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Fundamentals of Sprocket Design and Reverse Engineering of Rear Sprocket of a Yamaha CY80 Motorcycle

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ABSTRACT

The sprocket is a very vital component in the transmission of power and motion in most motorcycle; there is always a pair (rear and front) in a motorcycle. The front sprocket drives the rear sprocket via chain connection. They exist in various dimensions, teeth number and are made of different materials. This study involves the fundamentals of sprocket design and manufacturing of a Yamaha CY80 motorcycle rear sprocket through reverse engineering approach. It discusses dimensioning, drafting, chemical composition, material selection, choice of manufacturing process, heat treatment, surface finish and packaging as the eight steps that need to be followed sequentially in this reverse engineering approach. In this work, universal milling machine was used to produce the sprocket from the blanked medium carbon steel (AISI 1045) with chemical composition of C=0.45%, Mn=0.75%, P=0.03% max, S=0.04%. Induction heat treatment was applied to move the material hardness from 13 HRC to 45 HRC as shown by hardness test.

Keywords: *Fundamentals, Sprocket, Design, Reverse, Engineering, Yamaha, CY80 Motorcycle*

1. INTRODUCTION

The name 'sprocket' applies generally to any wheel upon which are radial projections that engage a chain passing over it. It is distinguished from a gear in that sprockets are never meshed together directly, and differs from a pulley in that sprockets have teeth and pulleys are smooth (Wikipedia). Sprockets can be supplied in various materials and styles, depending upon the application and severity of service requirements. Generally there are two major ways of categorising sprockets; by general form and form of the hub. Table 1 and Fig 1 show sprocket classification by general form and their applications while Table 2 shows classification based on hub form. For most applications, fabricated steel sprockets are recommended as offering the best combination of performance, availability, and price. Fabricated steel sprockets can be provided for every chain tooth combination and are readily available (Rexnord, n. d.).

Table 1: Sprocket Styles

S/N	Sprocket style	Use	Advantages
	Cast Arm Body	Used where larger sizes are required.	Reduction of weight
	Cast Split (Arm or Plate) Body	To prevent bearings or other connected equipment being disturbed.	Reduces installation and downtime.
	Cast Plate Body	Required for the smaller sizes where the use of arms is impractical and on larger sizes when the chain pull exceeds the strength of the arm body sprockets.	Transmits high torque
	Fabricated steel sprockets	Use of arms is impractical and on larger sizes when the chain's pull exceeds the strength of the arm body sprockets.	Transmits high torque and easy to manufacture
	Shear Pin like flanged-rim	They are used in special applications where jamming or overloading is prevalent	Protecting machinery and equipment from damage.
	Special Sprockets	used particularly in the rock products and fertilizer industries	

Source: Rexnord Sprocket Catalog (n.d.)

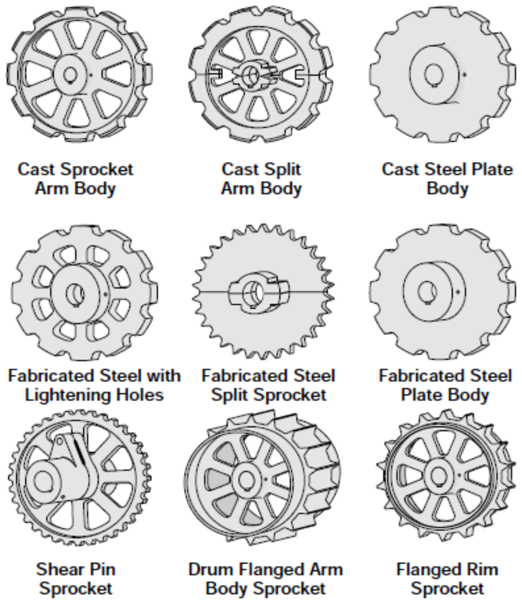
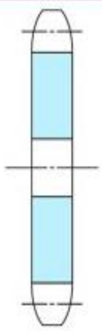
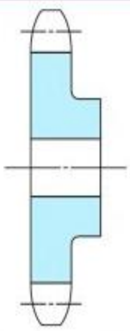
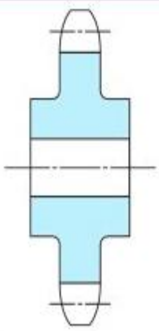
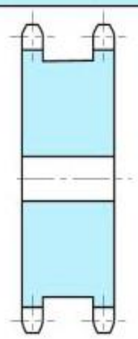


Figure 1: Sprocket Styles

Source: Rexnord Sprocket Catalog (n.d.)

Table 2: Sprocket Classification by Hub form

Type symbol	Type A (flat)	Type B (single hub)	Type C (both hubs)	Type SD (Single dual)
Construction				
Specifications	Flat structure with no hub (boss).	Flat structure with a hub (boss) on a single side.	Flat structure with hubs (bosses) on both sides.	Structure where two single-strand chains can be put.

2. PRODUCTION OF SPROCKET THROUGH REVERSE ENGINEERING

Reverse engineering is the practice of taking products apart (product dissection) to discover how it works and gain insight into why it was done that way. This is a common practice in industry and an important part of the product development cycle (Steven, 2008). For some product development processes reverse engineering (RE) allows to generate surface models by three-dimensional (3D)-scanning technique, and consequently this methodology permits to manufacture different parts (for cars, for household appliances) and tools (moulds, dies, press tools) in a short development period.

The choice of RE approach in this work is because of its immerse design and production time benefit. It is a necessary phase for rapid product development and pertinent to developing economies. Fig 2 shows the various RE steps followed to produced CY80 sprocket.

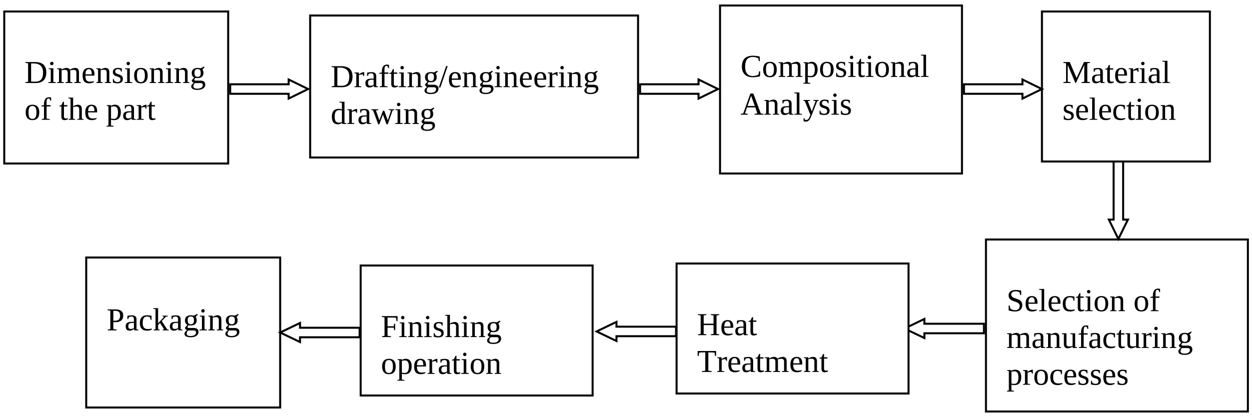


Figure 2: Generic Layer out of RE Operations for sprocket Production

2.1 Dimensioning: Use of Coordinate Measuring Machine (CMM)

A sprocket exists in various dimensions, teeth number and is materials depending on the function and brand. A coordinate measuring machine (shown in Fig 3) is a device for measuring the physical geometrical characteristics of an object. This machine may be manually controlled by an operator or it may be computer controlled. Measurements are defined by a probe attached to the third moving axis of this machine. Probes may be mechanical, optical, laser, or white light, amongst others. A machine which takes readings in six degrees of freedom and displays these readings in mathematical form is known as a CMM (Wikipedia, 2013). A CMM consists of a workspace in which parts are fixed, a sensor for detecting the part surfaces, a mechanical assembly for moving the part sensor around the workspace, and a computer with software used in calculating the part dimensions based on the sensor measurements. Many CMM designs strive for accuracies of 8-12 micrometer and repeatability of 3-5 micro-meters (Sokovic and Kopac, 2006).

The CMM was used to dimension the sprocket to be reversed and these values were obtained: the tooth parameters, dimension of the 4 attachment holes (diameter 8 mm), internal diameter (hub) of 64 mm, outer diameter of 156 mm and 6 mm thick. The sprocket has 36 teeth.

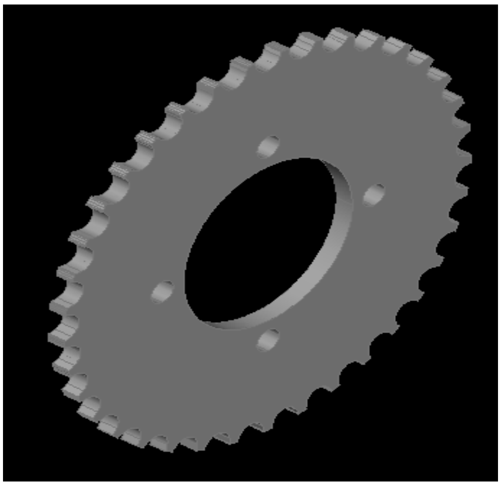
Table 3 shows the operations involve in RE of CY80 sprocket and equipment used

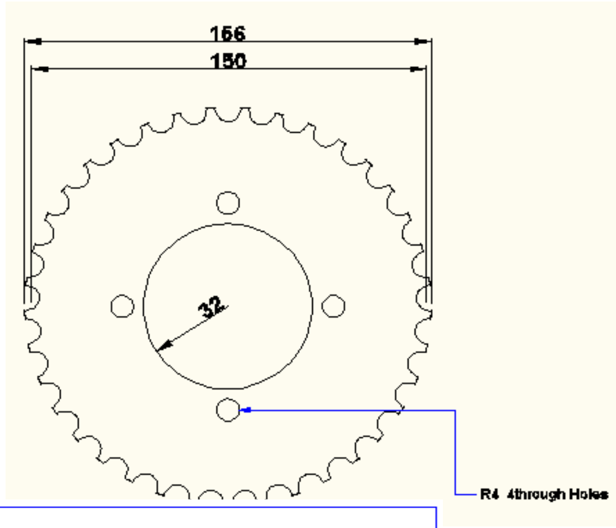
S/N	Operation	Equipment
i.	Dimensioning	Coordinate measuring machine (CMM)
ii.	Engineering drawing	Computer Aided Design (CAD); AutoCAD and ProE
iii.	Compositional analysis	Spectrometer
iv.	Material Selection	Pro Mechanica
v.	Selection of Manufacturing Processes	Punching machine, drilling machine and milling machine
vi.	Heat treatment	Induction Furnace
vii.	finishing operation	Sand machine and Spraying machine
viii.	Packaging (Carding)	Card sealing machine

Figure 3: Coordinate Measuring Machine

2.2 Engineering drawing of the Sprocket: Computer Aided Design (CAD)

AutoCAD and ProE softwares were used for both two dimension (2D) and three dimension (3D) drawings. Fig 4 and 5 are sprocket drawings made with AutCAD and ProE respectively.





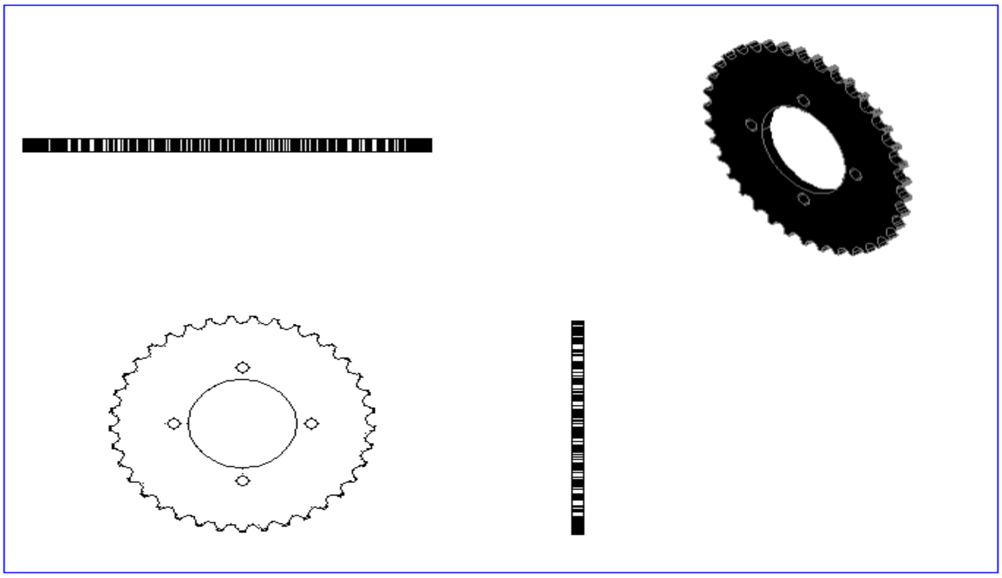


Figure 5: Sprocket 3D standard view drawn with AutoCAD

2.3 Material Selection

Selecting the right material for sprocket involves many factors, including the cost as well as the material performance required. Sprockets can also be supplied in various cast materials, with or without hardened teeth. For any application requiring rim speeds above 6,500 feet per minute (33.02m/s) are dynamically balanced to ensure safe drive operation (Gates n.d.).

Steels are alloys of iron and carbon, with the exception of stainless steels, which are alloys of iron, chromium and nickel. Steel is classified by its composition. Most general use steels fall into three categories: Carbon steels, Alloy steels and Stainless steels. Alloy steels are carbon steels with other elements added to increase hardness. These elements make alloy steels easier to heat treat for greater strength. The most commonly added alloys are nickel, chromium and molybdenum

2.3.1 Material Composition Test

Atomic Absorption Spectrometer was used to carry out the chemical composition of the sprocket to be reversed. The purpose of this test is to ascertain the alloying elements for the desired quality. The chemical composition is stated below:

Chemical composition:

C=0.40%, Mn=0.75%, P=0.03% max, S=0.05%

2.3.1 Material Used

Sprocket operating conditions, the required hardness and cost are important factors to consider when selecting materials for sprocket. Plain carbon steels and low-alloy steels containing 0.40 to 0.55% carbon content are commonly specified. Examples include AISI 1045, 1552, 4140, 4150, 4340, and 5150 (Valery, 2008).

The material used is a medium carbon steel (AISI 1045). Table 4 shows the chemical composition and mechanical properties of the material. The choice of this material is a result of it characteristics. Generally, AISI 1045 steel has a tensile strength of 570 - 700 MPa and Brinell hardness ranging between 170 and 210 (7 HRC and 17 HRC). AISI 1045 steel is characterized by good weldability, good machinability, and high strength and impact properties in either the normalized or hot rolled condition. These attributes make it suitable for sprocket.

Table 4: Chemical composition and Mechanical Properties Mechanical Properties of the material used

Chemical composition: C=0.45%, Mn=0.75%, P=0.03% max, S=0.04%	
Mechanical Property	**Value in metric unit**
Density	8×1000 kg/m^3
Poisson's Ratio	0.28
Elastic Modulus	205 (GPa)
Tensile Strength	580 (Mpa)
Yield Strength (Mpa)	500 (Mpa)
Hardness	170 (HB)

2.4 Manufacturing Processes for Sprocket

There are several methods that could be used to manufacture sprocket. The methods include milling, hobbing, powder metallurgy, sintering, and steel casting. The selection of a particular process is hinged on the sprocket material, equipment availability and cost.

A hobbing machine is a milling variant used to cut sprockets, gears, and splined parts using a specialist cutting tool known as hob. The hob is a cylindrical cutting tool that features a series of helical rows of teeth. The hobbing machine features two spindles, one of which holds the work piece and the other the hob. Both spindles rotate at a set ratio while the hob is advanced into the work piece to cut the teeth. Cutting toothed parts on a hobbing machine is a cheap yet accurate method of production of a wide range of products including worm gears, ratchets, involute gears, and helical gears.

In most cases, the manufacturing process to be used greatly lies on the facility available. Though, hobbing remains one the best methods that could be used, in this work universal milling machine was used. The operation layout of the manufacturing process is shown in Fig 6:

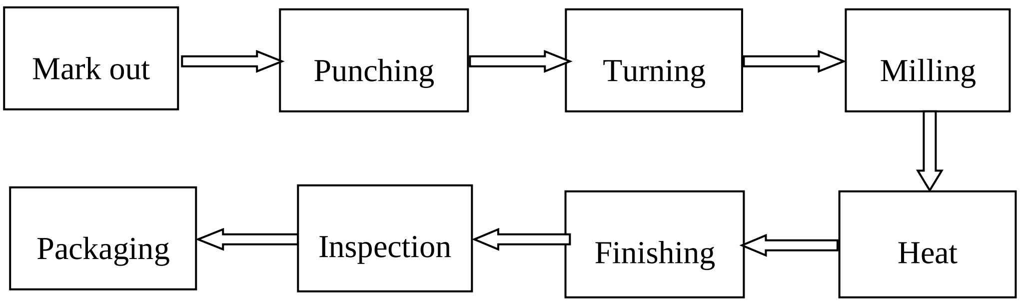


Figure 6: Manufacturing layout of a CY80 Motorcycle Rear Sprocket

2.4.1 Mark out

This involves the scribing of mark which is equivalent to the form/shape and size of the work piece on a material (stock) that the product will be made from. In this case, the work piece was cut off from 6mm mild steel plate.

2.4.2 Punching

Punching is a manufacturing process in which a strip of predetermined shape is cut in a single press stroke, from a strip or sheet. Punching operations can mainly be categorised into three. The three classes are blanking, piercing and notching (Bluescope Steel, 2003).

The punching process in which the punched out is the workpiece is termed blanking while the outside piece is the scrap. Blanking is cutting up a large sheet of stock into smaller pieces suitable for the next operation, such as drawing, machining and forming. For production parts, the final configuration of the drawn or formed shape need to be established before the blank die can be built-since the blank size and the slit width size needs to be established precisely (Jonathan, n. d.). Piercing is another punching operation that is similar to blanking; the only different is that the outside piece is the workpiece while the punched out is the slug or scrap. The cutting of the edge of the workpiece by punch is called notching (Bluescope Steel, 2003). Mechanism of Punching and main features of a punch are shown in Fig 7.

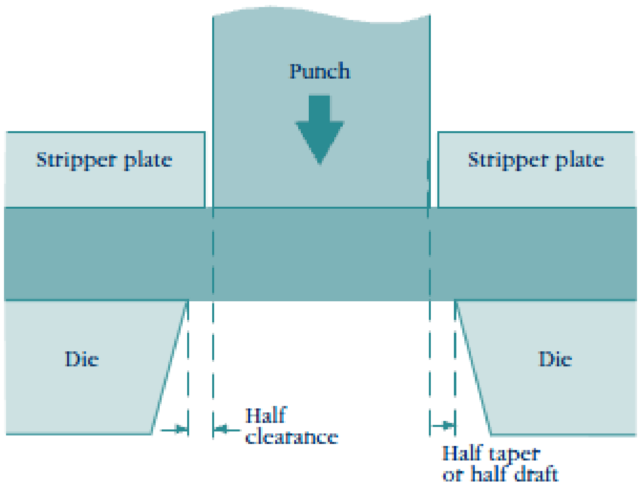


Figure 7: Features of a Punch

2.3.4 Design of Punch and Die

The design involves the determination of punching force and clearance (c) between the punch and the die. The general punching force (F) formula is given below:

Punching Force (F)

$$Punching.Force = Perimeter * Thickness * Shear.Strength$$

$$F = P * t * \sigma_s \quad \text{.................................(1)}$$

If the tool shape is round or circular shape;

$$F = \pi * D * t * \sigma_s \quad \text{................................(2)}$$

Where:

δ_s = shear strength of the material

P = perimeter of the shape of the tool

T = thickness of the material to be punched

D = diameter of the tool

Table 4: Shear Strength

Material :	psi/in^2(kN/mm^2)
Aluminum	25000(0.1724)
Brass	35000(0.2413)
Mild Steel	50000(0.3447)
Stainless	80000(0.5516)

Also, Punch Force in terms of tonnage:

Tonnage = Punch Perimeter x Material Thickness x Material Tonnage Value x Material Multipler

Material tonnage: Metric (Metric Tons/mm^2) = 0.0352; Inch (Imperial Tons/in^2) = 25

Table 5: Material Multiplier

MATERIAL TYPE	MATERIAL MULTIPLIER
Aluminum (soft sheet)	0.3
Aluminum (1/2 hard)	0.4
Aluminum (full hard)	0.5
Copper (rolled)	0.6
Brass (soft sheet)	0.6
Brass (1/2 hard)	0.7
Mild Steel	1.0
Stainless Steel	1.6

Source: Mate (2007)

For blanking of the workpiece for the CY80 sprocket, punching force (F); recalling equation (2):

$$F = \lambda \times D \times t \times \delta_s$$

D = 156mm = 0.156m, t = 6mm = 0.006m,

δ_s = 3.447 x 10^8 N/m^2 (shear strength of mild steel as contained in table 4)

$F = 3.14 \text{ x } 0.156 \text{ x } 0.006 \text{ x } 3.447 \text{ x } 10^8$

$= 1013601\text{N}$

= **103.36 Tons**

In this work, a 125T mechanical press was used for the sprocket punching.

Die Clearance

Die clearance is the difference between the punch diameter and die diameter. It is equal to the space between punch and die when the punch enters the die opening. It is usually about 20% of the material thickness as shown in Table 4 (Mate, 2007). Regardless of sheet thickness, the recommended penetration of the punch into a Slug Free die is 0.118(3.00).

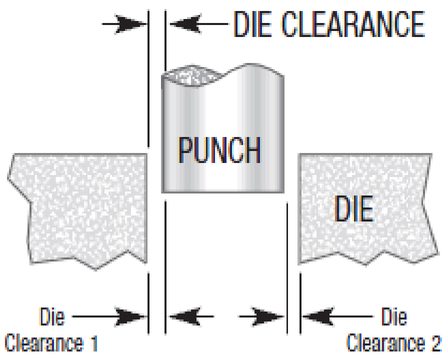
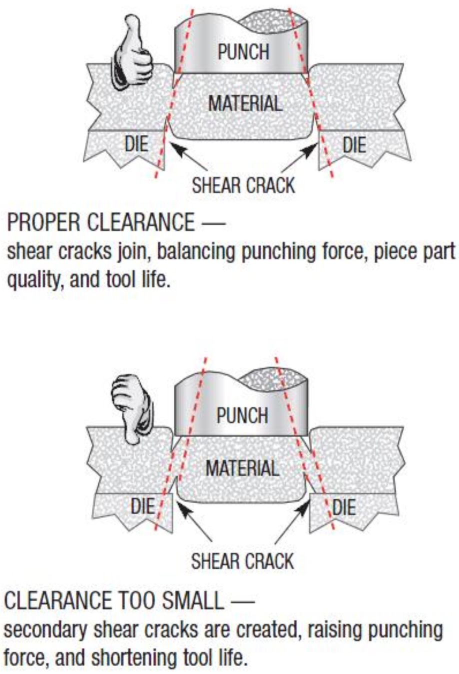


Figure 7: Die Clearance



TC = Die Clearance on both sides of punch

TC = Die Clearance 1 + Die Clearance 2

TC = 20% of t; t = 6mm

= 1.2 mm

Figure 8: Effects of Clearance

That is, die clearance 1 = 0.6mm and die clearance 2 = 0.6mm, see figure 7

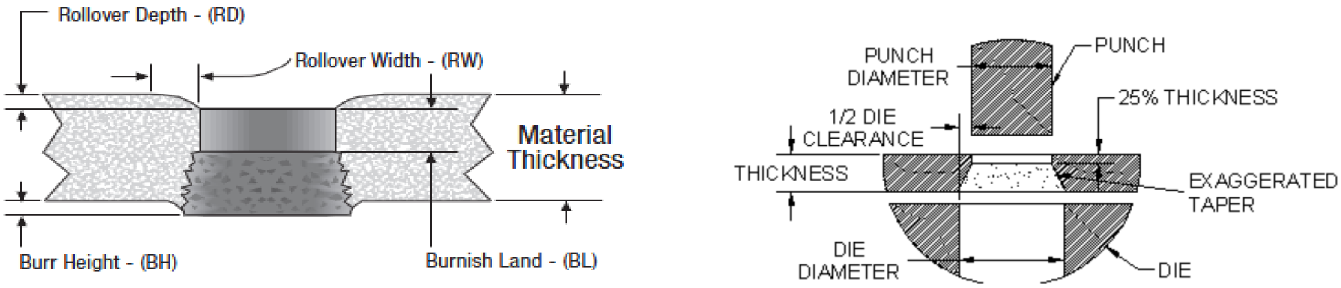


Figure 9: Anatomy of a punched Hole

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Table 4: Die Clearances for different Materials

Blanking Tools are used to punch out a small part down the slug chute.		Piercing	Blanking
Material Type (Typical Shear Strength)	Material Thickness (T)	Total Die Clearance (% of T)	Total Die Clearance (% of T)
Aluminum 25,000 psi (0.172 kN/mm²)	Less than 0.098(2.50)	15%	15%
	0.098(2.50) to 0.197(5.00)	20%	15%
	Greater than 0.197(5.00)	25%	20%
Mild Steel 50,000 psi (0.344 kN/mm²)	Less than 0.118(3.00)	20%	15%
	0.118(3.00) to 0.237(6.00)	25%	20%
	Greater than 0.237(6.00)	30%	20%
Stainless Steel 75,000 psi (0.517 kN/mm²)	Less than 0.059(1.50)	20%	15%
	0.059(1.50) to 0.110(2.80)	25%	20%
	0.110(2.80)to 0.157(4.00)	30%	20%
	Greater than 0.157(4.00)	35%	25%

Source: Mate (2007).

2.3 Milling of the Sprockets

After the blank (workpiece) has been properly mounted on the machine and the other set up in the machine completed, the longitudinal feed of the table was engaged. The blank moves under the rotating cutter and tooth space cut. The movement of the table is reversed so that the cutter again clears the space. The workpiece is then indexed to the next position for cutting the second tooth space. This procedure is repeated until all the teeth are milled.
The formula used in the calculation is,

$$Crank\ turns = {}^{40}/_{N} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where N = the desired number of equal division at the spindle.

Reduce this fraction to its simplest form. Use any whole number to represent complete turns, and use the denominator to determine the index plate to use.

Therefore, since the numbers of teeth on the Rear sprocket are 37 we have,

$$Crank\ turns = {}^{40}/_{37}$$

$$= 1\frac{3}{37}$$

2.4 Heat Treatment of a Sprocket

Most steel sprockets to be used on motorcycles are heat treated, which changes the hardness of the material. If not done correctly it can produce a brittle part. After hardening, the sprockets are tempered to produce exactly the correct hardness for durability and efficient power delivery. To correct any distortion that may have occurred during these stages, the sprockets are put through a final flattening machine (AFAM, 2011).

There are different methods of hardening the surface but the commonest, easy to use and most economical are electrical induction or flame hardened to Rockwell “C” 40 to 50 that is of tensile strength of 160-247 (per square inch). Depending on the application, tooth hardness after tempering is typically in the 48 to 60 HRC range. Core hardness primarily depends upon steel chemical composition and steel condition prior to induction hardening. For quenching and tempering, prior structure core hardness is usually in the 28–35 HRC range (Valery, 2008).

A major goal of induction sprocket hardening is to provide a fine-grain martensitic layer on specific areas of the part resulting to increases part’s hardness, wear resistance, contact fatigue and impact strength. Another goal of induction sprocket hardening is to produce significant compressive residual stresses at the surface and in a subsurface region. Compressive stresses help inhibit crack development and resist tensile bending fatigue.

Not all gears, sprockets and pinions are well suited for induction hardening. External spur and helical gears, worm gears, and internal gears, racks and sprockets are among the parts that are typically induction hardened as shown in Fig

10. Conversely, bevel gears, hypoid gears, and noncircular gears are rarely heat treated by induction (Rudnev et al, 2003).

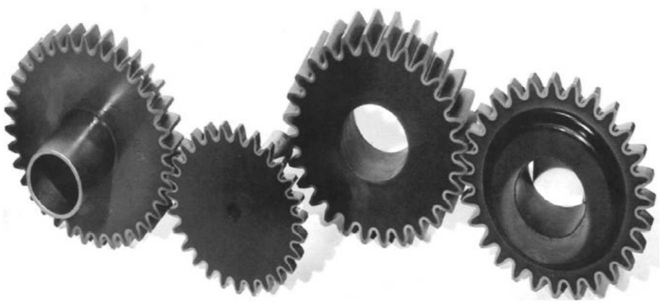

Figure 10: Typical induction-hardened sprockets and

With induction, heating can be precisely localised to the specific areas where metallurgical changes are desired (e.g., sprocket flank, root and tip can be selectively hardened) and the heating effect on adjacent areas is minimum. Depending upon the application, tooth hardness ranges typically from 42 to 60HRC. A tough-hardened gear tooth, with a hardness reading exceeding 60HRC, is too brittle and will often experience a premature brittle fracture. Hardened case depth should be adequate (not too large and not too small) to provide the required gear tooth properties (Rudnev et al, 2003).

2.5 The test result of the sprocket produced

The hardness of the material used before heat treatment is 13 HRC and the hardness of the sprocket produced after heat treatment is 45 HRC

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