Two-Step Die Motion for Die Quenching of AA2024 Aluminum Alloy Billet on Servo Press

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The authors reported that die quenching of a cylindrical AA2024 aluminum alloy billet less than 9 mm in height was feasible on a servo press. However, it was also found that the reduction in height was limited less than 5% due to partial melting. In order to enhance the deformability in single operation, the two-step die motion is proposed. A cylindrical billet was heated to 823 K and transferred to the press. Then, the billet was uniaxially compressed with a reduction in height (Δh/h0) of 5%, and further held between the dies for cooling. After sandwiching for 8 s, the billet with a height of h1 = 7.6 mm was further compressed with a reduction in height (Δh/h1) of 2% or 5% at lower temperature. The die quenching process with the two-step die motion leads to increase the total reduction in height to 10%. It is confirmed that super-saturated solid solution successfully formed at the 1st step is maintained in the 2nd step. It is found that the peak hardness of the two-step processed billet is higher than that of the one-step processed billet, and that the precipitation kinetics in artificial aging is accelerated by the two-step motion.


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1. Introduction

In automotive industries, there is a rapid growth in demand of lightweight components such as aluminum alloy part to improve fuel consumption. At present, the required strength is achieved by precipitation hardening of age-hardenable aluminum alloys after forming, solution heat treatment (SHT) and quenching. Though the ductility recover and uniform microstructure develops in the solution heat treatment, it often results in thermal distortion of formed components. In order to suppress thermal distortion of formed components and to improve its strength and to form desirable shaped microstructure, die quenching processes were studied in recent years.1–4 In these processes, first the aluminum alloy is heated to dissolve the precipitates within the primary α-Al matrix. Then, forming and quenching are simultaneously performed. In other words, the material is formed as well as cooled by the dies at once. Then, the processed aluminum alloy is artificially aged for precipitation hardening. Thus, this technique is able to manufacture stronger products with complicated shapes through less number of processes with less thermal distortion compared with the conventional T6 treatment. Most of past papers were related to sheet metals due to easier rapid cooling because automotive bodies were considered for applications.1–3) In previous study, the authors investigated the feasibility on die quenching of a cylindrical AA2024 aluminum alloy billet after the two different SHT temperatures using highly conductive WC–20 mass%Co dies.5) Die quenching was feasible after SHT at 823 K under limited conditions, while not feasible after SHT at 773 K due to precipitation caused during slower cooling. The authors also reported that the billet height should be less than 9 mm for die quenching.6) It was also found, however, the reduction in height (Δh/h0) was very limited less than 5% (A billet height of h0 = 8 mm) due to crack formation on side surface.

Wang et al. also reported the lower ductility of an AA2024-T3 aluminum alloy at die quenching process.2) It was supposed that cracks were formed by partial melting at grain-boundary triple junctions.5,6) It could be a serious drawback for industrial applications because thick or complicated parts are not die-quenchable.

Thus, the objective of this study is that in order to apply higher reduction in single operation, the two-step die motion is proposed. After the one-step die quenching, further compression is applied without opening dies. Therefore, the second compression can be regarded as pre-straining process. The effectiveness of the two-step motion is investigated. In addition, the aging behavior of the die-quenched billet is made clear.

2. Two-Step Die Motion

In general, the age-hardenable aluminum alloy billet is solution heat-treated followed by the water quenching as shown in Fig. 1(a). On the other hand, in the one-step process for die quenching of age-hardenable aluminum alloy billet, fully solutionized billet is plastically deformed before precipitation start, simultaneously rapidly cooled down to below the nose of the CCT diagram by sandwiching between the conductive dies to form super-saturated solid solution (SSSS) as shown in Fig. 1(b). In the two-step process proposed by the authors, after the first compression further cold compression is applied. In detail, after the first compression as Fig. 1(b), then straightly the die-quenched billet is further cold worked in single operation with die motion control as shown in Fig. 1(c).

The expected advantages of the proposing two-step process are classified into two main points. First, it will enhance the deformability in total during the die quenching process. It widens shaping and forming applications. Based on the previous studies,5,6) if a billet was compressed over 6% in height, cracks were initiated at voids caused by partial melting at grain-boundary triple junctions and that were
subjected to tensile stress. So the deformability may be improved if further compression is applied sufficiently below the solidus temperature.

Second, it will accelerate the precipitation kinetics and increase the strength during isothermal artificial aging. Age-hardening is essential because it is the final stage in the development of the properties of heat-treatable alloys such as AA2xxx, AA6xxx and AA7xxx, which is the controlled by decomposition of the SSSS to form finely dispersed precipitates. It is well known that deformation has a substantial effect on the precipitation behavior.\(^7\)\(^8\) Gomiero et al. reported that the role of dislocations generally results in acceleration of the precipitation kinetics and coarsening of the precipitates.\(^9\) Yassar et al. reported that pre-straining before aging accelerates precipitation due to decreased activation energy for the growth of precipitates.\(^10\) Kim et al. found that pre-ECAP solution treatment combined with post-ECAP aging is very effective to enhance the strength of AA6061 aluminum alloy.\(^11\) These suggest that the combined effect of the two-step process which consists of first compression of die quenching and second cold compression may be useful. Using a servo press, the pre-straining before aging does not require further process because the main straining and the pre-straining can be conducted in single operation if die motion is controlled. So strain aging can be utilized without decreasing productivity or increasing cost. Therefore, servo press is an advantageous machine because press ram motion can be controlled flexibly to increase the strength with strain aging.\(^12\)

3. Experimental Procedures

The material used was a cylindrical AA2024-T4 aluminum alloy billet. The chemical composition of this alloy is given in Table 1. Billets with a diameter of 16 mm and a height of \(h_0 = 8\) mm were machined from a round bar of 20 mm in diameter. The Vickers hardness of the as-received billet was 124 HV. The forming was conducted on a 450 kN servo press. The tool arrangement for the die quenching is shown in Fig. 2. In this hot forming and die quenching (HFQ) process, first the billets were solution heat-treated at 823 K for 1.8 ks in an electric furnace under air and transferred to the press within a few seconds. The billets were loosely supported by copper wires between the dies to avoid contact with lower die before the HFQ process. Cemented tungsten carbide dies (WC–20 mass\%Co) were used. The thermal conductivity of the die was approximately 70 W·m\(^{-1}\)·K\(^{-1}\), which was much larger than that of tool steels.\(^13\) The surface roughness of the dies were 0.02–0.04 \(\mu\)m\(Ra\). The dies were kept at room temperature before the HFQ process. Then, the billet was compressed by 5% in height (\(\Delta h/h_0\)) during the first motion because the maximum reduction by the one-step die motion was \(\Delta h/h_0 = 5\%\) due to partial melting in previous studies.\(^5\)\(^6\) The deformation duration was 0.238 s for the billet with \(\Delta h/h_0 = 5\%\). The corresponding mean strain rate was 0.21 s\(^{-1}\) for the billet with \(\Delta h/h_0 = 5\%\). The compressed billet with a height of \(h_1 = 7.6\) mm was further held between the dies for quenching; sandwiching duration by dies, \(t_{d.q.} = 8\) s. And then straightly the second reduction in height (\(\Delta h/h_1\)) of 2 or 5% was applied without opening gap between the dies. As the billet temperature was cooled in the first step, the second step was cold compression. Therefore, the total reduction was \(\Delta h/h_1 = 7\%\) (\(1 - 0.95 \times 0.98 = 0.07\)) or \(\Delta h/h_1 = 10\%\) (\(1 - 0.95 \times 0.95 = 0.1\)). The deformation durations were 0.216 s for the billet with \(\Delta h/h_1 = 2\%\)

Table 1 Chemical composition of the alloy utilized in this study [in mass\%].

<table>
<thead>
<tr>
<th>Element</th>
<th>Si</th>
<th>Fe</th>
<th>Cu</th>
<th>Mn</th>
<th>Mg</th>
<th>Cr</th>
<th>Zn</th>
<th>Ti</th>
<th>Zr+Ti</th>
<th>Others</th>
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<td>AA2024</td>
<td>0.16</td>
<td>0.19</td>
<td>4.8</td>
<td>0.59</td>
<td>1.6</td>
<td>0.06</td>
<td>0.02</td>
<td>0.01</td>
<td>0.08</td>
<td>0.05</td>
</tr>
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Fig. 1 Schematic illustration of the conventional process for the water quenching (a), the one-step process for die quenching (b), and the two-step process for die quenching (c) imposed on the CCT diagram.
4.1 Deformability

By the one-step die motion the height of the billet can be compressed without cracks by less than 5% in height. Above the reduction, cracks occur along the thickness direction on bulged side surface during the HFQ process as shown in Fig. 4. In other words, by the one-step die motion the deformability of the alloy in HFQ process is rather limited by the intergranular fracture. On the other hand, the billet is compressed by less than 10% in height by the two-step die motion without defects. It means that in the case of the two-step, the total reduction in height ($\Delta h/h_1$) increases up to 10% as expected. The mechanism of fracture during the HFQ process by the two-step die motion will be discussed later when the total reduction is over 11% in height ($\Delta h/h_1$). Interestingly, the appearances of the as-HFQed billets by the one-step and the two-step die motion over 6% reduction in height show that more vertical profile around the end surfaces than that of the lower reduction which just shows slightly bulged side surface with decreasing reduction. The vertical profile implies that the cooling rate is higher near the end surfaces so that the deformation is concentrated around the center. The billets show similar vertical profiles over 6% reduction in height.

4.2 Temperature change

The measured temperature changes of the WQ, the AC and the HFQ by the one-step and the two-step die motion are compared in Fig. 5. The temperature was measured by a K-type thermocouple welded at the center of side surface. In the case of the one-step shown in Fig. 5(a), the cooling rate of the WQ is the fastest as expected. The temperature decreases to below 400 K within one second. The next is the HFQ with $\Delta h/h_0 = 5\%$ and that with $\Delta h/h_0 = 2\%$ in order. The cooling rate of the higher reduction ($\Delta h/h_0 = 5\%$) is faster than that of the lower ($\Delta h/h_0 = 2\%$) until the ejection from the press. It is found that higher reduction is effective to increase the cooling rate. This may be due to the fact that more heat is transferred from the billet to the dies due to higher pressure and higher contact ratio on the interface when the reduction is higher. The continuous cooling time (CCT) diagram of AA2024 in literature is super-imposed on Fig. 5. The cooling curves of the WQ, the HFQ with $\Delta h/h_0 = 2\%$ and that with $\Delta h/h_0 = 5\%$ are located below the nose of the precipitation-start curve. It is supposed that die quenching of the billet was successfully carried out by the HFQ as well as the WQ without precipitation. On the other hand, the cooling curve of the AC is placed above the nose so
that precipitation takes place. The longer dotted line imposed on the CCT diagram is an imaginarily curve because the precipitation of HFQ may be accelerated by the strain introduced.

In the case of the two-step shown in Fig. 5(b), the cooling rates of the two HFQ processes show almost the same as that of the one-step with $\Delta h/h_0 = 5\%$ in Fig. 5(a) because the HFQ process just before the second compression is the same as that of $\Delta h/h_0 = 5\%$ by the one-step die motion. And temperatures just slightly increase at the second compression due to the heat generation by plastic work. It means that cold compression was conducted at the second step after sufficient cooling. The two cooling curves of the HFQ are also below the nose of the precipitation-start curve. Therefore, it is supposed that super-saturated solid solution is maintained through the two-step process. The longer dotted line is also imposed on the CCT diagram because the precipitation of HFQ by the two-step die motion may be more accelerated by additional strain introduced at the second step.

4.3 Hardness change

The hardnesses at the center of the billet after cooling are compared in Fig. 6. Vickers hardnesses of the as-WQed billet and the as-ACed billet are 107 and 117 HV, respectively. In the case of the one-step, Vickers hardnesses of the as-HFQed billets with $\Delta h/h_0 = 2\%$ and that with $\Delta h/h_0 = 5\%$ are 108 and 109 HV, respectively. The hardness of the as-WQed billet shows the lowest. On the other hand, the hardness of the as-ACed billet is the highest. This is due to precipitation hardening occurred during cooling. The two as-HFQed billets show similar hardness as the as-WQed billet. The hardnesses of the as-HFQed billets well account for successful formation of super-saturated solid solution (SSSS) as the water quenching. These hardness changes well correspond with the reported precipitation curve shown in Fig. 5(a).

In the case of the two-step, Vickers hardnesses of the as-HFQed billet with $\Delta h/h_1 = 7\%$ and that with $\Delta h/h_1 = 10\%$ are 114 and 121 HV, respectively. The hardnesses of the two as-HFQed billets are higher than that of the one-step processed billets and increase with reduction at the second step. The reason is work hardening caused by the second step.

4.4 DTA analysis

Figure 7 shows the results of TG-DTA analysis. It is known that major strengthening phase of AA2024 alloy is S' precipitate formed around 553–563 K.\textsuperscript{13} In the case of the one-step shown in Fig. 7(a), the peak temperatures of the as-WQed billet, the as-ACed billet, the as-HFQed billet with $\Delta h/h_0 = 2\%$ and that with $\Delta h/h_0 = 5\%$ are 554, 578, 546 and 542 K, respectively. Those of the two as-HFQed billets are even lower than the as-WQed billet due to strain aging. The peak temperature of the as-HFQed billet with $\Delta h/h_0 = 5\%$ is the lowest. The peak temperature of the as-ACed billet is far higher than that of the as-WQed billet. It means that the precipitates were well formed during the cooling.

In the case of the two-step shown in Fig. 7(b), the peak temperatures of the as-HFQed billet with $\Delta h/h_1 = 7\%$ and that with $\Delta h/h_1 = 10\%$ are 530 and 528 K, respectively. The peak temperatures of the two as-HFQed billets are much lower than the two as-HFQed billets by the one-step die motion. In addition, the peak temperature is lower when higher reduction is applied. Therefore, it is found that
successful die quenching is maintained during the two-step die motion. And the billet is work-hardened in the second step.

4.5 Aging behavior

Hardnesses at the center of the as-quenched and the peak-aged billets are summarized in Fig. 8. Hardness changes during isothermal aging at 463 K are shown in Fig. 9. From the hardness of the as-quenched state, the hardnesses of all the billets increase with increasing aging time to their peaks. The peak aging time of the WQed billet and the ACed billet are 46.8 and 86.4 ks, respectively and hardness of that billets are 149 and 141 HV , respectively. The WQed billet shows earlier precipitation kinetics and higher hardness as expected due to its higher cooling rate. In the case of the one-step, hardnesses of the two HFQed billets increase rapidly than that of the WQed and the ACed billets in turn. The hardness increase of the HFQed billet with the $\Delta h/h_0 = 5\%$ is earlier than that of the $\Delta h/h_0 = 2\%$. The peak aging time of the HFQed billet with $\Delta h/h_0 = 5\%$ is at 32.4 ks and that with $\Delta h/h_0 = 2\%$ is at 36.0 ks. The peak hardness of the HFQed billet with $\Delta h/h_0 = 5\%$ is 145 HV and that with $\Delta h/h_0 = 2\%$ is 141 HV. It is found that faster precipitation kinetics and higher hardness are achieved with increasing reduction in the second step. However, the peak hardness of the billet with $\Delta h/h_0 = 5\%$ is lower than that of the WQed billet. It is supposed that the number of heterogeneous nucleation sites on dislocations for precipitates in the HFQed billet with $\Delta h/h_0 = 5\%$ are higher than that of the WQed billet.

In the case of the two-step, from the hardness of the as-quenched state, the hardnesses of the two HFQed billets increase with increasing aging time to their peaks. Especially the two HFQed billets by the two-step die motion increase rapidly than that of the billet with $\Delta h/h_0 = 5\%$ by the one-step die motion. The peak aging time of the HFQed billet with $\Delta h/h_1 = 10\%$ is at 21.6 ks and that with $\Delta h/h_1 = 7\%$ is 25.2 ks. The peak hardness of the HFQed billet with $\Delta h/h_1 = 10\%$ is 150 HV and that with $\Delta h/h_1 = 7\%$ is 146 HV. The peak hardness of the HFQed billet with $\Delta h/h_1 = 10\%$ shows comparable value with the WQed billet and the peak aging time is the earliest among all the conditions due to the second strain introduced during the HFQ process. It is also found that the HFQ process by the two-step die motion more accelerates the precipitation kinetics and increases the peak hardness than that by the one-step die motion.

4.6 Hardness distribution

Hardness distributions through the billet height processed
the center is attributed to the work hardening introduced during additional compression is mainly concentrated at the center. Hardness distribution of the as-HFQed billet with $\Delta h/h_1 = 10\%$ toward the center is wider than that of $\Delta h/h_1 = 7\%$ as shown in Fig. 10(b). It is thought that the amount of work hardening near the center is greater due to higher amount of reduction and relatively higher temperature at the center during the process. In the peak-aged state, the two HFQed billets show slightly curved distributions in hardness. It is thought that strain accumulation near the center is relieved during the artificially aging.

5. Discussions

It is confirmed that the HFQ process using the proposed two-step die motion is effective to increase the total reduction in height compared with the one-step die motion under certain conditions. It is proved that super-saturated solid solution is successfully maintained through the two-step die motion without precipitation as well as the one-step die motion and even the WQ. It is confirmed by the fact that the cooling curves of the HFQ by the two-step die motion are almost the same as that of the HFQ with $\Delta h/h_0 = 5\%$ by the one-step die motion. Those are below the nose of the reported precipitation curve results in super-saturated solid solution as the WQ.

The hardnesses of the as-HFQed billets by the two-step die motion are higher than that of the billets by the one-step die motion, while those are very similar to that of the as-WQed billet. This is partly due to work hardening introduced by additional compression of the second step. The work hardening is verified as a restoration process by the TG-DTA analysis. Hence, higher hardnesses of the as-HFQed billets by the two-step die motion are caused by work hardening. The peak aging time and hardness of the HFQed billet with $\Delta h/h_0 = 5\%$ processed by the one-step die motion are 32.4 ks and 145 HV, respectively, while the peak aging time and hardness of the HFQed billet with $\Delta h/h_1 = 10\%$ processed by the two-step die motion are 21.6 ks and 150 HV, respectively. It is found that the two-step die motion accelerates the precipitation kinetics and increases the peak hardness more rather than that of the one-step die motion due to strain aging of higher strain introduced at the second step.

5.1 Improvement in deformability

The total reduction in height increases from the billet with $\Delta h/h_0 = 5\%$ of the one-step to $\Delta h/h_1 = 10\%$ by the two-step die motion. Above the reduction, cracks occur on bulged side surface of the billet. In previous study, the HFQ process over 6% reduction in height ($\Delta h/h_0$) by the one-step die motion leads to cracks occurred by intergranular fracture due to partial melting at grain-boundary triple junction even though the SHT temperature at 823 K was closed to the solidus temperature at 775 K in an AA2024 aluminum alloy.\(^5\) To investigate the formation of cracks, SEM images of fractured surface on the billet with $\Delta h/h_1 = 11\%$ by the two-step die motion are shown in Fig. 11 and compared the billet with $\Delta h/h_0 = 6\%$ by the one-step die motion. Tool marks formed in machining were observed in the horizontal direction. In images of high magnification, intergranular fracture is also observed on the as-HFQed billet by the two-
step die motion as Fig. 11(b). This phenomenon is not usual in aluminum alloys because ductile fractured surface with dimples are generally observed after deformation even at R.T. Also temperatures of the two HFQ by the two-step die motion at the second compression are below 320 K near room temperature as shown in Fig. 5(b). To verify the mechanism of the intergranular fracture during the HFQ process by the two-step die motion, cross-sections of the same two specimens are shown in Fig. 12. Traces of liquid phases appeared along grain boundaries are observed on the billet of the two-step die motion. It is supposed that voids are formed at grain-boundary triple junctions and propagate along grain boundaries leading to intergranular fracture especially on bulged side surface of the billet as a result of tensile stress as shown in Fig. 11. The number of voids on the billet by the two-step die motion is less than that of the one-step die motion. This may be due to forming temperature difference. Second compression is conducted at low temperature without liquid phase in

Fig. 11 SEM images of fractured surface on the bulged side surface of the as-HFQed billets. (a) One-step ($\Delta h/h_0 = 6\%$) and (b) Two-step ($\Delta h/h_1 = 11\%$).

Fig. 12 SEM images for voids at grain junctions on the cross-section of the as-HFQed billets. (a) One-step ($\Delta h/h_0 = 6\%$) and (b) Two-step ($\Delta h/h_1 = 11\%$).
the two-step die motion. In other words, voids are closed by the compression at the second step.

5.2 Hardness distributions

In hardness distributions through the height, the two as-HFQed billets show curved hardness distributions with higher hardeneses near the center, while the billets by the one-step die motion show uniform hardness distributions through the height. To reveal this phenomenon, TG-DTA analysis was carried out at the surface and at the center of the as-HFQed billet with $\Delta h/h_1 = 7\%$ and that with $\Delta h/h_1 = 10\%$ by the two-step die motion to compare kinetics of precipitation as shown in Fig. 13. The peak temperature at the surface of the as-HFQed billet with $\Delta h/h_1 = 7\%$ and that with $\Delta h/h_1 = 10\%$ are 536 and 534 K, respectively, and those of the center are 530 and 528 K, respectively. The peaks at the center of the two as-HFQed billets are lower than that of the surface. It is supposed that work hardening is more concentrated at the center rather than the surface due to the temperature distribution and frictional constraint. Sufficient holding time may be useful to decrease temperature gradient and to obtain uniform hardness distributions. Better lubrication maybe also effective. Also, the peak temperature is lower when higher reduction is applied. Therefore, hardness near the center of the as-HFQed billet with $\Delta h/h_1 = 10\%$ is higher than that of $\Delta h/h_1 = 7\%$ due to higher amount of work hardening as shown in Fig. 10(b).

5.3 Aging behavior

It is well known that the hardness and the strength of the alloy are affected by the precipitate morphology and distribution developed during aging. The precipitation sequence of AA2024 aluminum alloy is reported in literature\(^{[5]}\) as $\alpha_{ss}$ $\rightarrow$ GPB zones $\rightarrow$ S’ $\rightarrow$ S (CuMg$_2$Al), where GPB zones stands for Guinier Preston Bagaryatsky zones and is an atomic arrangement of Cu and Mg atoms on {100}$_a$ of the Al matrix. For AA2024 aluminum alloy in the T6 state, initial strengthening is caused by GPB zones. At the stage of the peak aging, it is thought that the metastable phase of S’, which is normally nano-orders with needle- or plate-like shape,\(^{[15]}\) is precipitated since it is the major strengthening precipitate in a commercial AA2024 aluminum alloy. After the peak aging, the hardness decreases by the phase transformation of the strengthening precipitate to the equilibrium precipitate. Transformation to the equilibrium precipitate occurs coupled with growth of larger precipitates at the expense of finer ones as Ostwald ripening, reducing strength.

It is found that the HFQ process accelerates the precipitation kinetics and increases the peak hardness of an AA2024 aluminum alloy billet with $h_0 = 8$ mm after SHT at 823 K by strain aging due to higher dislocation densities introduced during the process. The possible mechanism for the acceleration is heterogeneous nucleation of precipitates from segregated solutes on dislocations.\(^{[5,17]}\) In addition, it is found that more effective acceleration and strengthening by the two-step die motion is suggested to be linked with the higher dislocation accumulation rate in the solutionized matrix and presence of higher density of fine precipitates in the aged matrix.

6. Applications

The two-step process combined die quenching and pre-straining in single operation using die-motion control on a servo press has been proposed in this study. It shows that the process can improve its deformability in die quenching of age-hardenable aluminum alloys. It leads the acceleration of the precipitation kinetics and increase the peak hardness without adding another process. Therefore, the process can improve the productivity in industries. This novel process is realized by die motion control on a servo press.

However, the two-step process may not be always effective if applications to other alloys of higher deformability are considered. It would be better to apply only the one-step process. In applications of the two-step process, such an AA2024 aluminum alloy billet is one of the most applicable materials. In previous study, the authors pointed out that the HFQ process must be initiated above the precipitation-start temperature of approximately 760 K to avoid precipitation start. Therefore, the HFQ process was conducted after the SHT at 823 K to consider temperature drop caused by time interval for transfer from the electric furnace to the press although the recommended SHT temperature for a commercial AA2024 aluminum alloy is approximately 763–773 K.\(^{[5,18]}\) However, the higher SHT temperature caused voids formation at grain-boundary triple junctions due to partial melting, then leading to intergranular fracture along grain boundaries when reduction applied over 6% in height. Therefore, only small reduction less than 5% in height was applicable to avoid intergranular fracture, and then the compressed billet was further held between the dies for quenching. The temperature after the first-step die quenching is far below the solidus temperature close to room temperature so that further compression is sufficiently applied to the billet up to 5% in height without any defects. Thus, the two-step process for die quenching is appropriate for such an AA2024 aluminum alloy billet because the improved deformability can be obtained using microstructure control by die motion control in single operation on a servo press.
In addition, servo press with flexible ram motion has been developed to lead new forming processes such as reducing friction in sheet forging, suppressing defects during extrusion against counter tool, supplying liquid lubricant through internal channel into the hole during extrusion, reducing springback by holding of dies at the bottom dead center, and so on.\textsuperscript{19–22} It is notable that die motion control on servo press can be a metallurgical means for microstructure control and property improvement though they have not been studied widely.

7. Conclusions

Die quenching of a cylindrical AA2024 aluminum alloy billet was feasible on a servo press by sandwiching with dies of WC–20 mass\%Co. However, the reduction was limited less than 5\% in height. In order to apply higher reduction, just after die quenching further compression was conducted straightly on the same machine (two-step die motion). Following remarks have been drawn in this study:

(1) The low deformability due to partial melting at grain-boundary triple junctions is improved using the two-step die motion. The total reduction increases from the billet with $\Delta h/h_0 = 5\%$ of the one-step to $\Delta h/h_1 = 10\%$ by the two-step die motion.

(2) Temperature change and TG-DTA results show that the two-step die motion does not cause precipitation hardening during the process. The hardness is higher near the center of the die-quenched billets by the two-step die motion. The distribution reflects work hardening introduced during the second step mainly concentrated at the center.

(3) As the pre-straining is realized in the second step, the peak aging time and hardness of the HFQed billet with $\Delta h/h_1 = 10\%$ by the two-step die motion are 21.6 ks and 150 HV, respectively, while those by the one-step die motion are 32.4 ks and 145 HV. Therefore, the two-step die motion is more effective to accelerate the precipitation kinetics and increase the peak hardness than that of the one-step die motion.

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