Elasto-thermoviscoplastic finite element analyses of cold upsetting and forging processes of S25C steel with dynamic strain aging considered

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Abstract. A practical methodology is presented to characterize the thermoviscoplastic flow stress at larger strain over the temperature range of cold metal forming using tensile and compression tests. Its importance is emphasized for non-isothermal finite element (FE) analysis of automatic multi-stage cold forging (AMSCF) process where maximum strain and strain rate exceed around 3.0 and 200/s, respectively. The experimental compressive flow stress is first characterized using traditional bilinear C-m model with high accuracy. It is employed for describing the closed-form function model to extrapolate the experimental flow stress over the experimentionally uncovered ranges of state variables. The strain effect on the flow stress is then improved using the experimental tensile flow stress accurately calculated at large strain and room temperature. A complicated flow behavior of S25C characterized by its dynamic strain aging features is expressed by the presented methodology, which is utilized to analyze the test upsetting and AMSCF processes by the elasto-thermoviscoplastic finite element method for revealing the effects of flow stresses on the process.

1. Introduction

In most engineering activities for cold metal forming, the thermal effect on flow behaviors during has been neglected even though a few research works have been made on this topics [1-5]. The temperature effects can be remarkable, especially in AMSCF of aluminum alloys [4] due to their low melting temperatures, preheat-treated steels [6] and a stainless steels [5]. The temperature of materials during consecutive cold metal forming increases considerably due to less thermal diffusion, for example, the local temperature of a stainless steel (SUS304) ball-stud reached around 440°C [5].

The instability of the plastic deformation of materials, first observed by Portevin and Le Chatelier [7], may occur if they exhibit the features of dynamic strain aging (DSA) [8-11]. In AMSCF, the DSA may occur because of relatively high temperature rise during the process. DSA causes non-uniformity of plastic deformation during metal forming, which not only incurs unpredicted forming load change with the stroke but also impairs formability [12-15], surface quality [16], and mechanical and metallurgical properties [10,12,17,18-20].
Transformation- and twinning-induced plasticity steels have been very attractive to the researchers owing to their better mechanical properties of ductility and strength. However, a lot of such steels exhibit DSA, which are associated with abnormal work hardening, non-uniform elongation, and reduced total elongation to failure [21-24]. DSA is one of actual phenomena occurring in cold forging, which emphasizes the importance of non-isothermal analysis of cold forging processes even though most cold forging processes have been analyzed by the isothermal analysis function.

From a theoretical standpoint, the non-isothermal analyses of cold forging processes have no difference from those of hot forging processes. To the contrary, there is a big practical problem of acquiring flow stress at the larger strain of at least 3.0, for an example, in AMSCF [4,5] because such the considerable metallurgical softening occurring in hot metal forming does not take place. When the experiments to reveal flow behavior of a material rely on the solid cylinder compression test, which is prevalent, the flow stress at the strain over 0.4 is exposed to inaccuracy due to the friction-incurred barreling phenomena. It is still difficult to find a practical way of acquiring flow stress at the larger strain for engineering of cold forging, especially AMSCF where no annealing can be intervened.

On the contrary, flow behaviors of the materials with DSA phenomena are too complicated to be mathematically described with acceptable accuracy by a limited number of material constants [25]. In particular, the flow modeling techniques currently under study have very rarely been applied to computer simulation [26] of metal forming processes of such materials. Most flow characterization studies considering DSA used some limited ranges of state variables or closed-form functions. However, state variables tend to be coupled; additionally, DSA is dependent on the microstructure of the material [12]. Therefore, flow modelling of the materials with DSA is so difficult.

Recently, Joun et al. [27] showed that traditional piecewise bilinear C-m model is beneficial for describing the flow behavior of the S25C material with typical dynamic strain aging features with acceptable or high accuracy. However, the accuracy is meaningful only in the ranges of test strain rates and temperatures and in the range of almost homogeneous strain in case of cylinder compression test. There exist some limitations of high strain rate and high strain. The extrapolation is thus inevitable in most practical cases. For this purpose, Lee et al. [28] suggested a closed-form function model for the S25C material.

Because there is a distinct limitation on the reliable ranges of strain as well as strain rate and temperature, some extrapolations of the flow curves for the greater state variables than of their test limit values are inevitable. The piecewise description has a weakness in this point. Thus, we characterized the flow behaviors of S25C using the closed-form function model constructed in the previous study [28], which gives the flow information at large strain necessary to extend the material constants of the C-m model. The constructed material models were employed for non-isothermal FE analysis of an AMSCF process. The results were compared with iso-thermal FE analysis results and the predictions obtained by the closed-form flow model to emphasize the importance of the extrapolation.

2. Modelling of flow stress curves
Figure 1, flow stress-strain curves at the fixed temperatures 20, 100, 200, 300, 400 and 500 (℃) and the strain rates 1.0, 5.0, 10.0 and 20.0 (1/s), shows the flow stress curves of S25C (equivalent to AISI1025) obtained in the previous study [27].

As stated in the work of Joun et al. [27], Figure 1 indicates that the disorder of flow stress with respect to temperature grows more prominently in a relatively small strain, particularly at a strain rate of 5/s. The disorder is true of the other conditions. It is thus very difficult to configure the flow behaviors of the material in Figure 1.

To make it easy to understand the flow behaviors, we redrew the flow curves with respect to temperature at the fixed sample strains and strain rates, as shown in Figure 2. Note that Figure 2 shows a typical dynamic strain aging phenomenon of the S25C steel.
Figure 1. Experimental flow stress curves for various strain rates.
Figure 2. Change of flow curves with temperature at various fixed strains and strain rates.

In the previous studies, the experimental flow stresses were fitted using the traditional piecewise bilinear $C$-$m$ model [27] and by a closed-form function model [28]. In the piecewise bilinear $C$-$m$ model, the flow curves are formulated as

$$\sigma = C \dot{\varepsilon}^m$$  \hfill (1)$$

where

$$C = C(\varepsilon, T) \quad \text{and} \quad m = m(\varepsilon, T)$$  \hfill (2)$$

are the strength parameter and strain rate sensitivity, respectively, which are all piecewise bilinear functions of strain and temperature. The material constants were recalculated for the strain ranging from 0.0 to 0.5 in this study and listed in Table 1. Note that the sensitivity of the flow stress to the strain rate was nearly zero over strain ranges of 0.03 to 0.5 and 0.05 to 0.3 at 300°C and 400°C, respectively, as summarized in Table 1, owing to DSA. It is also noted that the dot marks in Figures 1 and 2 were the fitted flow stresses at the sample points using the piecewise bilinear $C$-$m$ model. The maximum error of 4.3% occurred at a strain of 0.4, the sample strain rate of 10/s, and the temperature of 500°C. Note that the dashed lines in Figure 2 were assumed based on the slopes at the right ends of the flow curves.

| $\varepsilon$ | 20   | 100  | 200  | 300  | 400  | 500  |
|--------------|------|------|------|------|------|------|
| $T (\degree C)$ | $C$  | $m$  | $C$  | $m$  | $C$  | $m$  |
| 0.01         | 238  | 0.306| 287  | 0.078| 254  | 0.088| 320  | 0.017| 312  | 0.039| 255  | 0.059|
| 0.03         | 436  | 0.083| 381  | 0.043| 342  | 0.033| 361  | 0.012| 398  | 0.003| 352  | 0.053|
| 0.05         | 465  | 0.072| 396  | 0.051| 351  | 0.040| 379  | 0.007| 428  | -0.003| 379  | 0.064|
| 0.1          | 505  | 0.060| 435  | 0.050| 382  | 0.046| 415  | 0.0002| 467  | 0.000| 414  | 0.071|
| 0.2          | 578  | 0.039| 496  | 0.037| 438  | 0.034| 465  | -0.005| 507  | 0.003| 453  | 0.063|
On the contrary, Lee et al. [28] represented the close-form function flow model of the S25C steel with an emphasis on DSA as

$$\sigma = \sigma_1 + \sigma_2 \quad (3)$$

where $\sigma_1$ and $\sigma_2$ are the state variable-effective and DSA-effective flow stresses, respectively, defined as:

$$\sigma_1 = Y_B \left( 1 + \beta_1 T + \beta_0 \left( \frac{T}{T_0} \right)^{\beta_3} \right)^{-\beta_2} \quad (4)$$

$$\sigma_2 = \frac{Y_1}{\pi} \left[ \tan^{-1} \left( \frac{T-T_1}{A} \right) - \tan^{-1} \left( \frac{T-T_2}{A} \right) \right] \quad (5)$$

where

$$Y_1 = \{ y_1 - y_2 (\langle \varepsilon - 0.3 \rangle - \langle \varepsilon - 0.4 \rangle) \} (y_3 \dot{\varepsilon} + y_4) \quad (6)$$

$$T_1 = T_{11} \dot{\varepsilon} + T_{12} \quad (7)$$

$$T_2 = T_{21} \dot{\varepsilon} + T_{22} \quad (8)$$

$$A = a_1 \dot{\varepsilon} + a_2 \quad (9)$$

$$\beta_2 = \beta_{21} \dot{\varepsilon} + \beta_{22} \quad (10)$$

$$T_0 = T_{01} \dot{\varepsilon} + T_{02} \quad (11)$$

$$\beta_3 = \beta_{31} \dot{\varepsilon} + \beta_{32} \quad (12)$$

$$\beta_0 = 1.2 \quad (13)$$

$$\beta_1 = \beta_{11} \left( \frac{1}{\varepsilon + r_1} + \beta_{13} \right) \left( 1 - \beta_{14} \dot{\varepsilon}^{\beta_{15}} \right) \quad (14)$$

$$Y_B = Y_0 (1 + B \varepsilon)^n g(\dot{\varepsilon}, T) \quad (15)$$

where

$$g(\dot{\varepsilon}, T) = g_1 + g_2 \dot{\varepsilon}^{\beta_3} (1 - (T-20)/450) \text{ for } T < 400^\circ C \quad (16)$$

$$g(\dot{\varepsilon}, T) = g_1 + g_2 \dot{\varepsilon}^{\beta_3} (1 + (T-480)/95) \text{ for } T \geq 400^\circ C \quad (17)$$

### Table 2. Material constants of the closed-form function.

|      | $Y_0$  | $B$   | $n$   | $\beta_{11}$ | $\beta_{12}$ | $\beta_{13}$ | $\beta_{14}$ | $\beta_{15}$ | $\beta_0$ |
|------|--------|-------|-------|--------------|--------------|--------------|--------------|--------------|-----------|
| Value| 400    | 147   | 0.117 | 0.00063      | 0.152        | 3.71         | 0.052        | 0.3          | 1.2       |

|      | $T_{01}$ | $T_{02}$ | $\beta_{31}$ | $\beta_{32}$ | $\beta_{21}$ | $\beta_{22}$ | $y_1$ | $y_2$ | $y_3$ | $y_4$ |
|------|----------|----------|--------------|--------------|--------------|--------------|-------|-------|-------|-------|
| Value| 17.2     | 584      | -0.0513      | 6.71         | 0.0052       | 0.656        | 23.2  | 25.6  | 0.0962| 2.1   |

|      | $T_{11}$ | $T_{12}$ | $T_{21}$ | $T_{22}$ | $a_1$ | $a_2$ | $g_1$ | $g_2$ | $g_3$ |
|------|----------|----------|----------|----------|-------|-------|-------|-------|-------|
| Value| 4.70     | 298      | 15       | 550      | 5.22  | 56.2  | 1.01  | 0.0086| 0.825 |
The material constants defined in the above formulation were recalculated for the strain ranging from 0.0 to 0.5 and summarized in Table 2. The average and maximum errors of the fitted flow stresses with respect to the experiments were 1.4% and 6.6%, respectively. Note that the errors are a little greater than those of strain range from 0.0 to 0.4 [28] because the material model of Equation (3) was developed for low strain at which the solid cylinder compression test is reliable.

Both the flow models above have some advantages and drawbacks at the same time. The piecewise bilinear $C$-$m$ model has the advantage that it can be locally adjusted to make the local maximum error reduced [29,30]. However, it has the drawback of quite small strain coverage which can be hardly extrapolated. To the contrary, the closed-form flow model can be easily extrapolated while its local adjustment is hard to be made. For example, in case that the extrapolated flow stress is so high at a certain strain, the former can deal with the problem with ease while the latter cannot do it. Therefore, we’d better take the advantages of both the flow models.

Figure 3 shows the material characterization of S25C using a tensile test at room temperature. The reference flow stress (RFS) curve was obtained using the Joun et al.’s algorithm [31], which is the true stress-strain curve corresponding to the tensile test of engineering stress-strain curve. With this RFS, we predicted the tensile test using a finite element method [32] and compared the predictions with experiments in Figure 3, revealing the experimental and predicted tensile tests are almost the same excluding in the low strain region. Note that the low strain before necking is less important than the higher strain in bulk metal forming.

![Figure 3. Modelling of strain hardening at large strain.](image-url)

We fitted the RFS using the Swift model in two ways. The first Swift model denoted by Swift-Pre ($Y_0 = 365$ MPa, $B = 29.5$, $n = 0.165$) was characterized by the yield and tensile strengths and Considéré condition and the second Swift model denoted by Swift-Post ($Y_0 = 406$ MPa, $B = 3.13$, $n = 0.451$) by the tensile strength, the Considéré condition and flow stress at point Q (0.72,692). They were compared with RFS in Figure 3, revealing that the Swift-Pre is quite different from the RFS in the post-necking region and that the Swift-Post is very close to the RFS in the post-necking region even though it is erroneous in the pre-necking region in terms of the RFS. The theoretical tensile tests predicted by the Swift-Pre and Swift-Post were compared with the experimental tensile test in the lower part of Figure 3.
revealing that Swift-Pre matches well with the experiment in the low strain range and exhibits great error in the post-necking region and that the Swift-Post is opposite. Since the flow stress in the post-necking region is much important in most bulk metal forming and the Swift-Post predicted quite accurate tensile test in the strain range of our interest, it can be used as the experimental flow stress for the sake of engineering.

It is interesting to note that the difference in flow stress between the compression and tensile tests is quite great, as can be seen in the strain ranging from 0.0 to 0.5 in Figure 3. A little larger compressive strain was presumed owing to strain rate [28] and friction [33] effects. Considering them as around 10%, both the flow stresses match acceptably with each other. Because the tensile flow curve is accurate at least in the tensile load incurred yielding and because it cannot only give us the flow stress at larger strain up to around 1.3 but it can also be extrapolated for the larger strain with potentially less error, we adopted it for \( Y_0 \), \( B \) and \( n \) of the closed-form function flow model.

![Figure 4. Comparison of the flow curves improved and extrapolated (solid lines) with those fitted by the piecewise bilinear \( C-m \) model (dot marks).](image)

It should be recalled that the material constants in Table 2 were calculated only considering the flow curves in Figure 1. Now we are going to replace the \( Y_0 \), \( B \) and \( n \) values in Table 2 by those values of Swift-Pre and Swift-Post to reflect the effect of large strain on flow stress. The former and the latter are denoted as CFFM-Swift-Pre and CFFM-Swift-Post, respectively. Now, we have two sets of the extended flow curves for flow stress at large strain. Because the Swift-Post is more reliable in terms of bulk metal
forming, we adopted the new closed-form function model improved by Swift-Post for the representative CFFM for S25C.

We calculated the flow stress over the larger strain up to around 3.0 at the sample strain rates and temperatures from the CFFM-Swift-Post to construct new flow curves shown in Figure 4.

Finally, we recalculated the material constants of the $C\cdot m$ model for the new extrapolated flow curves in Figure 4 and its material constants were listed in Table 3. The new flow curves fitted by the piecewise bilinear $C\cdot m$ model were denoted by dot marks in Figure 3 to be compared with the new flow curves improved and extrapolated. The comparison shows the acceptability of the final piecewise bilinear $C\cdot m$ model for covering the state variables of cold forging, especially in AMSCF. It is noted again that the piecewise bilinear $C\cdot m$ model can be flexibly modified to fix the theoretically obtained flow stress information in the procedure of reflecting the shopfloor’s experiences.

| Table 3. Material constants of the $C\cdot m$ model for the new flow stresses in Figure 4. |
|---|
| $T$ (°C) | 20 | 100 | 200 | 300 | 400 | 500 |
| $\varepsilon$ | $C$ | $m$ | $C$ | $m$ | $C$ | $m$ | $C$ | $m$ | $C$ | $m$ |
| 0.01 | 392 | 0.043 | 317 | 0.044 | 276 | 0.045 | 315 | 0.004 | 371 | 0.002 |
| 0.03 | 404 | 0.043 | 331 | 0.043 | 289 | 0.044 | 327 | 0.004 | 383 | 0.002 |
| 0.05 | 416 | 0.043 | 343 | 0.043 | 302 | 0.043 | 338 | 0.005 | 394 | 0.002 |
| 0.1 | 443 | 0.042 | 372 | 0.041 | 329 | 0.041 | 364 | 0.005 | 418 | 0.003 |
| 0.2 | 492 | 0.040 | 422 | 0.039 | 376 | 0.038 | 408 | 0.006 | 460 | 0.003 |
| 0.3 | 534 | 0.039 | 464 | 0.038 | 416 | 0.036 | 445 | 0.006 | 495 | 0.003 |
| 0.4 | 572 | 0.037 | 500 | 0.035 | 448 | 0.032 | 466 | 0.006 | 506 | 0.003 |
| 0.5 | 608 | 0.037 | 534 | 0.034 | 480 | 0.031 | 496 | 0.007 | 533 | 0.003 |
| 1 | 756 | 0.035 | 673 | 0.032 | 608 | 0.023 | 614 | 0.007 | 645 | 0.003 |
| 2 | 977 | 0.033 | 877 | 0.030 | 794 | 0.025 | 784 | 0.007 | 804 | 0.003 |
| 3 | 1150 | 0.033 | 1034 | 0.028 | 936 | 0.023 | 914 | 0.007 | 926 | 0.003 |
| 4 | 1290 | 0.032 | 1166 | 0.028 | 1055 | 0.022 | 1023 | 0.007 | 1028 | 0.003 |
| 5 | 1420 | 0.032 | 1282 | 0.027 | 1160 | 0.021 | 1118 | 0.007 | 1117 | 0.002 |

3. Non-isothermal and isothermal analyses of the upsetting and nut forming processes
An upsetting process was first simulated using seven different flow stresses summarized in Table 4 not only for verifying the validity of all the flow stresses but also for emphasizing the importance of material characterization and non-isothermal precision FE analyses in cold forging, especially in AMSCF. Case 1 is the traditional $C\cdot m$ model directly fitted using the compressive flow stresses. Case 2 is a closed-form function model proposed by Lee et al. [28]. Cases 3 and 4 are the improved closed-form function model for accurate strain effect on flow stress at large strain. The flow stress represented by Cases 6 and 7 were obtained from the tensile tests at room temperature with emphasis on pre- and post-necking regions, respectively. Cases 6 and 7 were employed to improve the strain effect in Cases 3 and 4, respectively. Case 5 is the $C\cdot m$ model description of Case 4 over the extended coverages of state variables.

Note that, in case that a state variable exists out of its coverage, the state variable should be replaced by its limit or boundary value during calculating its associated flow stress information.
Table 4. Flow stress cases.

| Case | Description                                      |
|------|--------------------------------------------------|
| 1    | C-m model in Table 1                             |
| 2    | Closed-form function model in Table 2            |
| 3    | CFFM-Swift-Pre                                  |
| 4    | CFFM-Swift-Post                                 |
| 5    | C-m model fitted for the CFFM-Swift-Post        |
| 6    | Swift-Pre                                       |
| 7    | Swift-Post                                      |

Figure 5 defines the test upsetting process. The frictional coefficients were assumed at 0.1 following Lee et al. [27]. The velocity of the upper die was equivalent to the sample strain rate of 5/s in the solid cylinder compression test [27]. The thermal information was summarized in Table 5 [5,34,35].

![Process design](image)

**Figure 5. Process design.**

Table 5. Thermal information for the non-isothermal analysis.

| Initial temperature (°C) | 300              |
|--------------------------|------------------|
| Heat transfer coefficient to ambient (W/mm²·°C) | 2.95x10⁻⁶          |
| Heat radiation coefficient to ambient (W/mm²·°C¹) | 3.97x10⁻¹⁴         |
| Heat transfer coefficient to workpiece from die (W/mm²·°C) | 0.01                |
| Thermal conductivity of die (W/mm²·°C) | 0.0251 (200°C) 0.0259 (800°C) |
| Thermal conductivity of material (W/mm²·°C) | 0.0255 (200°C) 0.0263 (800°C) |
| Thermal capacity of die (W/mm³·°C) | 0.0052         |
| Thermal capacity of material (W/mm³·°C) | 0.0052         |

An elasto-thermoviscoplastic FE software [36-38] was utilized for these FE simulations. Considering the solid cylinder compression test, we assumed the initial temperatures of material and dies at 300°C.
We compared the predictions of upsetting load-stroke curve and effective strain, temperature and effective stress for the seven cases in Figures 6 and 7, respectively. It can be seen from Figure 6 that the seven flow stress cases exhibited quite different characteristics in terms of upsetting load. The maximum difference (60kN) with respect to the least upsetting load (137kN) at the final stroke amounted to 44%. Cases 1 and 2 went along the similar loading path up to the stroke of 6mm where the strain reached around 0.7, implying that the CFFM for the Figure 1 is reliable. Similarly, Cases 3 and 4 ran along the similar loading path up to the strain of 0.4 (corresponding stroke = 4mm) after which the path was separated owing to the different strain hardening. The comparison of the upsetting loads between Case 4 and Case 5 showed that they are almost the same with each other, indicating that the final goals of Case 4 and Case 5 were accomplished. It is noted that the temperature-effect neglected cases of Cases 6 and 7 experienced greater upsetting loads then the other cases despite the dynamic strain aging phenomena. The maximum load of Case 7, which is of the usual case of isothermal analysis, is greater by 20% than the Case 5.

Figure 6. Comparison of upsetting load-stroke curves for the seven flow stress cases.

Figure 7 shows that the effective strains of all the cases at the final stroke are almost the same even though effective stresses are little or quite different. The greater stresses yielded the greater temperatures at the central spot. Because the temperature rise is dependent on the energy consumption, the smoothed increase in temperature at the final stroke is right. In other words, difference in stress is directly dependent on that in the upsetting load while temperature difference depends on the area difference below the upsetting load-stroke curve. These discussions verify the validity of all the flow models assumed or fitted.
Figure 7. Comparison of temperatures and effective stresses for the seven flow stress cases.
A practical process of fabricating a nut of which process design was described in Figure 8 was simulated using the Case 5 in Table 4. Friction was assumed $0.03+0.005\varepsilon$ [39]. The same thermal conditions in Table 5 were employed. Figure 9 shows the predictions of effective strain and stress and temperature. It is emphasized that the strain and temperature increased up to 4.5 and 550°C, respectively. The maximum strain rate reached around 1000/s. Note that the maximum values of strain and strain rate cannot be reached by practical solid cylinder compression test.

We also simulated the same process using the material flow information of the Case 7 where the material was assumed elasto-plastic. The isothermal FE prediction of the forming load were compared with that of the Case 5 in Figure 10, revealing that the maximum forming load at the third stage was reduced about 15% from the material modeling considering the strain rate and temperature effects on flow stress. Note that the reduction might become much increased [5] if there was no dynamic strain aging phenomenon increasing the flow stress owing to the viscous heating in the temperature range of cold metal forming. It is also noted that this forming load reduction is crucial especially for accurate prediction of high-cycle fatigue life in AMSCF.

**Figure 8.** Process design of an AMSCF of a nut.

**Figure 9.** Predictions of effective strain and stress and temperature.

**Figure 10.** Feasibility of reduction in forming load.
Figure 9. Predicted effective strain and stress and temperature of Case 5.

(a) Case 5

(b) Case 7

Figure 10. Comparison of upsetting load-stroke curve between Cases 5 and 7.
4. Conclusions
We examined the plastic deformation behaviors of S25C steel exhibiting the dynamic strain aging under typical AMSCF conditions with an emphasis on their application to non-isothermal FE analyses of cold metal forming, especially AMSCF processes. It was emphasized that experimental flow information of S25C to be cold forged, obtained by the solid cylinder compression test, could cover only the strain ranging from 0.0 to 0.4 for reliable solution because of the barreling.

However, actual ranges of strain, strain rate and temperature were presumed 0.0-4.5, 0/s-500/s and 20℃-550℃ in AMSCF of a nut. Thus, the strain and strain rate effects on flow stress cannot be appropriately reflected directly from any practical material test. That is one of the reasons why most researchers have relied on the iso-thermal FE analyses of cold metal forming processes. We thus presented a scientific methodology of acquiring an extended flow model with material constants applicable to large strain and large strain rate, which is based on the tensile and compression tests and the extrapolation scheme. We employed the closed-form function model previously presented to extrapolate the experimental flow stresses. The extended flow stress information was utilized to remodel the associated C-m model which covers the state variables with appropriate ranges. For example, the coverage of strain was extended from [0.0-0.4 or 0.5] to [0.0-5.0]. Note that the C-m model is more beneficial than the closed-form function model if the ranges of the state variables can cover those of real-world process because it can adjust locally the flow stress. Seven feasible flow stress descriptions involving five elasto-thermoviscoplastic flow equations were derived in the procedure of developing the methodology and the best description of Case 4 or 5, extrapolated closed-form function model and its corresponding C-m model, respectively, was proposed for the non-isothermal analysis of AMSCF process.

We compared the elasto-thermoviscoplastic or elasto-plastic FE predictions of an upsetting process obtained using the seven flow stress descriptions with different material constants. The comparison showed the importance of not only isothermal analysis of cold metal forming processes but also extrapolation technique of flow stress over the state variables, especially of AMSCF processes which run fast and does not allow any intervention for cooling or annealing.

The AMSCF process of a nut was analyzed by the elasto-thermoviscoplastic finite element method. It was shown that despite the exhibition of the dynamic strain aging, around 15% reduction of maximum forming load was obtained considering the strain rate and temperature effects on flow stress, which cannot be neglected especially in predicting the die life.

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References
[1] Qin Y, Balendra R and Chodnikiewicz K 2000 J. Mater. Process. Technol. 107 252-259
[2] Ishikawa T, Ishiguro T, Yukawa N and Goto T 2014 CIRP Ann. 63 289-292
[3] Nahrmann M and Matzenmiller A 2020 Int. J. Mater. Form. 26 1-22
[4] Yoo J D, Hwang T M and Joun M S 2020 Key. Eng. Mater. 830 93-100
[5] Byun J B, Razali M K, Lee C J, Seo I D, Chung W J and Joun M S 2020 Materials 13 5300-5316
[6] Eom J G, Son Y H, Jeong S W, Ahn S T, Jang S M, Yoon D J and Joun M S 2014 Mater. Des. 54 1010-1018
[7] Robinson J M and Shaw M P 1994 Int. Mater. Rev. 39 113-122
[8] Zhao Y, Dezerald L, Pozuelo M, Zhou X and Marian J 2020 Nat. Commun. 11 1-8
[9] Ramachandran V and Reed-Hill R E 1970 Metal. Trans. 1 2105-2109
[10] Van den Beukel A 1975 Phys. Status Solidi (a) 30 197-206
[11] Mulford R A and Kocks U F 1979 Acta Metall. 27 1125-1134
[12] Rodriguez P 1984 *Bull. Mater. Sci.* **6** 653-663
[13] Bayram B, Simşir C and Efe M 2017 *Mater. Sci. Eng. A* **704** 164-172
[14] Venugopal S, Venugopal P and Mannan S L 2008 *J. Mater. Process. Technol.* **202** 201-215
[15] Tabatabaei N, Taheri A K and Vaseghi M 2010 *J. Alloys. Compd.* **502** 59-62
[16] Jo M C, Yoo J, Jo M C, Zargazan A, Sohn S S, Kim N J and Lee S 2020 *J. Mater. Sci. Technol.* **43** 44-51
[17] Hong S G and Lee S B 2004 *Int. J. Fatigue.* **26** 899-910
[18] Mao C, Liu C, Yu L, Li H and Liu Y 2019 *Mater. Sci. Eng. A.* **739** 90-98
[19] Seol J B, Kim J G, Na S H, Park C G and Kim H S 2017 *Acta Mater.* **131** 187-196
[20] Serajzadeh S 2009 *Int. J. Adv. Manuf. Technol.* **40** 721-728
[21] Field D M and Van Aken D C 2018 *Metall. Mater. Trans. A.* **49** 1152-1166
[22] Koyama M, Sawaguchi T and Tsuzaki K 2018 *ISIJ Int.* **58** 1383-1395
[23] Lee S J, Kim J, Kane S N and De Cooman B C *Acta Mater.* **59** 6809-6819
[24] Oh S K, Kilic M E, Seol J B, Hong J S, Soon A and Lee Y K 2020 *Acta Mater.* **188** 366-375
[25] Van den Beukel A and Kocks U F 1982 *Acta Metall.* **30** 1027-1034
[26] Epperly E N and Sills R B 2020 *J. Mech. Phys. Solids.* **141** 103944
[27] Joun M S, Lee H J, Lim S G, Lee K H and Cho G S 2021 *Int. J. Mech. Sci.* **200** 106423
[28] Lee H J, Razali M K, Lee K H and Joun M S 2021 *Mater. Today. Comm.* **28** 102483
[29] Joun M S, Razali M K, Yoo J D, Kim M C and Choi J M 2021 *J. Magnes. Alloy.* Accepted.
[30] Song H N, Kim Y S and Joun M S 2021 *PI Mech Eng E-J Pro* **235** 274-284
[31] Joun M S, Eom J G and Lee M C 2008 *Mech. Mater.* **40** 586-593
[32] Joun M S, Choi I S, Eom J E and Lee M C 2007 *Comput. Mater. Sci.* **41** 63-69
[33] Luan J, Sun C, Li X and Zhang Q 2013 *Mater. Sci. Technol.* **30** 102-110
[34] Joun M S, Moon M K and Shivpuri R 1998 *J. Eng. Mater. Technol.* **120** 291-296
[35] Moon H K, Lee J S, Yoo S J, Joun M S and Lee J K 2007 *J. Eng. Mater. Technol.* **129** 349-55
[36] Joun M S, Chung W J and Chung S H 2021 *Jinsaem Media*
[37] Joun M S and Lee M C 1997 *Int. J. Numer. Meth. Eng.* **40** 4059-4075
[38] Lee M C, Joun M S and Lee J K 2007 *Finite Elem. Anal. Des.* **43** 788-802
[39] Lee S W, Lee J M and Joun M S 2020 *Tribol. Int.* **141** 105855