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Influences of electric-hydraulic chattering on backward extrusion process of 6061 aluminum alloy

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Abstract: The possibility of the electric-hydraulic chattering technology and its application in the cold extrusion were presented. The conventional and electric-hydraulic chattering assisted backward extrusion processes were performed on 6061 aluminum alloy billets at room temperature. The experimental results showed that 5.65% reduction in the extrusion load was attained if the die and ejector were vibrated at a frequency of 100 Hz and amplitude of 0.013 mm in the longitudinal direction. The friction coefficient at the billet and tool system interface determined from the finite element analysis (FEA) decreased from 0.2 without chattering to 0.1 with application of electric-hydraulic chattering. The higher values of instantaneous velocity and direction change of material flow were achieved during the chattering assisted backward extrusion process. The strain distribution of the chattering assisted backward extrusion billet revealed lower maximum strain and smoother strain distribution in comparison with that produced by the conventional extrusion method.

Key words: 6061aluminum alloy; conventional backward extrusion; electric-hydraulic chattering assisted backward extrusion; finite element analysis; material flow; strain distribution

1 Introduction

Vibration assisted metal forming is one of the most recent and beneficial process improvements in which vibration is applied on the billet or the die to improve forming process because of the lower forming load, better surface qualities and higher precision of the parts [1,2]. However, the influence that the extent to which the vibration may be advantageous depends on the type of process, the vibration exciting method, the mode of vibration, and so on [3].

Various types of deformation test have been carried out to investigate the influences of vibration. By using a piezoelectric transducer (PZT), BUNGET and NGAILE [4] superimposed ultrasonic vibration on micro-extrusion setup, and a significant reduction on the extrusion force and an obvious improvement in the surface of the deformed parts were observed. SIEGERT and MÖCK [5] reported similar results during vibration assisted wire drawing process. BAI and YANG [6] superimposed vibration on metal foil surface finishing process and found improvement in the surface roughness. SEO et al [7] developed an audio frequency vibration (AFV) micro-forming system and found experimentally that the formability could be increased. By means of magnetostrictive transducer, SUSAN et al [8,9] applied vibration on ball-bearing steel wire drawing and found the decrease of the friction coefficient between the workpiece and die interface. YAO et al [10] observed the stress decreasing during vibration assisted micro/meso upsetting process. JIMMA et al [11] observed experimentally that higher vibration frequency can lead to higher limiting drawing ratio, greater accuracy and deeper cups by using electrostrictive transducer. It should be noted that the exciting vibration technologies described above were applied only in the metal forming process requiring lower forming load, such as micro/meso forming and wire drawing forming process.

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Additionally, other exciting vibration technologies developed for the metal forming processes with higher forming load are also reported. OSAKADA et al [12] applied vibration on the container using a motor during enclosed-die forging and observed significant decrease in the forming load. CAI and JIANG [13] experimentally found that lower forming force, shorter forming time, and better forming quality can be attained by the hydraulic exciting vibration rotary forging. BOCHNIAK et al [14] superimposed rotary vibration on the punch or the anvil during compression and forging process and found that the lower forging force was required in comparison with the conventional method. MILENIN et al [15] investigated the process of flat rolling with additional vibration of rolls along their axes by using a numerical model. However, lower frequencies and greater amplitudes of the vibration were produced by these exiting vibration technologies. It may restrict the applications of these technologies in the metal precision forming processes. An electric-hydraulic chattering technology was presented to solve these problems [16].

Numerical simulations are often employed for understanding the metal forming process because of the difficulty of performing measurements inside a die. Therefore, the finite element method (FEM) is often used to predict the required forming load, effective strain, stress distribution and temperature gradient at any instant of time during a forming process [17].

The main aim of the present work is to study the differences between the conventional backward extrusion (CBE) and electric-hydraulic chattering assisted backward extrusion (EHCABE) processes in load requirement, material flow and strain distribution. Experiments of both processes at room temperature were performed. Additionally, a commercial finite element analysis software Deform-3D was employed to evaluate the friction coefficient between the billets and die interface, and predict the deformation behavior of the material in the CBE and EHCABE processes such as velocity of material flow and strain distributions.

2 Experimental

To carry out EHCABE process, a special experimental setup with electric-hydraulic chattering was designed and prepared (see Fig. 1). The electric-hydraulic chattering platform was composed of a circular plate used for fixing the die, an upper plate with grooves and a lower plate with oil duct for passing hydraulic oil. Due to the grooves, the chattering of upper plate could be excited by the hydraulic oil controlled by a high frequency exciting vibration valve. The frequency and amplitude of chattering can be adjusted by using a specially designed control test device with a frequency

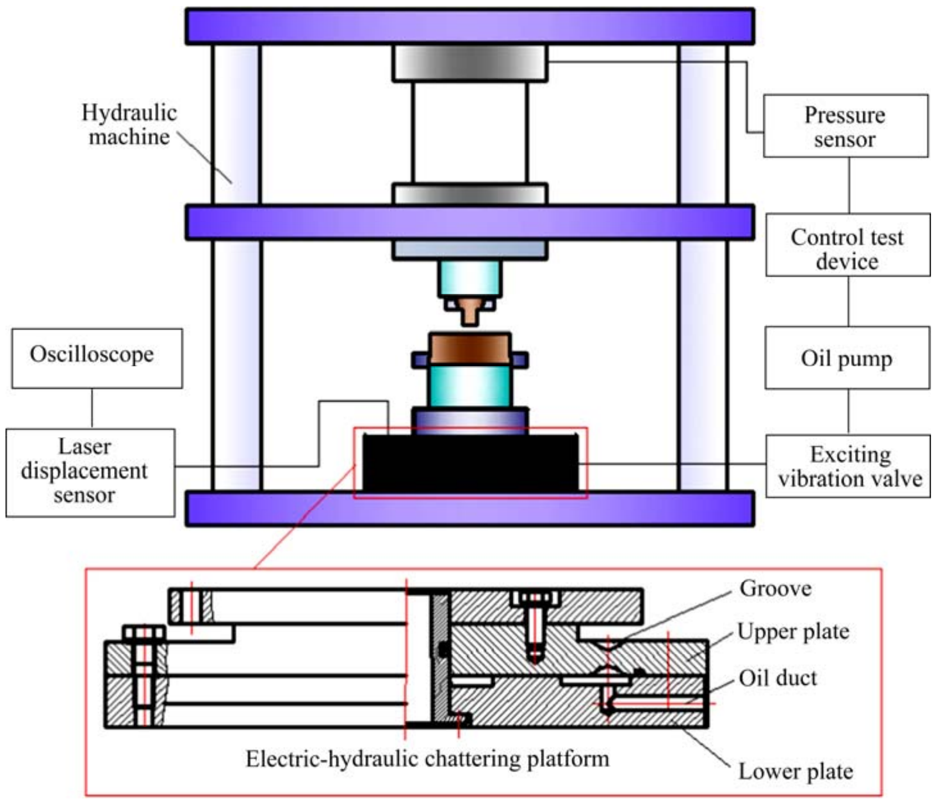

Fig. 1 Configuration of electric-hydraulic chattering assisted backward extrusion (EHCABE) experimental setup

generator and by changing the output fluid pressure of the oil pump respectively. A pressure sensor was used to detect the extrusion load, and a laser displacement sensor was utilized to measure the chattering amplitude and frequency. Furthermore, with a control test device, the value of the hydraulic fluid pressure can be measured and recorded.

In this research, the backward extrusion was performed at the room temperature of 20 °C. Figure 2 shows the schematic illustration of die assembly and the dimensions of the forming system. Aluminum alloy (6061) specimens were used in the backward extrusion tests. The chemical composition of 6061 aluminum alloy is shown in Table 1. The cylindrical specimens with 40 mm in diameter and 40 mm in height were machined from cylindrical bar. All the specimen surfaces were polished using a 600 grits diamond polishing paper to provide a surface roughness of 0.8 μm. The tool-billet interface was lubricated with molybdenum disulfide. The backward extrusion test was carried out at a constant extrusion speed of 10 mm/s without or with electric-hydraulic chattering, respectively. The extrusion tests were completed when the extrusion stroke reached 20 mm. The billet in the EHCABE process was subjected to a chattering frequency of 100 Hz and hydraulic fluid pressure of 5 MPa. A mean chattering amplitude of 0.013 mm was attained during the EHCABE process by using a laser displacement sensor.

3 Finite element analysis

The finite element simulation was conducted in order to analyze the plastic deformation behavior of the billet in the CBE and EHCABE processes. The simulation was done in a commercial CAE system, Deform-3D software. Due to symmetry, a 1/10 modeling was performed. The die, punch and ejector were modeled as rigid. The billet was defined as a plastic body and modeled with the same dimensions as the experimental workpiece.

A compression test was carried out on the 6061 aluminum alloy sample at a constant compression speed of 0.1 mm/s up to a strain of 0.8 to determine the deformation behavior of the materials used in the CBE and EHCABE process. The obtained data were then directly used in the finite element analysis. Tetrahedral mesh method was used to mesh the billet. A friction model adopted in FE simulation was Coulomb's law. Friction coefficient (μ) was determined by comparing the experimental and simulation extrusion load, and all of the contact surfaces were assumed equal in the back extrusion process. The extrusion velocity was 10 mm/s (v_e) and extrusion stroke was 20 mm. The die and ejector were chattered sinusoidally, a and f were the amplitude and frequency of chattering, the maximum chattering speed would be equal to $v=2\pi fa$. Figure 3 shows the 1/10 modeling for simulation of 6061 aluminum alloy CBE and EHCABE processes. The chattering amplitude of 0.013 mm attained from experiment and chattering frequency of 100 Hz were used in the simulation for chattering assisted backward extrusion processes. The sinusoidal chattering velocity was discretized with sampling period of 0.0005 s and used to control the movements of the die and ejector.

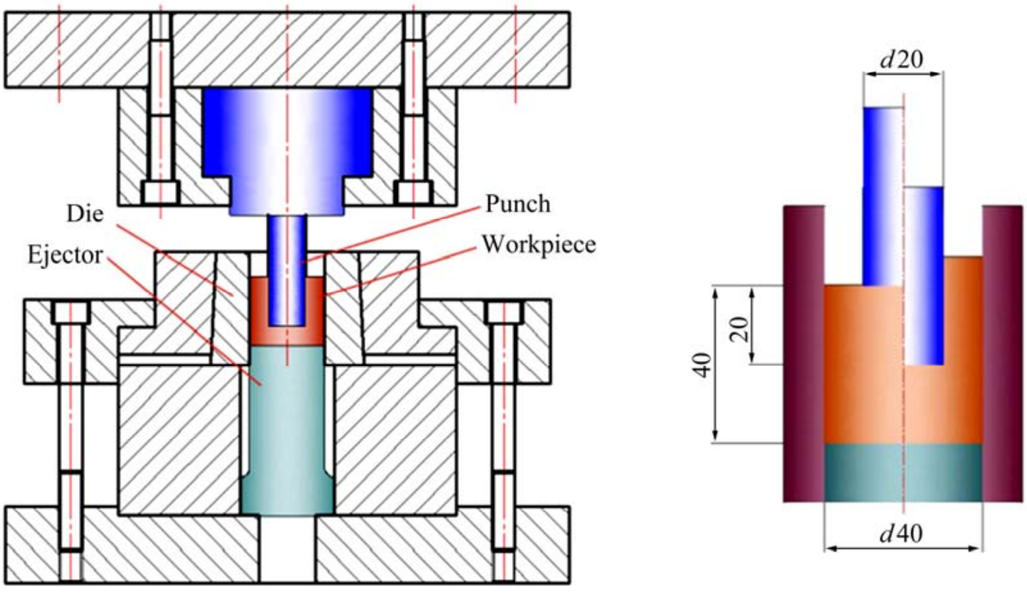

Fig. 2 Schematic illustration of die assembly and related dimensions of forming system (unit: mm)

Table 1 Chemical composition of 6061 aluminum alloy (mass fraction, %)

Si	Mg	Fe	Cu	Mn	Cr	Zn	Ti	Al
0.47	0.85	0.20	0.21	<0.05	0.13	0.25	0.15	Bal.

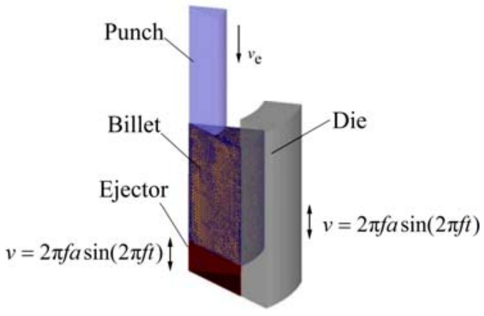

Fig. 3 1/10 modeling for simulation of conventional and chattering assisted extrusion backward processes

4 Results and discussion

4.1 Extrusion load requirement comparison

Figure 4 shows the experimental extrusion load and time graph for the CBE and EHCABE processes. Three distinguished stages can be observed. At the first stage, the billet expands and fills the cavity as the punch starts compressing the billet through the die. The extrusion load increases rapidly in this stage, attains a recognizable peak value (point *A*), and then increases gradually to a transition stage (from point *A* to point *B*). At the steady state stage, the extrusion load fluctuates generally (from point *B* to point *C*). It was obvious that the effect of chattering on the extrusion load was not significant at the first stage and transition stage. The extrusion load at the steady state stage during the EHCABE was less than the CBE process (with a maximum reduction of 5.65%).

Contact and separation mechanism [18] and frictional force vector cyclic change mechanism were proposed to explain the load reduction phenomenon in the vibration assisted forming process. According to the contact and separation mechanism, it was believed that the extrusion load and material flow stress would be decreased by applying vibrations if the extrusion velocity was below the critical speed ($v=2\pi fa$). It was obvious that this mechanism was unsuitable for explanation of the load reduction phenomenon in the EHCABE process due to the lower chattering velocity than the extrusion one.

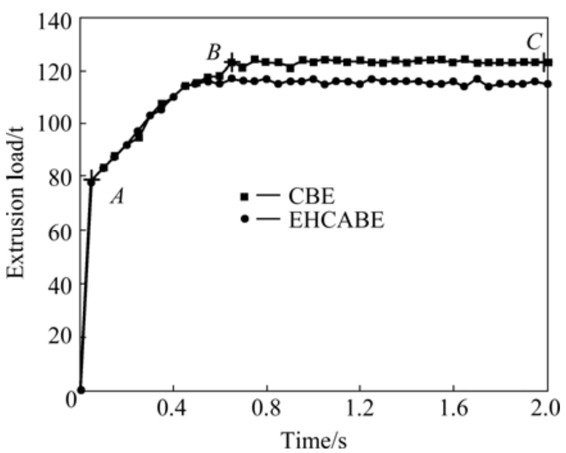

Fig. 4 Variations of extrusion load with time for CBE and EHCABE processes by experiments

The schematic diagrams of friction at the billet−die interface during the CBE and EHCABE processes are shown in the Fig. 5. The frictional force τ_f in the longitudinal direction resists invariably the billet material to flow into the cavity in both CBE and EHCABE processes. Therefore, the frictional force vector cyclic change mechanism may not be applied to explaining the load reduction phenomenon. In the case of the EHCABE process, when the die and ejector are moved in the opposite direction with the extrusion velocity v_e, the cup wall material is pushed upward. When the chattering velocity v_c is in the same direction as the extrusion velocity v_e, the material flow direction of the cup wall is reversed. The material flow velocity v_w of the cup wall is given by

$$v_w=\frac{v_e d^2+v_c D^2}{D^2-d^2} \qquad (1)$$

where d and D are the diameters of the ejector and the punch, respectively. It is obvious that the material flow velocity is controlled by the chattering one. And, this results in the higher relative velocity at the billet and die interface at some instant of time. Therefore, the reduction of the extrusion load may be partly a consequence of the lubrication conditions change. Because of the high instantaneous relative velocity at the billet and die interface, the adhesive bond formation is reduced. Moreover, the lubricant trapped in the pockets formed by the surface roughness is kept in the deformation zone and better distributed at the interface due to the expansion of the surface during the backward extrusion process. These lead to better lubrication conditions and hence result in reduction of the friction coefficient at the tool-billet interface. This matter is in good agreement with the results obtained by GUTOWSKI and LEUS [19]. It has been shown that the chattering with lower frequency or lower amplitude superimposed on the forming process can also lead to the reduction of the forming load.

4.2 Finite element analysis results

4.2.1 FEA verification

The friction between the die and billet plays a vital role in metal extrusion process. The extrusion load and

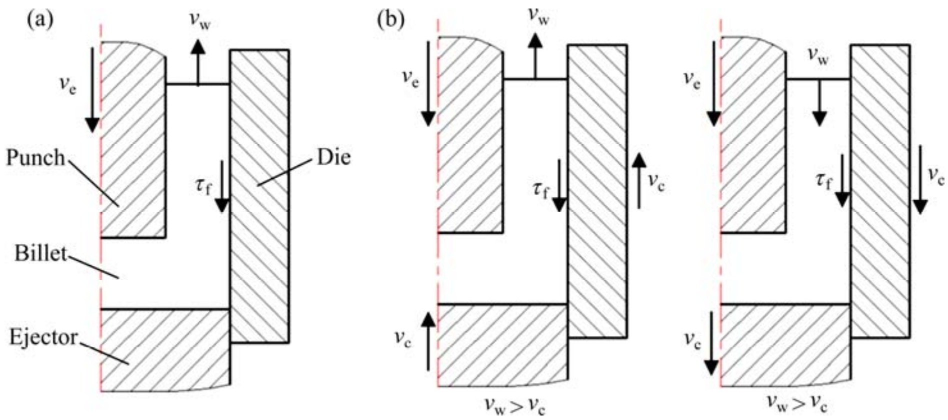

Fig. 5 Schematic diagrams of friction between billet−die interface during CBE process (a) and EHCABE process (b)

the mode of deformation were affected by the friction condition at the die and billet interface. SIEGERT and MÖCK [5] and GUTOWSKI and LEUS [19] have found that vibration can reduce friction. Direct measurement of the friction coefficient in extrusion process is difficult. Therefore, FE simulation was used to estimate the friction coefficients at the die and billet interfaces. The friction coefficient of 0.2 was obtained such that simulated extrusion load without chattering matched the experimentally measured extrusion load, which is shown in Fig. 6. Figure 7 shows extrusion load and time graphs for the EHCABE process in experiments and simulations. The results illustrate that the friction coefficient at the punch and sample and die interface reduced from 0.2 to 0.1 by applying chattering. It may also be concluded that a decrease in friction can be achieved by superimposed chattering on the die and ejector.

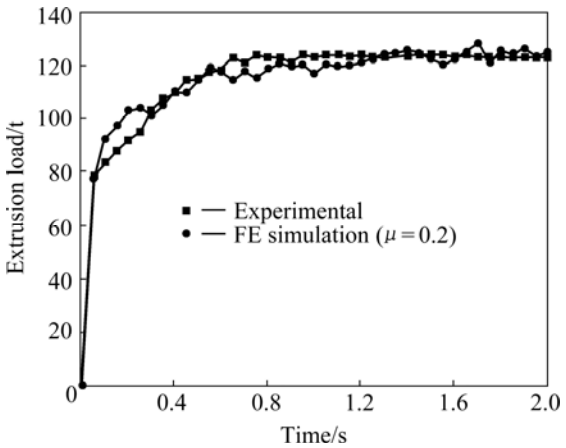

Fig. 6 Extrusion load and time graphs for experimental and FE simulation for CBE process

4.2.2 Material flow

Figure 8 shows the comparison of the typical velocity distributions of material flow at the first stage and steady state stage of the CBE and EHCABE processes. During the CBE process, four zones such as

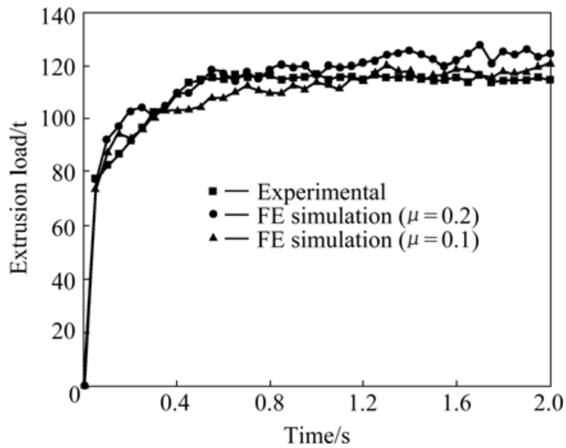

Fig. 7 Extrusion load and time graphs for experimental and FE simulation for EHCABE processes

formation dead zone (zone *A*), severe deformation zone (zone *B*), deformed-to-be zone (zone *C*) and rigid translation zone (zone *D*) were observed obviously. The material of zone *A* flows downward with an approximate extrusion velocity of 10 mm/s, and push zone *B* and zone *C* material flowing to zone *D* in a character-of-U form. The material in zone *D* flows upward with a constant approximate speed of 3.3 mm/s. The maximum velocity of 10 mm/s appears in zone *A* during the CBE process. In the case of the EHCABE process, the maximum velocity is observed in zone *D* and sometimes is more than that attained by the CBE method. An instant boundary of the velocity appears because the material of zone *A* is moved downward by the punch with the velocity of 10 mm/s, and the zone *C* is moved upward due to the chattering of the ejector. Consequently, the material flow velocity of zone *C* and zone *D* is changed due to the chattering superimposed on the ejector and die.

Figure 9 shows the comparison of material flow speed in the zone *D* between the CBE and EHCABE processes. It is obvious that the material flow speed attained by the chattering assisted extrusion method is higher than that achieved by the conventional method.

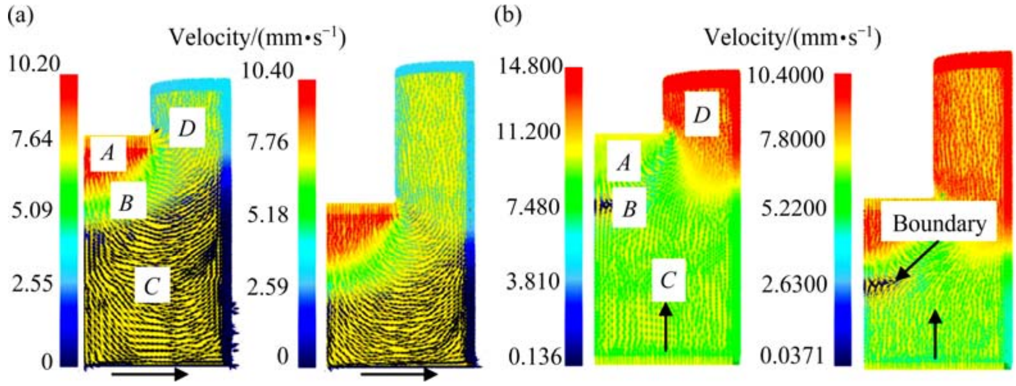

Fig. 8 Material flow velocity distributions at first stage and steady state stage for CBE (a) and EHCABE (b) pocesses

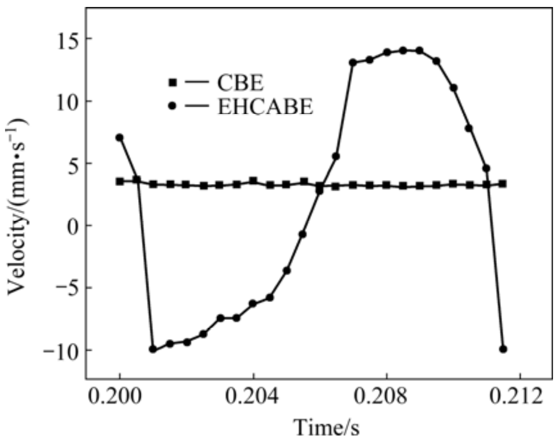

Fig. 9 Metarial flow speed in zone *D* for CBE and EHCABE pocesses

The chattering superimposed on the die and ejector changes the direction of the material flow and increases the material flow velocity of the zone *C* and zone *D*, hence, it reduces the friction coefficient between the billet and tool interface due to the reduction of adhesive bond formation because of high instantaneous relative velocities under electric-hydraulic chattering.

4.2.3 Strain distribution

Figure 10 depicts the evolutions of the strain distribution in both the CBE and EHCABE processes when the maximum strain of 3 is set to compare easily. It can be seen that the maximum strain was experienced on the surface which was directly in contact with the upper punch walls. The strain distribution of the rigid translation zone (zone *D*) attained by the conventional method was nearly the same as that achieved by the chattering assisted extrusion method. However, a higher strain area was observed in the formation dead zone(zone *A*) during the chattering assisted extrusion process. Moreover, the severe deformation zone (zone *B*) was expanded into zone *A* due to the chattering of the ejector. The range of the higher strain area was spread slowly and connected to zone *B* along with the increase of the stroke. So, a larger uniform strain area in the deformed workpiece was achieved at the location close to the punch by using chattering on the die and ejector. This phenomenon was also observed in the torsion extrusion process and upsetting process with ultrasonic vibration [20,21]. In order to quantitatively survey the strain change, Fig. 11 shows the differences in the maximum strain with time between the CBE and EHCABE processes. In the case of the CBE process, the maximum strain value of 105 was obtained at the transition stage. And, this value for the EHCABE process was equal to 22.8. The values of maximum strain during the CBE are higher than that from the EHCABE process. It is indicated that some local spots with high strain are torn easily during the CBE process. This matter may be attributed to the decrease and the uniform distribution of the friction force between the billet and tooling system due to the chattering [22].

5 Conclusions

1) Extrusion loads required for performing the conventional and electric-hydraulic chattering assisted backward extrusion processes were compared and the results showed that an extrusion load reduction of 5.65% was detected in the electric-hydraulic chattering assisted extrusion process.

2) The finite element analysis was carried out using DEFORM-3D. The friction coefficient values between the billet and tooling system interfaces were reduced from 0.2 to 0.1 and confirmed the fact for the reduction of friction coefficient by the chattering.

3) The material flow comparison of the conventional and chattering assisted backward extrusion workpieces showed higher material flow velocity and change of material flow direction in the chattering assisted extrusion workpiece, which can be considered as one of the most probable causes for the reduction of friction force.

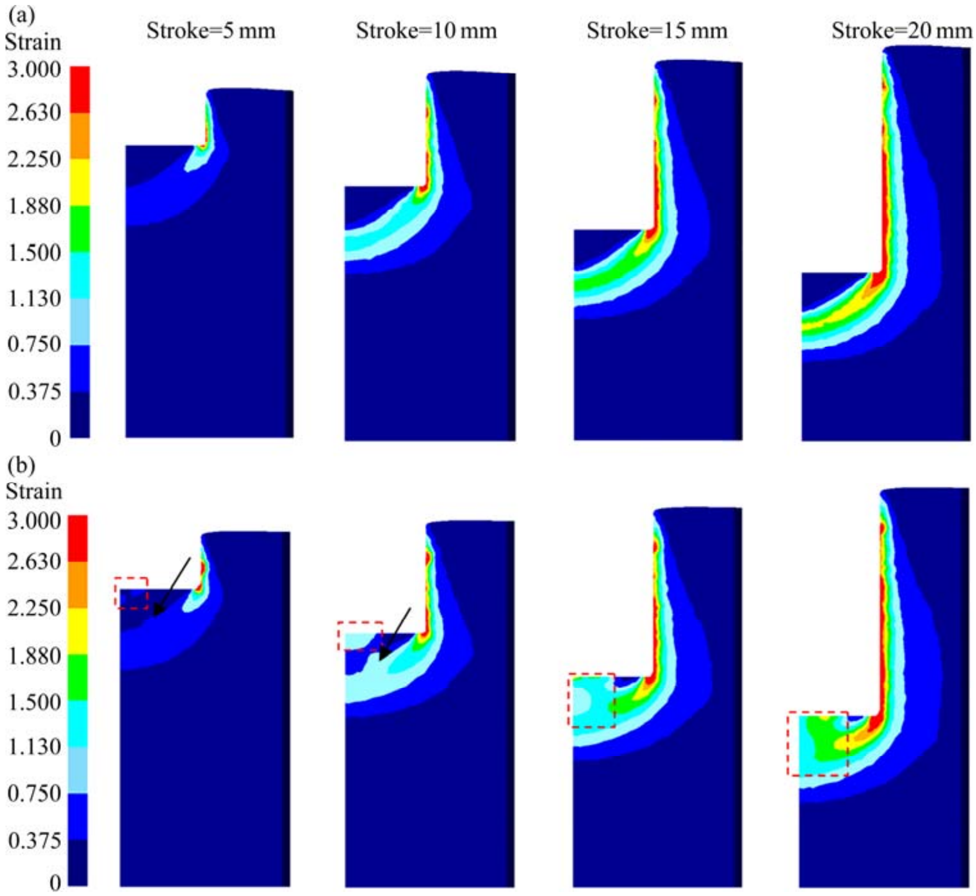

Fig. 10 Evolutions of strain distribution for CBE (a) and EHCABE (b) processes obtained by simulation

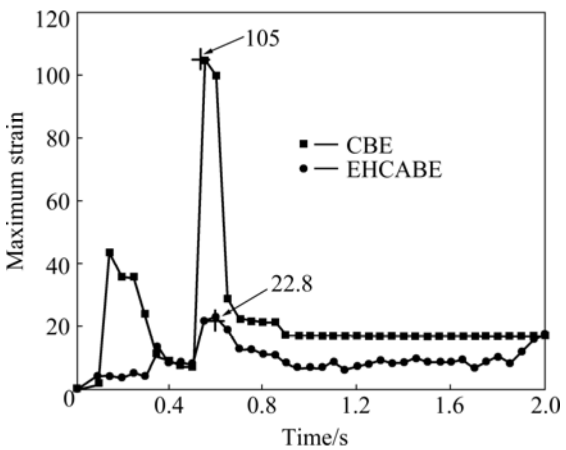

Fig. 11 Maximum strain comparison for CBE and EHCABE processes obtained by simulation

4) Lower maximum strain and more uniform strain area were achieved by applying chattering on the die and ejector.

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电液颤振对 6061 铝合金反挤压成形过程的影响

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摘　要：研究电液颤振技术在冷挤压成形中应用的可行性。在室温下对 6061 铝合金坯料进行传统反挤压和电液颤振辅助反挤压。实验结果表明，给凹模施加频率为 100 Hz、幅值为 0.013 mm 的颤振，可使最大挤压力下降 5.65%。采用有限元软件 Deform 模拟反挤压过程，结果表明，在反挤压过程中，颤振可使坯料与模具之间的摩擦因数从 0.2 下降为 0.1，改变材料流动的方向及提高材料流动的瞬时速度，同时使坯料承受较小的最大塑性应变，其应变分布较传统反挤压更均匀。

关键词：6061 铝合金；传统反挤压；电液颤振辅助反挤压；有限元分析；材料流动；应变分布

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