining, Favorable grain flow to improve strength, Greater toughness of the forged part.

2) Classification based on Arrangements of Dies

a) Open-die forging: Forging in which the flat dies of simple shape are used to allow the material to freely deform in lateral directions of applied load. Figure 1 shows open-die forging operation.

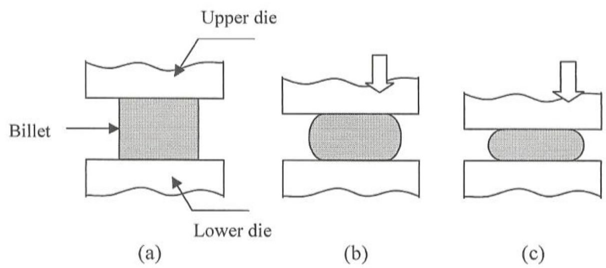

Figure 1: Open-die forging

Features: Less dimensional accuracy, Suitable only for simple shapes of work, Requires more skill of the operator, Usually used for a work before subjecting it to closed-die forging (to give approximate shape), Dies are simple and less expensive, It is simplest of all the forging operations.

b) Impression-die forging: Forging in which the material is shaped to fill out a die cavity created by the upper and lower die halves. The dies are not fully closed and allow some material to escape as Flash. Flash formation builds pressure inside the bulk of the work piece, aiding material flow into unfilled impressions. Requires more complex (and more expensive) dies. Figure 2 shows impression-die forging operation.

Significance of Flash: Excess metal is taken initially to ensure that die is completely filled with metal to avoid any voids. Excess metal is squeezed out of the die cavity as a thin strip of metal, called Flash. A flash gutter is provided to reduce the area of flash. Thin flash increases the flow resistance of the system and builds up the pressure to high values which ensures that all intricate shapes of cavity are filled. Flash design is very critical and important step. Extremely thin flash results in very high pressure build up which may lead to breaking of the dies.

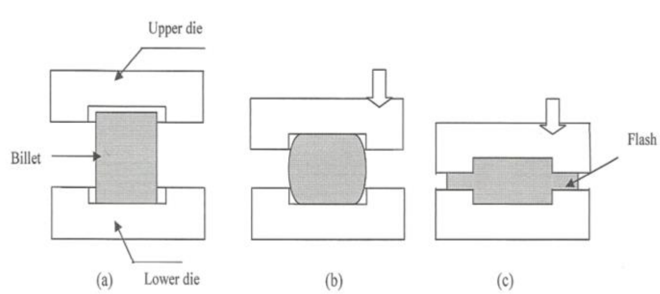

Figure 2: Impression-die forging

c) Closed-die forging: Forging in which the material is fully constrained in the cavity created by the upper and lower die halves. It allows more accurately shaped parts to be formed, No flash is formed in this process therefore no waste of material, Higher interface pressures required, Requires very accurate control of material volume and proper die design. Closed-die forging is a form of impression-die forging, which does not depend on flash formation to achieve complete filling of the die. Material is deformed in a cavity that allows little or no escape of excess material, thus placing greater demands on die design.

Features: Work is rough forged close to final shape by blocking die, Work is forged to final shape and dimensions by Finishing die, Both blocking die and finishing die are machined into the same die block, More number of dies are required depending on the complexity of the job, Two die halves close-in and work is deformed under high pressure, High dimensional accuracy/close control on tolerances, Suitable for complex shapes, Dies are complex and more expensive, Large production rates are necessary to justify high costs.

C. Die design parameters Die design depends on the knowledge of strength and ductility of work piece material, sensitivity of material to the rate of deformation and temperature, frictional characteristics, shape and complexity of work piece, die distortion under high forging loads.

Die material requirements: Strength and toughness at elevated temperature, Hardenability and ability to harden uniformly, Resistance to mechanical and thermal shocks, Wear resistance-to resist abrasion wear due to scales present on work piece.

Selection of proper die material depends on: Die size, Composition and properties of work piece, Complexity of shape-No. of performing steps, Forging temperature, Type of forging operation, Cost of die material, No. of forgings required, Heat transfer from work piece to dies, etc.

Die materials used: Tool and die steels with Cr, Ni, Mo, Va.

D. Forging equipments

Forged components are shaped either by a hammer or press. Forging on the hammer is carried out in a succession of die impressions using repeated blows. The quality of the forging, and the economy and productivity of the hammer process depend upon the tooling and the skill of the operator. In press forging, the stock is usually hit only once in each die impression and the design of each impression becomes more important while operator skill is less critical. The continuous development of forging technology requires a sound and fundamental understanding of equipment capabilities and characteristics. The equipment i.e. presses and hammers used in forging, influences the forging process, since it affects the deformation rate and temperature conditions, and it determines the rate of production. The requirements of a given forging process must be compatible with the load, energy, time, and accuracy characteristics of a given forging machine [1].

1) Forging Hammer: The most common type of forging equipment is the hammer and anvil. The hammer is the least expensive and most versatile type of equipment for generating load and energy to carry out a forging process. This technology is characterized by multiple impact blows between contoured dies. Hammers are primarily used for hot forging. There are basically two types of anvil hammers: Gravity-drop hammers and Power-drop hammers. In a simple gravity-drop hammer, the upper ram is connected to a board (board-drop hammer), a belt (belt-drop hammer), a chain (chain-drop hammer), or a piston (oil-, air-, or steam-lift drop hammer). The ram is lifted to a certain height and then dropped on the stock placed on the anvil. During the down stroke, the ram is accelerated by gravity and builds up the blow energy. The upstroke takes place immediately after the blow. The operation principle of a power-drop hammer is similar to that of an air-drop hammer. In the down stroke, in addition to gravity, the ram is accelerated by steam, cold air, or hot air pressure. In the power-drop hammer, the acceleration of the ram is enhanced with air pressure applied on the top side of the ram cylinder [1]. Figure 3 shows mechanical board hammer- It is a stroke restricted machine. Repeatedly the board (weight) is raised by friction rolls and is dropped on the die. Its rating is in the terms of weight of the ram and energy delivered. Figure 4 shows steam hammer- It uses steam in a piston and cylinder arrangement. It has greater forging capacity. It can produce forgings ranging from a few kgs to several tones. It is preferred in closed-die forging.

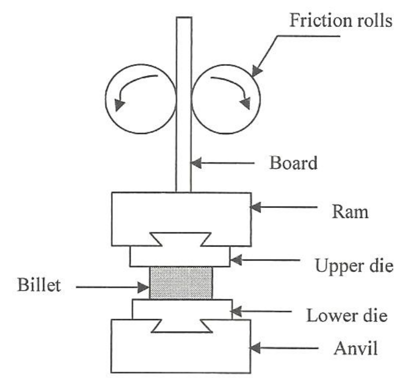

Figure 3: Mechanical board hammer

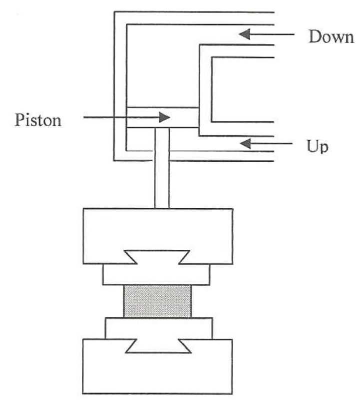

Figure 4: Steam hammer

2) Forging Press: In press forging, the metal is shaped not by means of a series of blows as in hammer forging, but by means of a single continuous squeezing action. There are two main types: mechanical and hydraulic presses. Mechanical presses function by using cams, cranks and/or toggles to produce a preset (a predetermined force at a certain location in the stroke) and reproducible stroke. Due to the nature of this type of system, different forces are available at different stroke positions. Mechanical presses are faster than their hydraulic counterparts (up to 50 strokes per minute). Their capacities range from 3 to 160 MN (300 to 18,000 short tons-force). Hydraulic presses use fluid pressure and a piston to generate force. Figure 5 shows hydraulic press. It is a load restricted machine. It has more of squeezing action than hammering action. Hence dies can be smaller and have longer life than with a hammer.

Features of Hydraulic Press: Full press load is available during the full stroke of the ram, Ram velocity can be controlled and varied during the stroke, It is a slow speed machine and hence has longer contact time and hence higher die temperatures, The slow squeezing action gives close tolerance on forgings, Initial cost is higher compared to hammers. The advantages of a hydraulic press over a mechanical press are its flexibility and greater capacity. The disadvantages include a slower, larger, and costlier machine to operate [1].

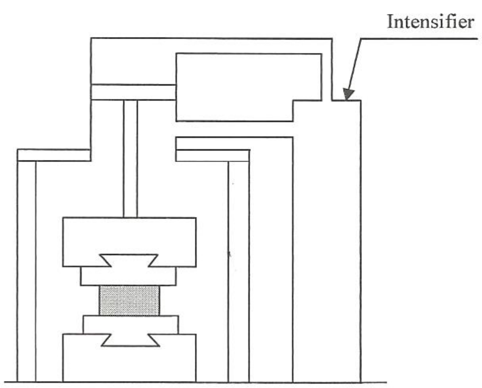

Figure 5: Hydraulic press

E. Selection of Forging machine

Selection of forging machine depends upon force and energy requirements, Material to be forged (soft material- use press, hard material- use hammers), Size-shape and complexity of forging, Strength of the work piece material, Sensitivity of material to rate of deformation, Production rate, Dimensional accuracy, Maintenance, Operating skill level required, Noise level, Cost.

Characteristics of Forging- Usually involves discrete parts, May be done on hot or cold materials, Often requires additional finishing processes such as heat treating, machining, or cleaning, May be done at fast or slow deformation rates, May be used for very small or very large parts, Improves the physical properties of a part by controlling and refining the flow or grain of the material.

Common Applications of Forging- Automotive passenger cars, trucks, buses, trailers, motorcycles and bicycles. Bearings, ball and roller. Electric power generation/transmission. Industrial and commercial machinery and equipments. Hand tools. Industrial tools. Mechanical power transmission equipments. Internal combustion engines. Oil field machinery and equipments. Off-highway, equipment (construction, mining and materials handling). Pipeline fittings. Plumbing fixtures, valves and fittings. Pumps and compressors. Railroad equipments and spikes. Metalworking and special industry machinery. Steam engines and turbines. Steel works, rolling and finishing mills. Ship and boat building and repairs. Aerospace aircraft engines. Guided missiles and space vehicles, etc.

III. Forging Defects

When 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. A brief description of defects and their remedial methods is given below:

1) Incomplete forging penetration:
Dendritic ingot structure at the interior of forging is not broken. Actual forging takes place only at the surface.
Cause- Use of light rapid hammer blows
Remedy- To use forging press for full penetration.
2) Surface cracking:
Cause- Excessive working on the surface and too low temperature.
Remedy- To increase the work temperature
3) Cracking at the flash:
This crack penetrates into the interior after flash is trimmed off.
Cause- Very thin flash
Remedy- Increasing flash thickness, relocating the flash to a less critical region of the forging, hot trimming and stress relieving.
4) Cold shut (Fold):
Two surfaces of metal fold against each other without welding completely.
Cause- Sharp corner (less fillet), excessive chilling, high friction
Remedy- Increase fillet radius on the die.
5) Unfilled Section (Unfilling/Underfilling):
Some section of die cavity not completely filled by the flowing metal.
Cause- Improper design of the forging die or using forging techniques, less raw material, poor heating.
Remedy- Proper die design, Proper raw material and Proper heating. Figure 6- Shows the fish-bone diagram for root-cause analysis of underfilling defect.
6) Die shift (Mismatch): Misalignment of forging at flash line.
Cause- Misalignment of the die halves.
Remedy- Proper alignment of die halves. Make mistake proofing for proper alignment for eg. provide half notch on upper and lower die so that at the time of alignment notch will match each other. Figure 7- Shows the fish-bone diagram for root-cause analysis of mismatch defect.
7) Scale Pits (Pit marks):
Irregular depurations on the surface of forging.
Cause- Improper cleaning of the stock used for forging. The oxide and scale gets embedded into the finish forging surface.
Remedy- Proper cleaning of the stock prior to forging.
Figure 8- Shows the fish-bone diagram for root-cause analysis of Scale Pits defect.
8) Flakes:
These are basically internal ruptures.
Cause- Improper cooling of forging. Rapid cooling causes the exterior to cool quickly causing internal fractures.
Remedy- Follow proper cooling practices.

9) Improper grain flow:
Cause- Improper die design, which makes the metal not flowing in final interred direction.
Remedy- Proper die design.
10) Residual stresses in forging:
Cause- Inhomogeneous deformation and improper cooling (quenching) of forging.
Remedy- Slow cooling of the forging in a furnace or under ash cover over a period of time.

IV. CONCLUSION

Forging is an experience oriented process. Throughout the years, a great deal of know-how and experience has been accumulated in this field, largely by trial-and-error methods. Forging process produces final products in very short time with little or no scrap. Thus there is saving in energy and material. Forgings sometimes cost more than parts produced by other processes like- casting or machining, but it gives more reliable parts with better mechanical and metallurgical properties.

Since defects causes high rejection rates, it is important to move any process in the direction of eliminating all imperfections as part of an effective continuous improvement program. A good quality program begins with an attitude of making it right the first time. Forging processes are no exception to this. Economically, as well as from a quality perspective, it is better to understand and control the process so as to avoid defects rather than scrapping the defective parts during final inspection.

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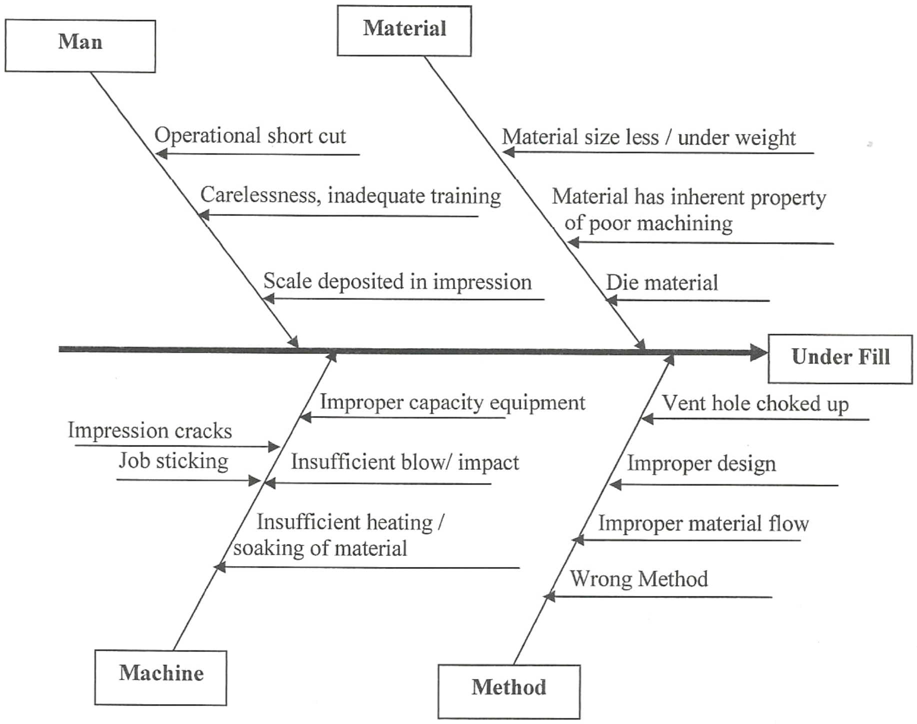

Figure 6: Fish-bone diagram for root-cause analysis of underfilling defect.

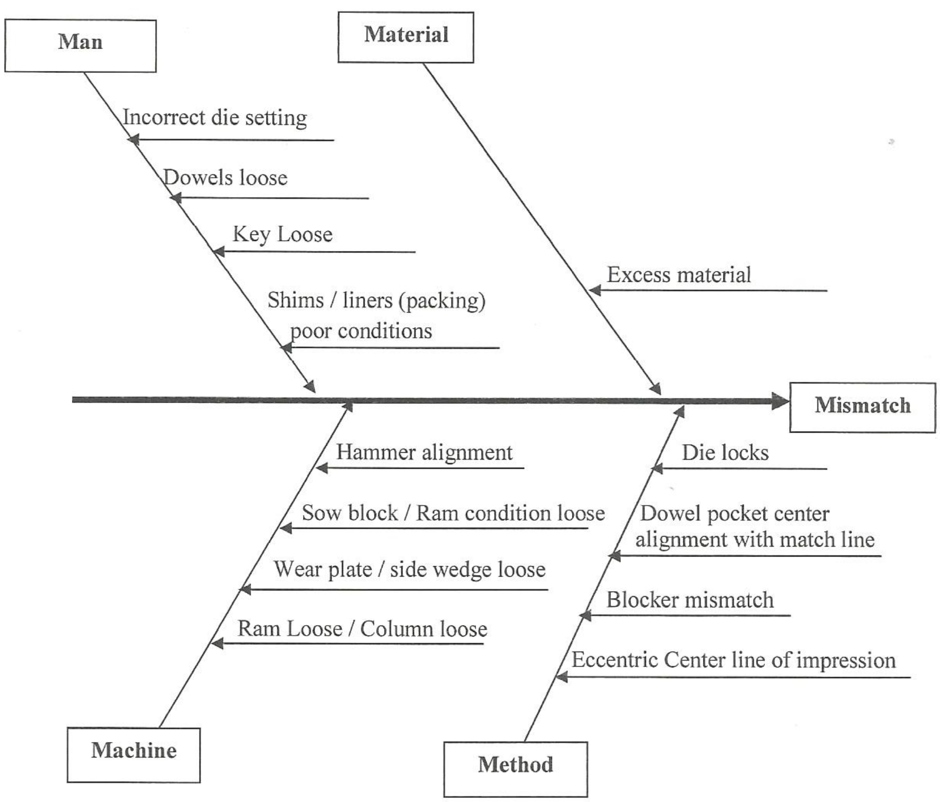

Figure 7: Fish-bone diagram for root-cause analysis of mismatch defect.

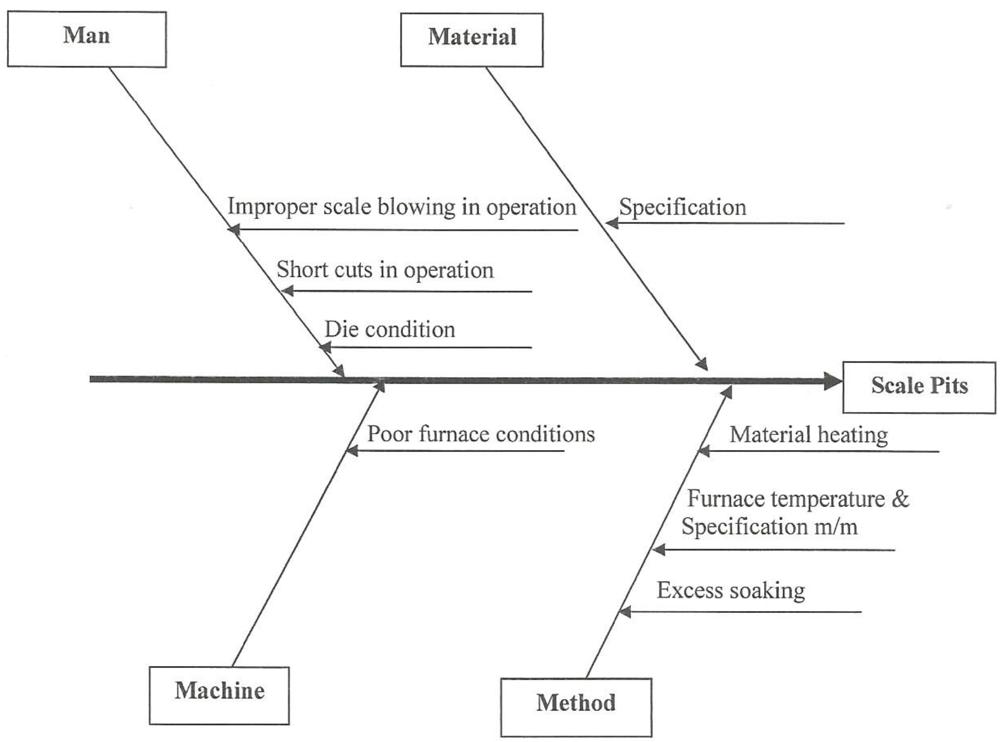

Figure 8: Fish-bone diagram for root-cause analysis of scale pits defect.