NUMERICAL SIMULATION OF COLD ORBITAL FORGING PROCESS FOR GEAR MANUFACTURING

Sundar Singh Sivam Sundarlingam Paramasivam, Durai Kumaran, Harshavardhana Natarajan, Avishek Mishra

Department of Mechanical Engineering, SRM Institute of Science and Technology, Kancheepuram District, Kattankulathur- 603203, Tamil Nadu, India

Corresponding author: Durai Kumaran, dkumaranmech@gmail.com

Abstract: Cold orbital forming is a novel metal forming process, which is employed to manufacture various parts such as gears, rings, disks etc. In this method, one of the dies is tilted to some angle and the top die performs a rocking motion. As a result the contact area between the die and work piece changes frequently. The final product that is obtained has a specific number of incremental steps and the work piece undergoes cyclic loading. The simulation of the whole setup is carried out and based on the result conclusions are drawn. The billet dimension play a significant role in the final output obtained by the forging process to have a better insight over the process two cases with dissimilar diameter are consider so as to study various cases that may arise due to the metal flow during the process. Two different cases one with work piece diameter 60mm and the other case with work piece diameter 80mm are chosen for understanding how different billet dimensions predict the gear product. Graphs of various basic parameters such as strain rate, plastic strain, temperature etc. are obtained and comparisons are drawn between the two cases. The graph patterns obtained are considered for the study of the process. This paper presents a brief overview of cold orbital forging process, its mechanical characteristics based on simulation of the gear.
Key words: Cold orbital forming, Gear manufacturing, near net shape technique.

1. INTRODUCTION

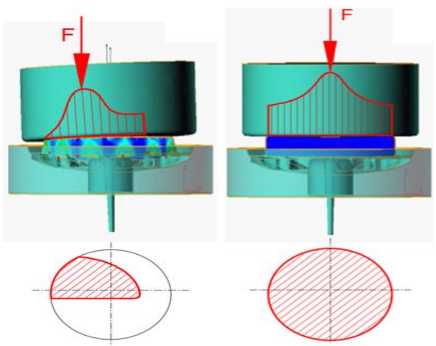
To analyze the process of gear manufacturing and study various parameters of cold orbital formed gear using Q Form software. The study of plastic strain, strain rate, temperature and yield stress leads us to the stress- strain graph which helps in analyzing the process and this in turn helps us to understand this process in more elaborate manner .The orbital forging is a method of cold or worm working of parts, which is based on methods patented in 1920 by Slick followed by Massey 1922 Massey. Precision forging, or net-shape forging, has become increasingly popular with the development of industrial technology due to savings in energy, material and less number of finishing steps. The upper die continuously oscillates around the vertical machine axis during orbital forming process. Simultaneously, the lower die pushes the work piece vertically with a stable feed rate so as to subject the work piece to axial compression without the accompaniment of rotation.

1.1 Need for Study

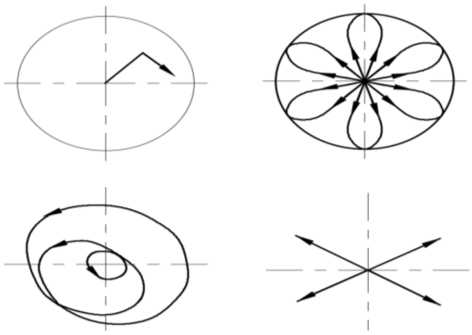
Cold orbital forming process is more useful and preferable in comparison to other manufacturing processes. It has higher efficiency and consumes less time. Gears manufactured through this process have a better surface finish. This process manufactures in bulk and is found to be economical. For understanding this process, the billet dimensions are altered and studied. The metal flow for the different billets produces various results. Cases of underflow and overflow may arise while the process is being carried out which in turn helps us to understand the process better and how billet dimension would affect the final output. To know the process better, intensive study of the process is needed. In our present study the billet dimensions have been studied and process parameters have been understood to carry out the process.

1.2 Process and its technical characteristics

The need for less force combined with better forming performance are the primary factors that make orbital forming technology a success [2, 5]. In just a single die-forging stage, you can produce work pieces of great dimensional and geometrical accuracy and with an outstanding surface finish. There are several different variants of orbital forging. Work piece is positioned between the upper tool and the lower tool in vertical press machine, where the axis of the upper tool is slightly tilted at an angle (generally 1 - 2°) [2]. Up-per tool performs only rotary motion and lower tool moves upwards. The tool is in full contact with the lower surface of the work piece, while the surface of contact between upper tool work piece surface and upper tool is small when compared to classical forging, because of the axis being tilted [2]. The decreased contact surface results in lower forming load. Comparison between classical and orbital forging is illustrated in Figure 1(a). In classical forging angle γ = 0° and there is no rotation of the die [2]. Contact area between upper tool and work piece is depended on tilted angle of upper tool axis: the bigger the angle, the smaller the contact surface and, therefore, lower forming load [2-4]. Larger the angle, more complex is the machine maintenance and greater is the frame deflection, which makes it more complex to keep constant forming precision. The tilted upper tool's axis can perform different motion styles presented in Figure 1(b). Orbital (circular) motion is most commonly used, especially when relatively thin parts are forged, as high deformation is required throughout the whole part volume. The parts which have large ribs and flanges, planetary motion becomes most appropriate. For parts in which most material flow occurs in central region, spiral motion is most suited and straight line motion is most convenient for long, narrow parts. The need for less force combined with excellent forming performance are the primary factors that make orbital forming technology a success [2-4]. In just a single die-forging stage, you can produce work pieces of great dimensional and geometrical accuracy and with an outstanding surface finish. There are several different variants of orbital forging. Work piece is positioned between the upper tool and the lower tool in vertical press machine, where the axis of the upper tool is slightly tilted at an angle (generally 1 - 2°) [2-4]. One of the main parameters which has impact on process development is the angle of inclination of upper die in relation to the vertical axis. Larger angle response in lower die contact surface between upper die and work piece and, consequently, in lower total load [7]. Larger the inclination angle, more is the vibration, when there is strong lateral loading of the machine and tooling and unbalanced process development in general [7]. Another parameter would be the influence of billet geometry on forging load. Three billets with the same volume but different diameter to height ratio are rotary forged to the final component. Highest load occurs in case of tallest initial billet and vice versa, lowest load is required for shortest and widest billet [7-10]. Materials used are Carbon and low-alloy steels, aluminium alloys and brasses, stainless steel. It is also called rotary forging, swing forging, or rocking die forging. In some cases, the lower die may also rotate as is shown in Figure 1 (a) and (b), [1].



(a)



(b)

Fig. 1. Principal difference between classical and orbital forging and various motion possibilities of upper tool's axis

2. METHODOLOGIES

2.1 Principle and process overview

It works on the principle of forming. Forming processes are particular manufacturing processes which make use of the stresses like compression, tension, shear or combined stresses to cause plastic deformation of the materials to produce the shapes needed. During forming processes no material is removed, i.e. they are deformed and displaced. The Die and billet 3D CAD models are designed using Solid Works software. The models generated are converted and imported into Q form software for the process simulation. Using this software the process analysis is done, and characteristic data are obtained and analyzed.

2.2 Calculations and simulation

2.2.1 Billet dimension

The equation (1) gives the right dimension of the height of the billet corresponding to the diameter of the billet.

$$h1 = 151.65(d1/D)2 - 270.5(d1/D) + 143.75 \quad (1)$$

Where: d1 =yield stress MN/m2; D =plastic strain No unit

Here, we consider two cases with different diameters. The first case is a billet with diameter 80mm and the second case is a billet with diameter 60mm. The obtained dimensions are used to design the dies on Solid Works software. The simulation is carried out using Q Form software until complete formation of the finished gear. The tool diameter is set at 88.5mm in diameter, shown in Table 1.

Table 1. Variations of perform dimensions (unit mm)

SERIAL NO.	D	d1	h1
1	88.95	50	39.63
2	**88.95**	**60**	**30.30**
3	88.95	70	24.81
4	**88.95**	**80**	**24.15**
5	88.95	90	25.32
6	88.95	100	31.32

2.3 Geometrical model and mesh

Spur gear being the investigated subject contributes to machine functioning's in the wide areas such as automobile, power plants, milling machines, marine engineering and various other sectors. According to the geometrical shape and dimensions, the 3D solid modeling of the upper die, lower die, and the cylindrical billet is developed using CAD software (Solid Works) and IGS for-mat files are loaded into the Q Form software. The upper die inserts and the ejector for providing the cavity in the gear is merged into the dies. Both the rotary forging dies are treated as analytical rigid bodies for the prime objective of decreasing the CPU time and each of the rigid bodies are assigned with reference point to represent its rigid motion in all degree of freedom. The formed is a 3D deformable solid body. An absolute meshing relation is considered for the work piece which has a minimum size ratio=3 and mini-mum element size >1and initially surface meshing is done which is later converted into a solid mesh .The minimum number of mesh elements taken is ≥100000 mesh elements for proper study of the deformation of the work piece. The above Figure 2 shows the complete assembly of the process of orbital cold forming.

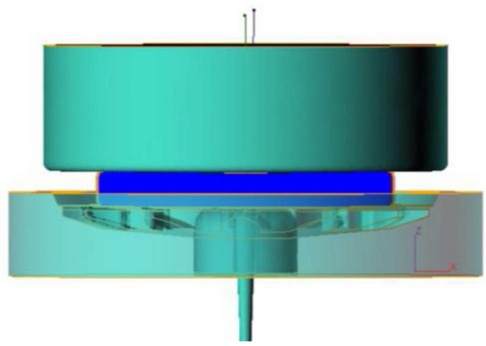


Fig. 2. Complete setup of the dies with work piece

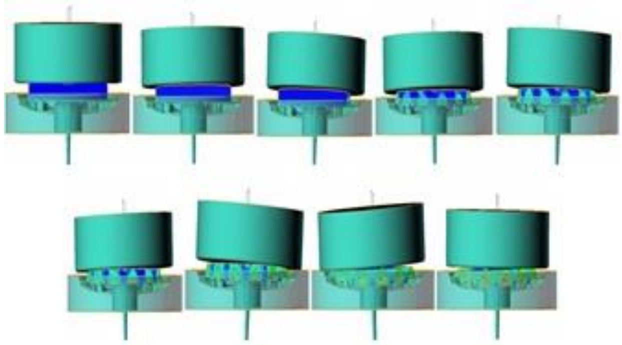


Fig. 3. Steps showing the development of gear in cold orbital forming

2.4 Material models

The material of the work piece used for this study is a low carbon alloy steel, AISI 1006. This particular material has good deforming property for which it has been considering for the current studies the material properties are: Poisson's ratio=0.29, Density=7.872g/cm^3, Yield strength=285MPa, bulk modulus=140GPa, Tensile strength=330MPa and steps showing the development of gear shown in Figure 3.

2.5 Friction condition

In cold orbital forging process, two contact pairs are defined. The contact pairs are defined as surface to surface contact type, which allows sliding between the surfaces. The surface of the rigid body is dominant surface while the surface of the deformable body defined as the slave surface MoS_2 is used as the lubricant and the value of friction factor is determined to be 0.12 [6].

2.6 Constraints

The rigid motion of the rigid body in all degree of freedom can be represented the reference point. So in the global coordinate system, the upper die is fixed to oscillate only about the 1 and 3 global coordinate axis while the lower die is constraint to translate only along the global 2 axis. For improving the surface finish the upper die has to oscillate at least one revolution along the machine axis after the lower die stops its translatory motion along the axis.

3. RESULTS AND DISCUSSION

3.1 Work hardening curve equation

The equation (2) used to calculate yield stress is *Work Hardening equation*.

$$\sigma_p=684\ \phi 0.098\ \acute{\varphi}\ 0.134\ \exp(-0.0058T) \qquad (2)$$

- σ_p =yield stress, [MN/m^2]
- Φ =plastic strain No unit
- $\acute{\varphi}$ =strain rate, [1/s]
- T =Temperature of work piece, [˚C]

The two cases (Case 1 and Case 2) are considered, and the yield stress, plastic strain, strain rate temperature data is fed into the equation. The corresponding values of required parameters like Billet with Diameter and parametric table 60 & 80mm, shown in Tables 2-5.

Table 2. Case 1: billet with diameter 60mm

D mm	d1 mm	H1 mm
88.95	60	23.15

Table 3. Parameter table for case 1

STEP NO	Φ Plastic strain No unit	$\acute{\varphi}$ Strain rate [1/s]	T Temperature of work piece, [˚C]	σ_p Yield stress [N/m^2]
1	0.0	8.4	20.0	0.0
10	0.2	6.7	117.2	380.6
20	2.8	208.6	137.8	694.8

30	3.6	97.3	149.3	337.2
40	3.6	54.3	122.9	655.1
50	3.6	201.6	103.0	868.2
60	3.6	54.8	123.2	772.0
70	3.6	39.0	109.6	731.8
80	3.6	90.6	105.5	814.8
90	4.6	156.6	144.3	677.3
100	4.9	61.3	133.1	640.6
110	4.9	130.4	105.3	832.9
120	5.5	34.3	162.8	505.3
130	5.5	59.5	148.4	590.8

Table 4. Case 2: billet with diameter 80mm

D mm	d1 mm	H1 mm
88.95	80	30.30

Table 5. Parameter table for case 2.

STEP NO	Φ Plastic strain No unit	ǿ Strain rate [1/s]	T Temperature of work piece, [˚C]	σ_p Yield stress $[N/m^2]$
1	0.0	8.4	20.0	0.0
10	0.2	6.7	117.2	380.6
20	2.9	203.3	139.1	689.7
30	3.6	47.5	135.0	594.7
40	3.6	44.0	166.9	489.5
50	4.2	144.1	129.5	723.3
60	5.3	176.8	145.6	857.9
70	5.3	73.8	113.3	742.3
80	5.3	34.9	116.0	661.3
90	6.2	119.6	129.3	733.4
100	6.5	29.9	127.8	616.8
110	6.5	21.4	108.2	661.0
120	7.2	78.1	131.4	694.7
130	7.5	69.6	129.4	694.7

3.2 Distribution of effective strain and strain rate

The distribution of effective strain (PEEQ) at various stages of the orbital cold forging process is studied. Contact is made between upper die insert and lower die insert with the billet at the beginning. The plastic deformation zone is firstly formed in the area which satisfies yield condition. The height of the work piece decreases over time and the metal near the upper die flows more vigorously than that near the lower die. This results in the increase in diameter of the upper surface significantly. This is the so-called “mushroom shape” effect, which is one of main deformation characteristics of orbital cold forging [3] as the forging process continues, the work piece enters a steady deformation stage and the profile of gear shape is gradually deformed. At the final stage, the radial flow resistance in-creases remarkably because of which the flash grows slowly and hence keeps the metal from flowing outwards. This flow resistance in turn forces the remaining metal to take the path of least resistance, which is an alternative route, thus resulting in filling the small-end gear shape [3]. Towards the end of forging, the central cavity portion is strain hardened the most Figure 4 [3].

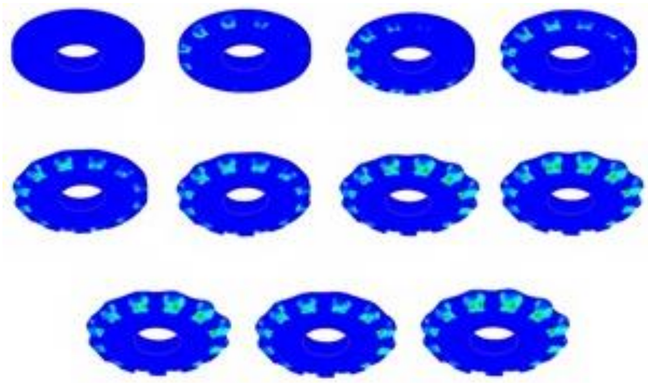


Fig. 4. The distribution of effective strain (PEEQ)

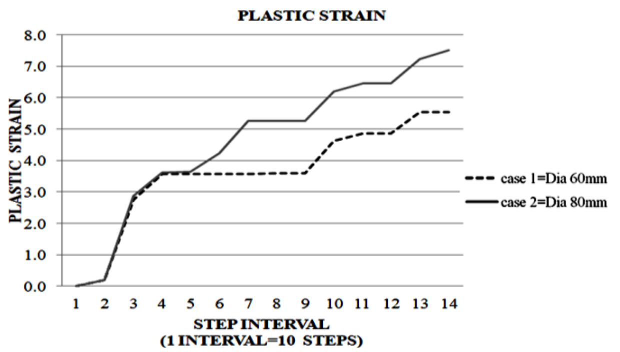


Fig. 5. Comparisons of strain rate distribution for case 1 and case 2

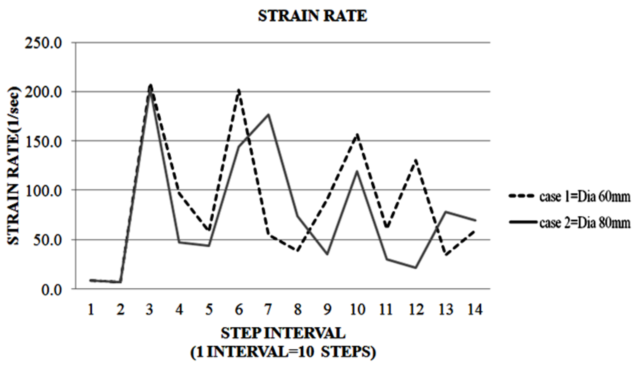


Fig. 6. Comparisons of plastic strain distribution for case 1 and case 2

In Figure 5 the graph for the plastic strain is plotted considering two cases- case 1 with work piece having diameter 60mm and case 2 with work piece diameter 80mm by considering the values obtained in Tables 3 and 5. The pattern suggests that the plastic strain for case 2 rises more steeply as the gradient is more when compared to case 1; where the pat-tern is rising at a less steep rate. Hence, case 1 work piece undergoes less plastic strain when com-pared to case 2. Hence, case 2 work piece is favored over case 1 work piece for gear manufacturing.

In Figure 6 the graph for strain rate is plotted from the data obtained from the Tables 3 and 5. Considering two cases: case 1 with work piece having diameter 60mm and case 2 with work piece diameter 80mm. The pattern suggests that the strain rate for case 1 is non uniform and rises suddenly at a point showing irregular strain distribution. However, in case 2 the pattern is uniform throughout and decreases to-wards the end. Hence, case 2 work piece is favored over case 1 work piece for gear manufacturing.

3.3 Distribution of effective stresses

Figure 7 shows the distribution of the equivalent stress in the deforming billet with time [3]. The top and bottom surface of the billet are the first regions to be stressed at the beginning of forging [3]. As the lower die pushes up, the height of the billet is reduced [3]. Hence the entire billet will be stressed beyond the yield point, and the gear starts to take shape [3].

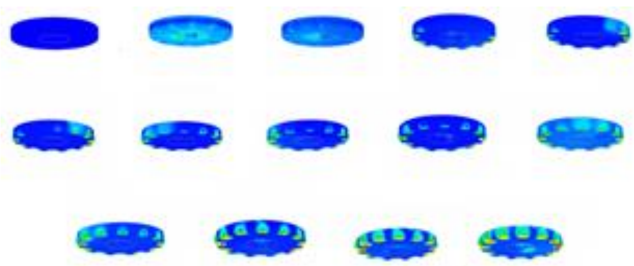


Fig.7. Equivalent Stress distribution of the deforming billet with time

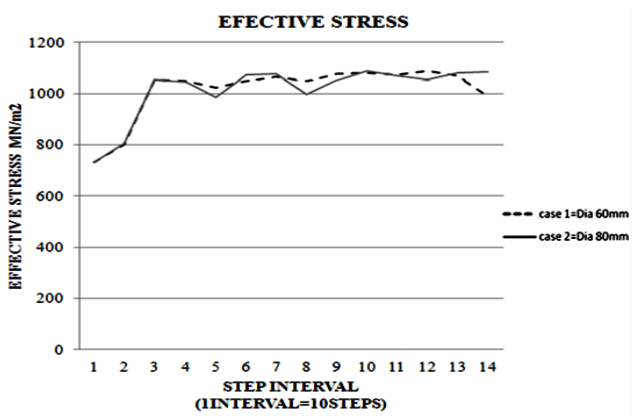


Fig. 8. Comparison of effective stress distribution for case 1 and case 2

In Figure 8 the graph for effective stress distribution is plotted from the data obtained from the simulation considering two cases- case 1 with work piece having diameter 60mm and case 2 with work piece diameter 80mm. The pattern suggests that the effective stress for case 2 is non- uniform and rises suddenly at a point showing irregular stress distribution. However, in case 1 the pattern is uniform through-out and decreases towards the end. Hence, case 2 work piece undergoes less stress when compared to case 2. Hence; case 2 work piece is favored over case 1 work piece for gear manufacturing.

3.4 Temperature

The material temperature increases steeply if the work piece is formed in cold conditions. Temperature distributions over the work piece are shown in the Figure 9 below. Significant temperature increase is caused by heat generated in the material. The resultant heat is generated due to:

1) friction on the surface of the contact between upper-die and work piece.

2) Plastic strains of the work piece material.

Once the upper die moves away from the point of contact, the material does not undergo intensive deformation any longer, and the heat wave is carried away to the environment.

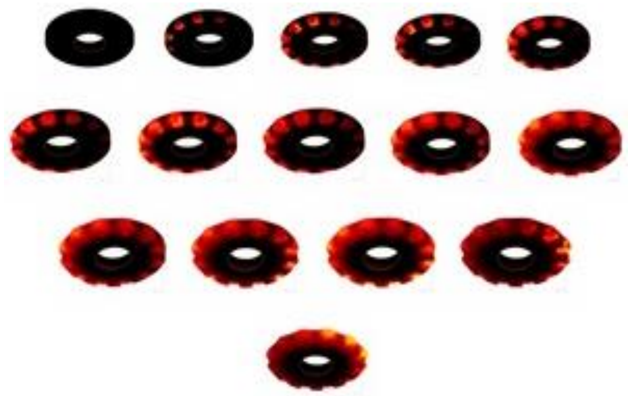


Fig. 9. Temperature distributions over the work piece

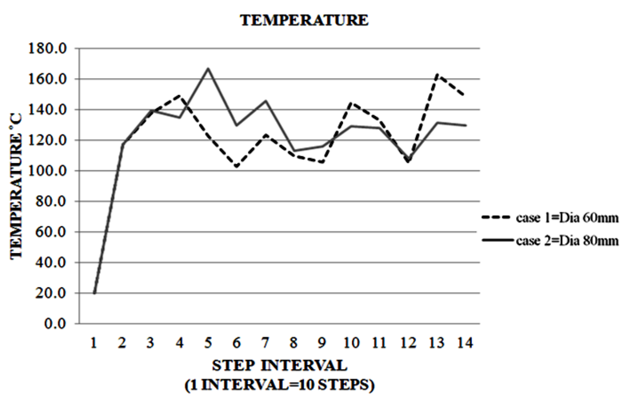


Fig. 10. Comparison of temperature distribution for case 1 and case 2

In Figures 9 and 10 the graph for temperature is plotted from the data obtained in Tables 3 and 5 by considering two cases - case 1 with work piece having diameter 60mm and case 2 with work piece diameter 80mm. The pattern suggests that the temperature distribution for case 2 is nonuniform and showing irregular distribution. In case 1 the pattern is similar, but the graph remains almost constant towards the end. Hence, case 2 work piece is favored over case 1 workpiece for gear manufacturing. As the process proceeds, there is a gradual increase of the work piece temperature while the temperature of the case 1 work piece decreases over time and hence shows defects arising in the workpiece during the deformations process while the case 2 work piece has a gradual rise in the temperature.

3.5 Stress-strain curve

The path followed by a body when subjected to deforming force is depicted by a stress – strain curve in Figure 11 which helps to study the material behavior during the process. Here, a comparison between stress-strain diagrams for two different cases has been done and it helps in drawing inferences of the conclusion for the study. The SS curve shows significant characteristic of the material behavior while it undergoes load by the upper die. The contact patch being less in this case needs lesser load to deform into the desired shape and size.

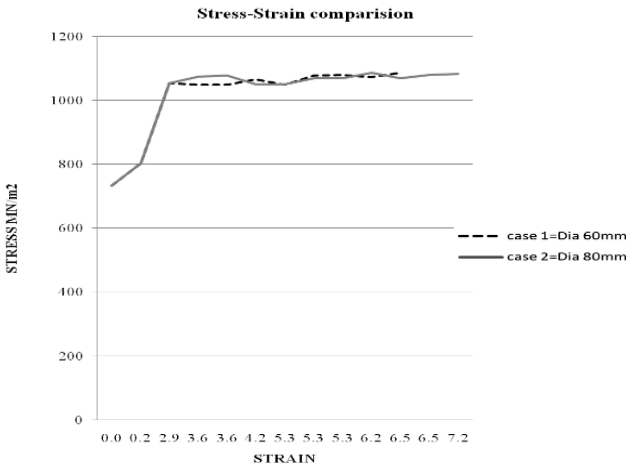


Fig. 11. Comparision of Stress-Strain Diagram for case 1 and case 2

4. CONCLUSIONS

Orbital forging is a typical incremental bulk metal operation, which offers a number of advantages when compared with other manufacturing techniques. The benefits includes high degree of accuracy, relatively short operation time of 5s – 10s, low axial force required, low tool wear. From the current study on simulation of orbital cold forging of gear manufacturing using the *Q form 3D version 8.0.7.1,* the following inferences were made.

•The Plastic strain rate for 80mm diameter workpiece is higher than 60mm diameter. The higher plasticity can result in higher formability for which in turn results in better gear manufacturing for 80mm diameter workpiece.

•The Effective stress distribution of 80mm diameter workpiece shows less stress compared 60mm diameter workpiece. So the latter can have a better formability even at lower stress value which in turn favors gear manufacturing.

•From temperature distribution, 80mm diameter experiencing higher temperature than 60mm diameter. This temperature in favors formability of the work piece.

•Finally, the stress-strain plot for both the cases shows an increase in strength till yield point and there is saturation at the plastic limit which is similar to the SS curve from experimental observation. There are no significant differences between both the cases which believe to follow the material properties. By considering the above parameters, it is concluded that, 80mm diameter workpiece suits better for gear manufacturing using the *Q form 3D version 8.0.7.1.* Hence, large diameter i.e 80mm is favored for gear manufacturing in this software.

5. ACKNOWLEDGEMENT

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