Effect of rotational speed in rotary hammer forging process

Muhammad M Hamdy[a]

Misr University for Science and Technology, Department of Mechatronics Engineering, Sixth of October City, Egypt

Abstract. Rotary press forging (RPF) has been used in the last century, but it produces many defects in the forgings. The author has invented the rotary hammer forging (RHF) process to reduce such defects. RHF is a multi-axes compression process where the material is partially and incrementally deformed by the action of several repeated hammering blows, while the produced deformation region is swept through the whole area of the workpiece. The aim of the present work is to study the effects of rotational speed on the forgings produced by RPF and RHF to compare between the two processes. It has been found that as the rotational speed increases the mushroom effect is constant in RHF while it is greater and increases in RPF. As the rotational speed increases, the twist angle increases in both RHF and RPF, but it is bigger in RPF. These results demonstrate the benefits of using RHF instead of RPF.

1. Introduction

Conventional forging (CF) is extensively used as a manufacturing process in industry. The forming forces are applied either by continuous pressing in press forging (PF) or in the form of repetitive blows in hammer forging (HF). CF is a single axis compression (SAC) process since the upper and lower dies have the same axis. Rotary forging (RF) was first introduced in the 1910 [1], and hereafter many rotary forging machines have been developed as reviewed by Standring and Appleton [2–4].

RF machines have an inverted conical upper forming head of a wide angle with its apex in the center of workpiece top surface as shown in Fig. 1a. The axis of the cone is offset to the bottom die axis by a small angle θ, called the inclination angle. The die approaches the forming head by a continuous relative feed motion between the die and the forming conical head. The forming head produces an indent in the top surface of the work piece as shown in Fig. 1b. The indent is about 10% of the whole area of the top surface of the workpiece. As the feed motion continues, the machine's mechanism gives simultaneously the forming head a continuous rock-rolling motion, causing the indentation to sweep along the surface of the workpiece until the final shape is achieved.

The author [5] found it more definite to name RF precisely as rotary press forging (RPF). RPF has received increased attention since 1970's for its advantages and applications [2, 6]. Although, RPF has some disadvantages and defects given elsewhere [2, 7]. The author [5, 8] has patented a new manufacturing process, namely, rotary hammer forging (RHF) to avoid or reduce such defects.

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[a] Corresponding author: `drmuhamdy@yahoo.com`

In RHF an oscillatory relative motion (in the form of hammering blows) is applied by either the forming head (the indenter) or the die as shown in Fig. 1. Thus, RHF is considered as a multi-axes compression process, where the material is partially and incrementally deformed by the action of several repeated hammering blows, while the produced deformation region is swept through the whole area of the workpiece. It can be concluded that the only difference between RPF and RHF is that RPF is a continuous (permanent) contact incremental process, while RHF is a discrete (interrupted) contact incremental deformation one.

With hammer forging, the workpiece/die contact time under load is measured in milliseconds, thus minimizing the workpiece's surface heat loss. Also the rapid strain rate in hammering produces adiabatic heating, which compensates the heat loss. Another benefit of adiabatic heating is that it enhances recrystallization processes. These in-process heating characteristics of hammer forging reduce surface chilling and improve mechanical properties of the workpiece. Many works [9–11] have studied the effects of applying ultrasonic vibrations during metal forming processes. They found that the application of ultrasonic vibrations causes a reduction of the forming load and a beneficial effect on metal characteristics. They attributed this to a reduction in flow stress and friction force, and the generation of localized heat due to the friction at the interface between the workpiece and the forming tool. This localized heat causes thermal softening of the material. It is worth mentioning that RHF resembles to some extent ultrasonic-assisted forging, and may have the same effects.

In RF, it is important to consider that there is an angle of inclination θ between the forming head axis and the specimen's axis, and there is a relative sweeping motion of the indent, thus, there is an applied forming force "Q" which has the following components as shown in Fig. 1b:

Q_x = the radial force,
Q_y = the sweeping or circumferential force,
Q_z = the indenting or axial force.

Standring et al. [12] has divided the RF process into indentation phase and rotary or sweeping phase. In the indentation phase of RF, a deformation region is produced as shown in Fig. 2. The region comprises of penetration zone of depth j and protrusion one of height k. During the rotary phase, the deformation region is sweeping through the whole area of the workpiece, and the protrusion builds up as a wave at the front edge of the upper die/workpiece contact boundary (the leading edge). As Q increases, the wave becomes bigger, thus, j & k increase, resulting in an increase in Q_y.

The need to know the characteristics of RHF led the author to study the effects of the specimen's geometry and the inclination angle [5]. It has been found that the specimen's geometry and the inclination angle affect the extruded length, the mushroom effect, the eccentricity, the twist angle, the buckling and the forming time. The defects of buckling, mushroom, eccentricity and twist are less severe in RHF than RPF.

The aim of the present work is to know more about the characteristics of the RHF process by studying the effects of the rotational speed. Thus a comparison can be done between RHF and RPF.

2. Experimental work

An experimental set-up is given elsewhere [5]. The material of the specimen is a commercially pure lead due to its high ductility and because forging it at room temperature is considered as a hot forming process. The independent variables in the present work are the rotational speed (N), i.e. the speed of rotation of the die about its axis. In this set-up it is the lathe chuck rotational speed. Four speeds have been chosen, i.e. 25, 80, 260 and 840 rpm. The other independent parameters are kept constant and chosen as follows:

Specimen's diameter D = 15 mm.
The inclination angle (θ) = the forming conical head angle (α) = 4°.
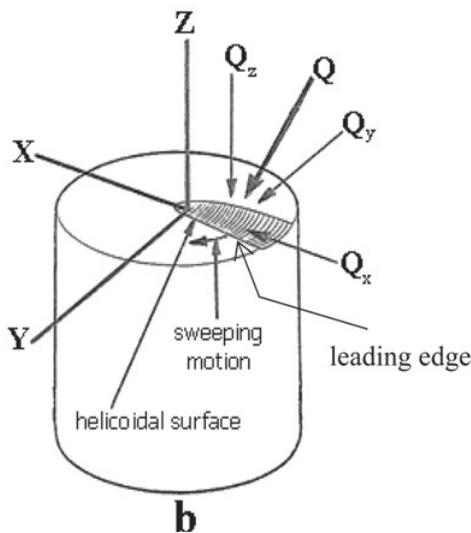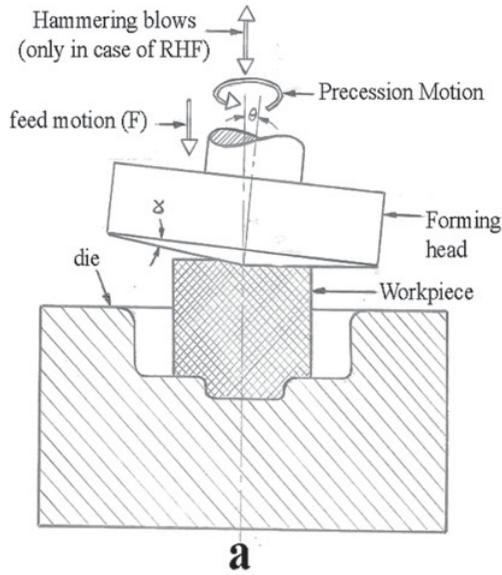The pneumatic pressure (P) = 620 KPa.

Figure 1. Rotary press and hammer forging processes. a) Main elements and movements. b) The forming force and its components.

The specimen's geometry (H/D) = 1.
The feed (F) in case of RPF = the lathe carriage feed = 0.3 mm/rev.
Forming degree = H-h / H = 0.5.
The dependent variables are described elsewhere [5] and include the extruded length (L_e), the mushroom effect (ψ), the twist angle (ϕ), the eccentricity (e) and the forging time (T).

3. Results and discussions

Study of the defects and economics is a direct mean of comparing RPF with RHF to find the advantages and disadvantages of each.
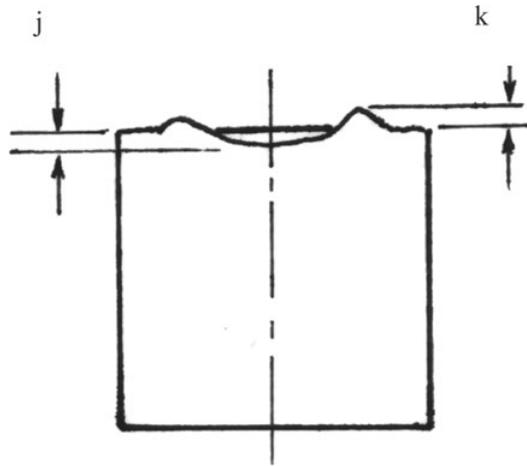
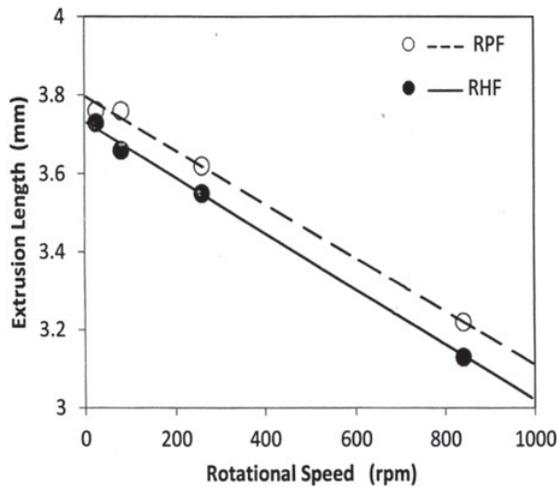**Figure 2.** Elevation view of indented workpiece.

Figure 3. Effect of rotational speed on the extruded length.

3.1 Effect of rotational speed on the extruded length

The results show that as the rotational speed increases, the extruded length linearly decreases as shown in Fig. 3. This is true for both RHF and RPF, but there is no significant difference in the extruded length in both RHF and RPF. This behavior in case of RHF is attributed to the number of hammering blows/revolution. As the speed increases, the number of hammering blows/revolution decreases, hence the extruded length decreases. Also as the speed decreases, the successive indents caused by hammering become closer, resulting in an increase in the extruded length. In case of RPF, as the speed decreases, the forging time increases, allowing enough time for the metal to flow into the die hole.
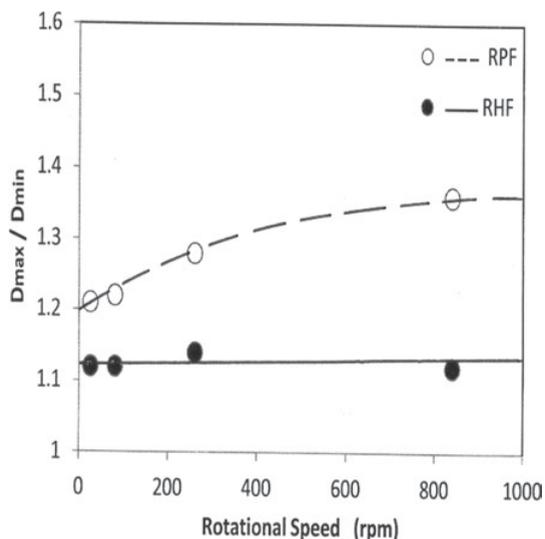
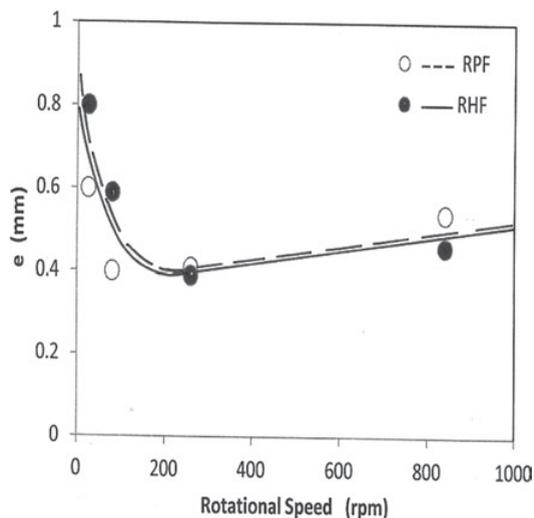**Figure 4.** Effect of rotational speed on the mushroom effect.

Figure 5. Effect of rotational speed on the eccentricity.

3.2 Effect of rotational speed on the mushroom effect ψ

The mushroom effect ψ (D_{max}/D_{min}) occurs when the shear strains inside the specimen are not uniform. The shear strains on the top and bottom surfaces of the specimen are high, while they are smaller at the mid-height of the specimen. It can be seen in Fig. 4 that the rotational speed does not affect the mushroom effect in the case of RHF. This is because the rotational speed has no much influence on the axial force Q_z as found in previous work [13]. In RPF, the mushroom effect increases with the increase in the rotational speed. In RPF, the feed/rev. is constant, producing constant ψ/revolution. Thus, increasing the rotational speed causes an increase in ψ. Also the mushroom effect is bigger in RPF than in RHF. The explanation to this behavior is that the forming force is large enough in RHF to produce uniform shear strain throughout the specimen as stated in previous works [3,12]. Liu et al. [14] have used a 3D rigid-plastic finite element method to simulate RPF and to reveal the deformation mechanism of the mushroom shape workpiece. They concluded that the mushroom shape is due to nonuniform deforming degrees along the tangential direction at various heights of the workpiece.

3.3 Effect of rotational speed on the eccentricity

Increasing the eccentricity causes problem for die filling and final workpiece quality. Figure 5 shows that there is no significant difference in eccentricity between RPF and RHF. The results show that the eccentricity decreases sharply as the speed increases in both RHF and RPF in the range below 260 rpm. Above 260 rpm, the eccentricity in both RHF and RPF increases slightly as the speed increases. The eccentricity defect is attributed to the inhomogeneous metal flow during forging and parelling in small portion of the specimen. Standering et al. [12] stated that when the indentation is insufficient for the whole of the upper surface of the workpiece to be brought into contact with the indenter, radial flow occurs preferentially to one side, causing eccentricity in the workpiece. Below speed of 260 rpm, as the
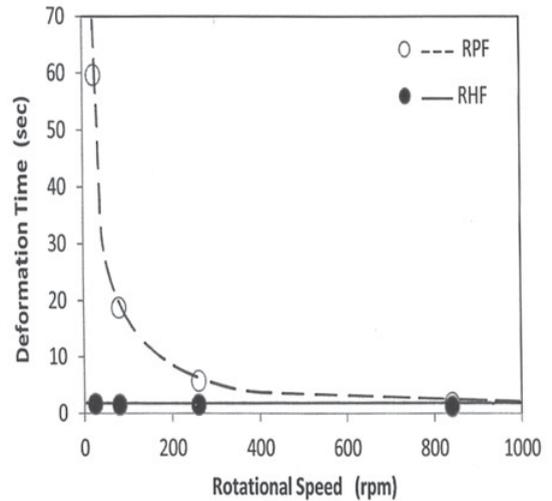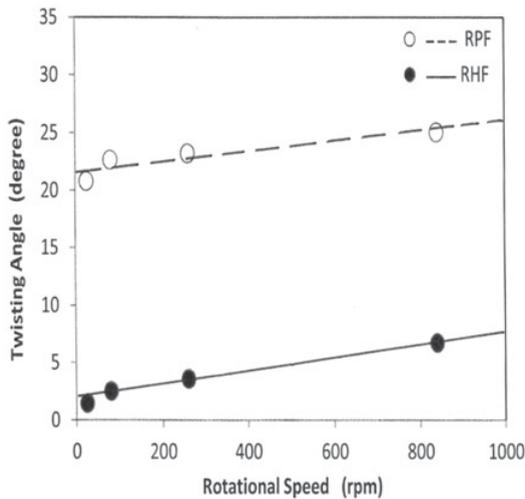
Figure 6. Effect of rotational speed on the twist angle.

Figure 7. Effect of rotational speed on the forming time.

speed decreases, there is more time to allow the preferential radial flow to take place, resulting in larger eccentricity. Above 260 rpm, there is no much allowable time for the radial flow to occur.

3.4 Effect of rotational speed on the twist angle

Figure 6 shows that as the speed increases, the twist angle slightly and linearly increases in both RPF and RHF. This is attributed to large Q_y at high speeds. Also the twisting in RPF is about 5 to 10 folds of that in RHF. This is because Q_y is partially effective in RHF due to the jump of the forming head over the leading edge wave during the noncontact phase of the stroke, causing Q_y to be zero in the noncontact phase. In case of RPF, Q_y is continuously acting causing high values of twisting. Thus, the contact time between the top surface of the specimen and the forming head is less in the case of RHF.

Standring [4] mentioned that twisting being predominantly determined by the "bite size". The bite size is the instantaneous feed rate, S, which depends on the speed of rotation. Han & Hua [15] found that the contact pressure only occurs on the contact area while it does not occur in the noncontact area. During RF a material builds up as a wave at the leading edge of the contact area between the upper die & the workpiece. Meanwhile, the hammering action during RHF causes jumping over this wave either partially or completely, resulting in interruption in the contact area. This depends on many parameters such as hammering frequency, rotational speed and wave shape. Thus further studies have to be carried out to include such parameters which help in understanding the RHF process.

3.5 Effect of rotational speed on forming time

The results show that the speed does not affect the forming time in RHF as shown in Fig. 7. In RPF, as the speed increases, the forming time is sharply reduced up to 300 rpm. Also the forming time is much greater in RPF than in RHF at speeds below 300 rpm, but at higher speeds they are nearly equal. This is because in RPF the forming time depends on the automatic feed (i.e. the lathe feed and the rotational speed). On the other hand, in RHF the forming time depends on the blow energy (i.e. pneumatic pressure used to operate the hammering pistol).

4. Conclusions

It could be concluded that:

1- The rotational speed affects the extruded length, the mushroom effect, the eccentricity, the twist angle and the forming time.
2- Defects of mushrooming, eccentricity and twisting are less severe in RHF than RPF.
3- The extruded length and the forming time are less in RHF than in RPF.
4- RHF is more beneficial and superior than RPF.
5- Further studies will be required to predict and minimize defects, study the characteristics & mechanisms of RHF, and exploring the effects of different parameters on the process.

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