

Numerical Simulation of Orbital Cold Forging of a Bevel Gear

Devanathan. R¹, Vela Murali²

Final Year PG Student, Engineering Design Division, Department of Mechanical Engineering, College of Engineering, Guindy, Chennai, India¹

Professor, Engineering Design Division, Department of Mechanical Engineering, College of Engineering, Guindy, Chennai, India²

ABSTRACT: Orbital cold forging, an innovative incremental metal forming process, is employed to manufacture various parts such as gears, rings, flanges, disks, etc. Compared with conventional forging, this method has many advantages such as lower level of noise and vibration, uniform quality, smooth surface, low power requirement, etc. In this method, one of the dies is tilted to some angle and performs a complex rocking motion. As a result, the contact area between the dies and the workpiece is reduced and is continuously moved. A numerical analysis of orbital forging is difficult to perform due to the complex rocking motion of the die. In the present work, a FEM simulation of the orbital cold forging of bevel gear is developed using ABAQUS software. Through simulation, the distributions and histories of different field-variables such as stress, strain, etc. are investigated in detail. The numerical simulation results provide valuable guidelines for better understanding the deformation characteristics of orbital cold forging of the bevel gear.

KEYWORDS: Bevel gear forming, Orbital forging, FEM simulation.

I. INTRODUCTION

Orbital Cold forging, a promising incremental metal forming process, is widely applied for fabrication of engineering components such as disks, rings, gears. Compared with conventional forging, orbital cold forging has many excellent advantages, such as great reduction of raw material and energy expenses, remarkable increase in dimensional accuracy and surface finish, and considerable improvement in mechanical properties of products. In order to produce high-quality bevel gears utilising the orbital cold forging process, detailed understanding of this process is required. At present, the literature on the study on the orbital cold forging process of the gears has been still scant.

Miroslav E. Plancak et al (2012) presented a brief overview of orbital forging characteristics and comparison with classical forging. Lin Hua and Xinghui Han (2009) developed a 3D elastic-plastic dynamic explicit FE model of orbital cold forging of a cylindrical workpiece. In another work, they developed a 3D elastic-plastic dynamic explicit FE model of the orbital cold forging process of ring workpiece and verified experimentally. The research results provide valuable guidelines for better understanding the deformation characteristics of orbital cold forging of the simpler workpieces. Xinghui Han et al (2014) investigated the process design and control method in orbital cold forging of parts with non-rotary upper and lower profiles. Xiaobin Deng et al (2011) developed a 3D rigid-plastic finite element (FE) model of orbital cold forging of spur bevel gear. Samołyk (2013) discussed the numerical analysis of orbital forging of bevel gears which is very difficult to perform due to the complex rocking motion of the die. Consequently, the work presented here is devoted to the numerical simulation of orbital cold forging of a spur bevel gear with cavities under the ABAQUS platform, aiming to illustrate the feasibility and reveal the deformation mechanism of this process.

II. ORBITAL COLD FORGING

It is unique feature of the orbital forging process that the upper die axis is inclined from the major axis by some angle as shown in Figure.1. Owing to this die inclination, a certain reduction in the instantaneous contact area between the upper die and the workpiece is obtained. During the orbital cold forging process, the upper die continuously oscillates around the vertical machine axis. Simultaneously, the lower die pushes the workpiece vertically at a constant feed rate v so as to subject the workpiece to axial compression. Under the action of the oscillation of the upper die and the axial feed of the lower die, the workpiece is pressed repeatedly and thus the material is progressively flowing into the die cavity, ultimately the desired gear shape will be completed perfectly. The die precession can be performed with or without the accompaniment of rotation. However, the inclination angle is either a constant or a variable, and is always greater than zero. For the current work, the die precession is performed without the accompaniment of spin. The circular rocking motion of the upper die is discussed.

III. FEM SIMULATION

A complete FE modelling process involves the selection of suitable software, the construction of accurate geometry and material models, the determination of realistic boundary conditions and process parameters.

Software:

The orbital cold forging process by nature, like other incremental forming processes, is exceptionally difficult to model because of its nonlinearity in geometry, material and contact conditions. A 3D dynamic explicit FE model is developed for numerical simulation of orbital cold forging of a spur bevel gear using the ABAQUS/Explicit software.

Geometrical models and Mesh:

The spur bevel gear served as a component of the automobile differential mechanism is regarded as the subject investigated. According to the practical geometry shape and dimensions, the 3D solid modelling of the upper die, lower die and the cylindrical billet is developed using CAD software Pro/E and IGES format files are loaded into the ABAQUS software as shown in Figure. 2. The upper die insert and the ejector for providing the cavity in the gear is integrated into the dies itself. For the sake of decreasing computer CPU time, both the rotary forging dies are treated as the analytical rigid bodies and each of the rigid bodies is assigned with a reference point (RP) to represent its rigid motion in all degrees of freedom. The billet is defined as a 3D deformable solid body and the 3D linear reduction integration continuum element with eight nodes (C3D8R) is used to discretise it.

Material Models:

The material of the workpiece used in this current study is a low-carbon alloy steel, SCr420HB. This particular material is used to manufacture some typical automobile components such as transmission gears, gear rings and gear shafts under the condition of high-speed impact and heavy loads. The material properties are: Poisson's ratio $\mu = 0.3$, Density $\rho = 7800 \text{ kg/m}^3$, Yield strength $\sigma_y = 325.68 \text{ MPa}$, Young's modulus $E = 225.5 \text{ GPa}$.

Modelling of the upper die motion:

The current work deals with a rocking motion where precession is performed without the spin of the upper die. A numerical modelling of such rocking-die motion is not simple. A solution to this problem is to define two orthogonal axes of rotation. The upper die is therefore made to oscillate about two axes of the global co-ordinate system by providing periodic amplitudes.

Friction conditions:

In ABAQUS/Explicit, the master-slave algorithm is adopted. The surface of rigid body is defined as the master surface while the surface of deformable body is defined as the slave surface. In the orbital cold forging process, two contact pairs are defined. The contact pairs are defined as surface-to-surface contact type, which allows

sliding between the surfaces. MoS₂ is used as the lubricant and the value of friction factor is determined to be 0.14 which is obtained from the related papers [1, 9].

Constraints:

As described above, the rigid motion of the rigid bodies in all degrees of freedom can be represented by the reference point. So in the global coordinate system, the upper die is constrained to oscillate only about the global 1 and 3 axis while the lower die is constrained to translate only along the global 2-axis. In order to improve the surface quality of the upper surface of the workpiece, finishing procedure, in which after the lower die stops the axial feed until the specified stroke, the upper die still has to oscillate at least one revolution around the machine axis, is carried out.

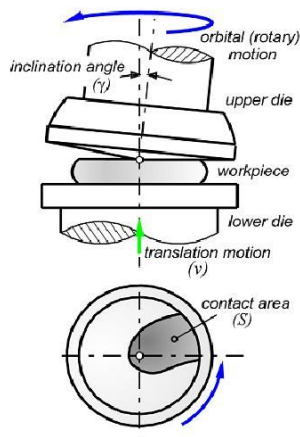


Figure.1. General Scheme of Orbital Cold Forging

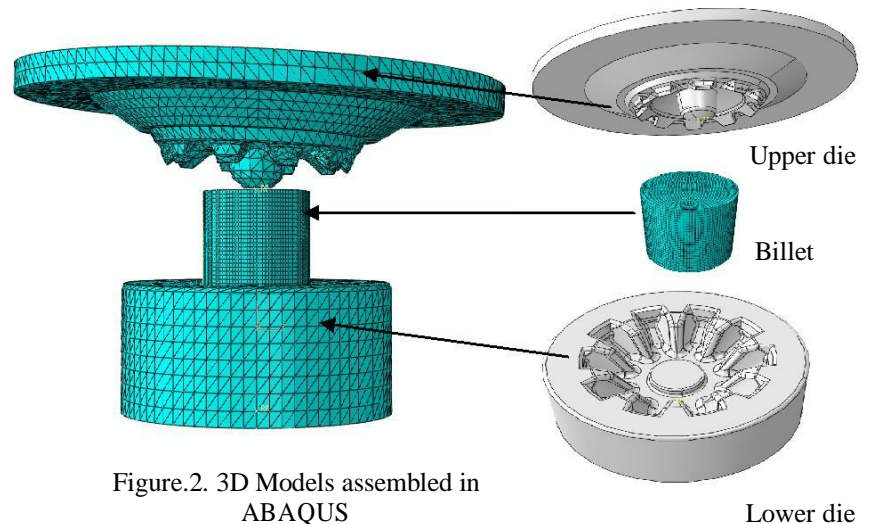
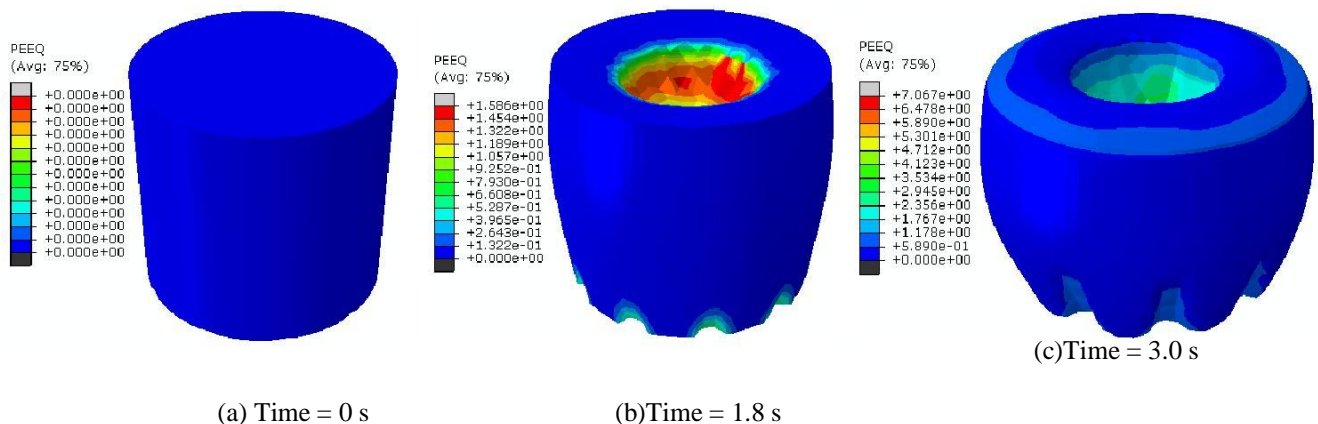


Figure.2. 3D Models assembled in ABAQUS

IV. RESULTS AND DISCUSSION

Distribution of Effective Strain:

The distribution of effective strain (PEEQ) at different stages of the orbital cold forging process is illustrated in Figure. 3. The upper die insert and the lower die ejector make contact with the billet at the beginning. The metal in these areas satisfy the yield condition to arrive at the plastic deformation state. Naturally, the plastic deformation zone is firstly formed in this area (Figure. 3b).



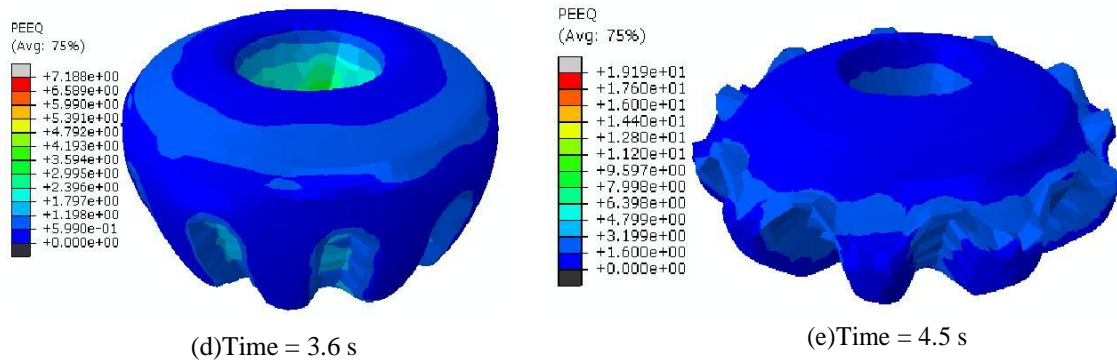
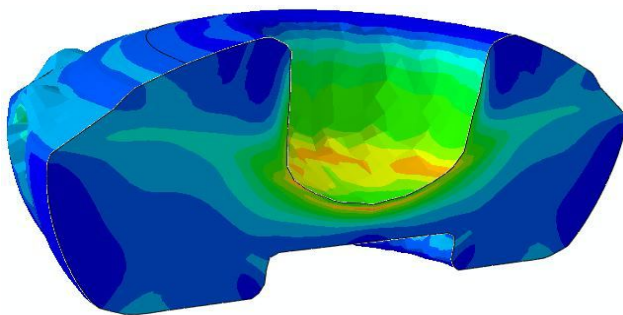


Figure.3. Plastic strain distribution of the deforming billet



Over time, the height of the workpiece decreases and the metal near the upper die flows more severely than that near the lower die, thus resulting in the significant increase in diameter of the upper surface (Figure. 3c). This is so-called „mushroom shape” effect, which is one of main deformation characteristics of orbital cold forging. As the forging process continues, the workpiece enters a steady deformation stage and the profile of gear shape is gradually deformed (Figure.3d). At the final stage, the flash grows slowly due to the radial flow resistance increases remarkably and hence keeps the metal from flowing outwards. This flow resistance in turn forces the remaining metal to take an

alternative route, namely the path of least resistance, thus resulting in filling the small-end gear shape (Figure.3e). Towards the end of forging, the central cavity portion is strain hardened the most (Figure.4).

Distribution of Metal Flow:

In the orbital cold forging process of a spur bevel gear, the workpiece under the local load can be divided into two areas: active deformation area contacting the upper die and passive deformation area separating with the upper die. For this reason, the metal flow in orbital cold forging is much more complex as compared to the conventional forging process. In ABAQUS, metal flow velocity fields are represented by line segments with arrows, in which colours of arrows stand for flow velocities, and directions of arrows represent directions of metal flow. Figure.5 illustrates the distribution of flow velocity fields with time for both orbital cold forging and conventional forging methods. It is evident from the figure that metal flows uniformly in all direction in conventional method. But in orbital cold forging method, the metal flows according to the upper die oscillation. The cross section of the workpiece shows how the metal flows in the two cases (Figure.6). The upward arrows indicated in the Figure.6 show the direction of flash formation.

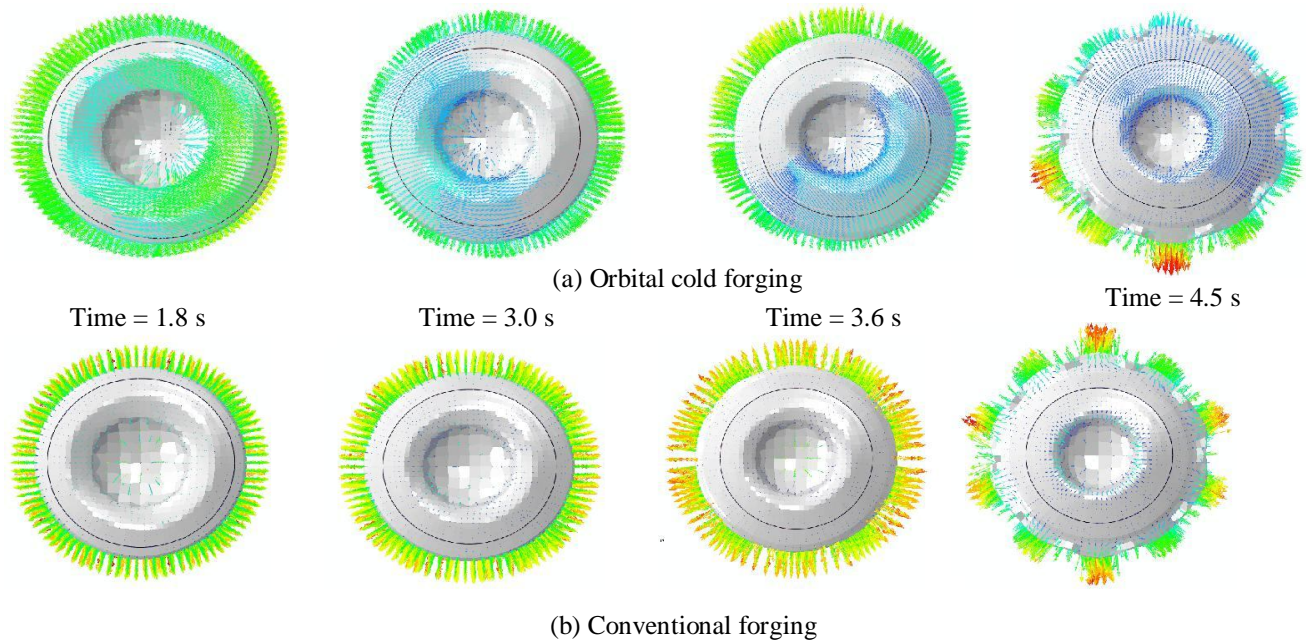


Figure.5 Top view showing Metal Flow Distribution of the deforming billet with time

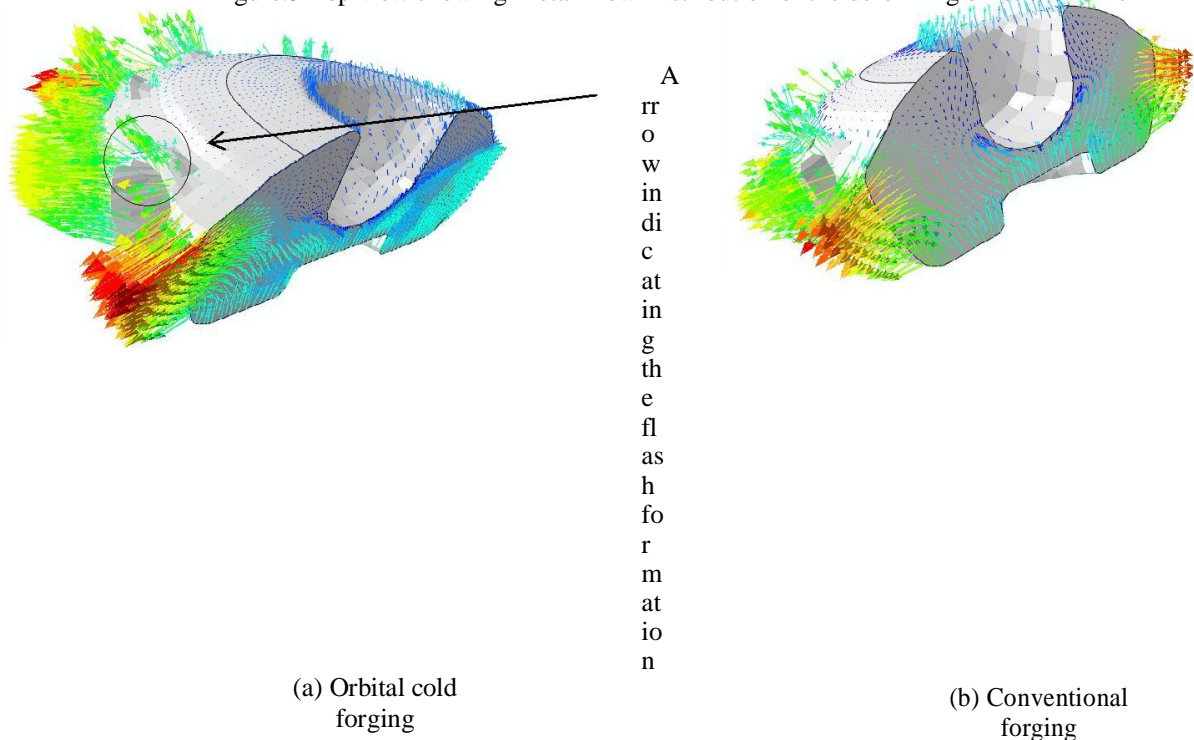


Figure.6 Sectional view showing the metal flow

Distribution of Stresses:

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

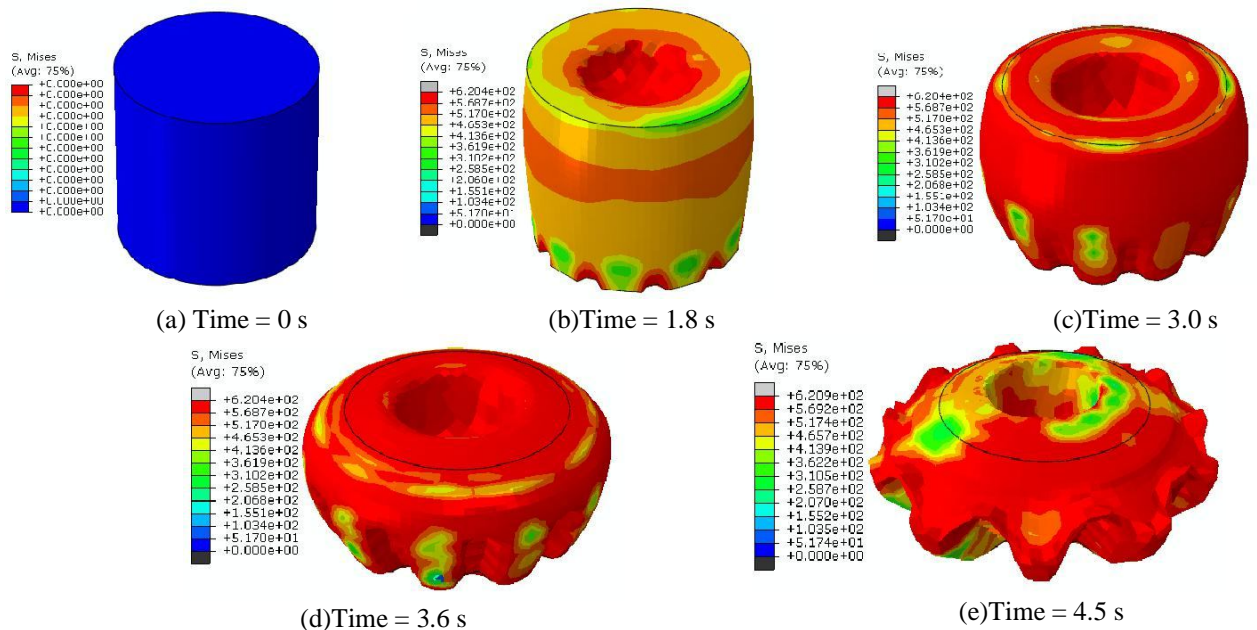


Figure.7. Equivalent Stress distribution of the deforming billet with time

V. CONCLUSION

In this work, a 3D FE model of orbital cold forging of a spur bevel gear is established utilising the ABAQUS software. The FE analysis provided detailed information on the forming mechanism, metal flow, effective strain and stress distributions. The following conclusions can be drawn from the main results:

- 1) The deformation mechanism of orbital cold forging of a spur bevel gear revealed that the workpiece in orbital cold forging can be divided into active deformation area and passive deformation area.
- 2) The effective strain (PEEQ) of orbital cold forged gear is highly concentrated at the central cavity region indicating that it has undergone the most strain hardening when compared to other regions;
- 3) The velocity distribution is uniform in all directions in conventional forging whereas in orbital forging, it is travelling with the oscillation of the upper die;
- 4) The metal first fills the large end of the gear and only during the final stages, the small end of the gear is formed.

In summary, the research results demonstrate the feasibility of orbital cold forging of complicated spur bevel gears with central cavities and provide a firm foundation for the practical utilisation of this technology. Furthermore, the modelling methods presented in this paper have the general significance to study other rotary forging processes.

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