Processing map of as-cast 7075 aluminum alloy for hot working

Guo Lianggang a, Yang Shuang a, Yang He a,*, Zhang Jun b

a State Key Laboratory of Solidification Processing, Northwestern Polytechnical University, Xi’an 710072, China
b China National Heavy Machinery Research Institute Co. Ltd, Xi’an 710032, China

Received 24 June 2015; revised 14 July 2015; accepted 2 August 2015
Available online 28 August 2015

1. Introduction

The 7075 aluminum alloy has been widely used in aerospace and automobile industries because of its excellent properties such as light weight, high strength and high stress corrosion resistance. In order to shorten the process, the as-cast 7075 aluminum alloy is directly used as billet in some hot working processes such as extrusion. The short-process hot working technology based on as-cast billet will greatly save energy and lower the cost by avoiding long preforming process for manufacturing forging state billet. However, it is well-known that the as-cast 7075 aluminum alloy is such sensitive to deformation temperature and strain rate that it has pretty narrow forming window due to the dendrite and the second phase in as-cast structure. Especially, the alloy is very easy to crack during hot plastic deformation. Therefore, a fundamental and important issue for planning and optimizing hot working processes based on as-cast 7075 aluminum alloy billet is to
establish its hot processing map, which can be used to describe hot workability of the alloy and determine suitable processing window with preferable microstructure and free from forming defects such as crack.

The processing map based on Dynamic Material Model (DMM) is an important method which is usually used to describe the response relationship between workability and processing parameters, thus having a great significance in planning and optimizing hot working processes in practice. Lin et al. established the hot processing map of as-forged 7075 aluminum alloy based on DDM using Prasad instability criterion by isothermal compression tests and determined the optimum hot working area by analyzing the deformed microstructures in different areas in the processing map. Yang et al. established the hot processing map of as-extruded 7075 aluminum alloy and found out the influences of loading direction to the axis of extruded 7075 aluminum alloy bar on the flow stress behavior. Taheri-Mandarjani et al. studied the ductility behavior of extruded 7075 aluminum alloy using the tensile testing method. Yan et al. investigated the flow stress behavior and microstructural evolution of Al-6.2Zn-0.70Mg-0.3Mn-0.17Zr alloy during the hot deformation process using hot compression test. Mirzadeh explored the hot working behavior of 7075 aluminum alloys and established physically-based constitutive equations for this material. Using the developed processing map based on flow localization parameter, Jenab and Taheri revealed the thermomechanical behavior of as-extruded 7075 aluminum alloy and obtained the reasonable range of deformation temperature and strain rate by analyzing the deformed microstructure of different areas in the processing map. But the above studies all focus on deformed aluminum alloy which has obvious different hot deformation behavior compared with as-cast aluminum alloy. So the motivation of this work is to establish processing map of as-cast 7075 aluminum alloy during hot plastic deformation based on DMM, consequently to provide a basis for planning and optimizing some advanced shot-process metal forming processes such as profile extrusion based on as-cast billet.

In this work, firstly, the true stress–strain curves under different deformation conditions have been obtained by thermal compression tests on Gleeble thermal simulator. Secondly, the appropriate instability criterion is selected according to the crack prediction ability, then we establish the hot processing map of as-cast 7075 aluminum alloy-based DMM model. Lastly, a suitable working window for as-cast 7075 aluminum alloy has been suggested through analyzing the deformed microstructure of different deformation areas in the processing map.

2. Experimental

The experimental material used is the industrial 7075 aluminum alloy ingot prepared by the same level hot-top casting whose chemical compositions are shown in Table 1. The sizes of the used cylindrical compression specimens, randomly taken from arbitrary positions in the axial direction of the ingot, are 10 mm in diameter and 15 mm in height. The isothermal compression tests were conducted on the Gleeble1500 thermal simulator at temperatures of 300–500 °C and strain rates of 0.01–10 s−1 to a height reduction of 50% (strain is 0.7). The microstructure after deformation was observed on Leica DMI3000 M optical microscope. The initial microstructure of the alloy before compression presents a dendritic network structure with rods’ second phase distributing on the material matrix, as shown in Fig. 1.

3. Results and discussion

3.1. True stress–strain curves

The hot processing map based on DMM is usually established by a superimposition of power dissipation map and instability map developed from calculating the data of true stress–strain curves. Therefore, the true stress–strain curves (see Fig. 2) of as-cast 7075 aluminum alloy at different temperatures (T) and strain rates have been obtained from the isothermal hot compression tests in order to establish the hot processing map of the material. The flow stress increases sharply until a peak stress with the increase of the strain at the early deformation stage, and then slightly decreases as a result of the dynamic softening. And the flow stress increases with decreasing the deformation temperature and increasing the strain rate. And it can be seen from Fig. 2(d) that the stress–strain curves appear fluctuation when the temperature is higher than 350 °C. This may be the result from combined action of the second phase particles’ strengthening and dynamic recovery softening.

Fig. 3 shows the true stress–strain curves of as-forged 7075 aluminum alloy at strain rates of 0.1 and 1 s−1 in Ref. Compared with Figs. 2 and 3 shows that the peak stress and the corresponding strain of as-forged 7075 aluminum alloy are larger than those of as-cast 7075 aluminum alloy at the same deformation temperature and strain rate. This is because the as-forged alloy usually has higher dislocation density and storage energy resulting from plastic deformation. Besides, the loose and inhomogeneous structure of as-cast 7075 aluminum alloy also leads to the lower strength level.

3.2. Establishment of hot processing map for as-cast 7075 aluminum alloy

3.2.1. Power dissipation map

The DMM theory claims that (1) the material under deformation is a nonlinear energy dissipation body; (2) the total energy (P) absorbed by the material can be divided into two parts: the first part is called dissipation energy (G content) which is used to produce plastic deformation and another part is called complementary dissipation energy (J co-content) which is used to produce material microstructure evolution. According to the above theory, the relationship between the total energy P, J co-content and G content can be expressed as

| Table 1 Chemical compositions of as-cast 7075 aluminum alloy. |
|-------------------|---|---|---|---|---|---|---|---|---|
| Composition       | Cu | Mg | Mn | Fe | Si | Zn | Cr | Ni | Ti |
| Content (wt%)     | 1.58 | 2.51 | 0.23 | 0.28 | 0.1 | 5.75 | 0.211 | < 0.001 | 0.06 |
\[ P = \sigma \dot{\varepsilon} = G + J = \int_0^{\dot{\varepsilon}} \sigma d\dot{\varepsilon} + \int_0^\infty \dot{\varepsilon} d\sigma \]  

where \( \sigma \) is true stress and \( \dot{\varepsilon} \) strain rate. The distribution relationship between \( J \) co-content and \( G \) content is decided by the strain rate sensitivity \( m \), which is expressed by

\[ m = \frac{\partial J}{\partial G} = \frac{\partial \ln \sigma}{\partial \ln \dot{\varepsilon}} \]

Meanwhile, the efficiency factor of power dissipation \( \eta \) is defined as

\[ \eta = \frac{2m}{m + 1} \]

The greater the \( \eta \) value, the better the formed microstructure can be improved, which may lead to dynamic recovery or dynamic recrystallization and local flow instability. The power dissipation map is built by the contour map of \( \eta \) with the variation of temperature and strain rate. The calculated values of power dissipation efficiency factor at strain of 0.7 from true stress–strain data at different temperatures and strain rates are shown in Table 2. So the power dissipation map has been built as shown in Fig. 4. It can be seen that the efficiency factor \( \eta \) of power dissipation has higher values in the temperature range of 400–500 °C and strain rate range of 0.01–1 s\(^{-1}\). This indicates that in the above temperature and strain range, the as-cast microstructure of 7075 aluminum alloy is most possibly improved due to dynamic recovery or dynamic recrystallization although local flow instability may occur.

### 3.2.2. Instability map

Though the power dissipation map can reflect the microstructure evolution to some extent under different compression conditions, the adverse micro-mechanism such as dynamic strain aging and adiabatic shear band during the hot working is difficult to be reflected in the power dissipation map. Therefore, it is necessary to establish the processing instability map by which the working instability area of the alloy can be determined.

In most literature, only one instability criterion was usually used to establish the instability map of materials. However, the work carried out in literature demonstrated that the proper instability criterion should be selected according to experimental results about unstable plastic flow during hot plastic forming process. Therefore, in consideration of the fea-

![Fig. 1 Raw microstructure of as-cast 7075 aluminum alloy.](image1)

![Fig. 2 True stress–strain curves of as-cast 7075 aluminum alloy.](image2)
ture of being easy to crack of as-cast 7075 aluminum alloy, the appropriate instability criteria have been selected by comparing the crack prediction ability of different plastic flow instability criteria. And then the instability map of as-cast 7075 aluminum alloy has been established based on the selected instability criteria. The main flow instability criteria are as follows:

(1) Prasad instability criterion

According to the principle of maximum entropy production rate, Prasad and Seshacharyulu\(^{14}\) gave the following instability criterion expressed by

\[
\zeta(\dot{\varepsilon}) = \frac{\partial \ln(m/m + 1)}{\partial \ln \dot{\varepsilon}} + m < 0
\]  

So the instability map based on the Prasad instability criterion can be plotted according to the function of \(\zeta(\dot{\varepsilon})\) correlating to temperature and strain rate based on the processing map data in Table 2. The area with positive values of \(\zeta(\dot{\varepsilon})\) in the instability map represents stable area, as shown in Fig. 5(a).

(2) Murthy instability criterion

For the case of non-constant strain rate sensitivity parameter \(m\), Murthy and Rao\(^{21}\) proposed the instability criterion which is applicable of any type of \(\sigma-\varepsilon\) curves:

\[
2m < \eta \leq 0
\]  

Table 2  Possessing map data of as-cast 7075 aluminum alloy.

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>Strain rate (s(^{-1}))</th>
<th>Power dissipation efficiency factor (\eta)</th>
<th>Prasad</th>
<th>Murthy</th>
<th>Gegel A</th>
<th>Gegel B</th>
<th>Gegel C</th>
<th>Malas</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>0.01</td>
<td>19.763</td>
<td>0.102</td>
<td>0.110</td>
<td>-0.369</td>
<td>-0.093</td>
<td>0.948</td>
<td>-0.002</td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>17.852</td>
<td>0.015</td>
<td>0.0436</td>
<td>-3.401</td>
<td>-0.314</td>
<td>0.793</td>
<td>-0.021</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>12.606</td>
<td>-0.166</td>
<td>-0.093</td>
<td>-6.774</td>
<td>-0.227</td>
<td>0.751</td>
<td>-0.039</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>4.4669</td>
<td>-0.466</td>
<td>-0.423</td>
<td>-5.204</td>
<td>0.546</td>
<td>0.562</td>
<td>-0.027</td>
</tr>
<tr>
<td>350</td>
<td>0.01</td>
<td>17.713</td>
<td>0.210</td>
<td>0.097</td>
<td>4.639</td>
<td>0.093</td>
<td>0.825</td>
<td>0.028</td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>22.084</td>
<td>0.121</td>
<td>0.175</td>
<td>-0.153</td>
<td>0.068</td>
<td>0.811</td>
<td>-0.001</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>16.44</td>
<td>-0.202</td>
<td>-0.066</td>
<td>-11.028</td>
<td>0.095</td>
<td>0.605</td>
<td>-0.065</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>-0.082</td>
<td>-1.487</td>
<td>-1.011</td>
<td>-12.198</td>
<td>0.168</td>
<td>0.575</td>
<td>-0.061</td>
</tr>
<tr>
<td>400</td>
<td>0.01</td>
<td>18.677</td>
<td>0.246</td>
<td>0.221</td>
<td>6.200</td>
<td>0.165</td>
<td>1.080</td>
<td>0.0378</td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>25.130</td>
<td>0.165</td>
<td>0.008</td>
<td>1.227</td>
<td>-0.320</td>
<td>0.898</td>
<td>0.008</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>20.178</td>
<td>-0.127</td>
<td>-0.012</td>
<td>-11.085</td>
<td>-0.308</td>
<td>0.535</td>
<td>-0.068</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>2.776</td>
<td>-1.796</td>
<td>-0.729</td>
<td>-13.181</td>
<td>0.228</td>
<td>0.407</td>
<td>-0.068</td>
</tr>
<tr>
<td>450</td>
<td>0.01</td>
<td>18.055</td>
<td>0.389</td>
<td>0.075</td>
<td>0.099</td>
<td>0.560</td>
<td>1.316</td>
<td>0.075</td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>31.670</td>
<td>0.255</td>
<td>0.034</td>
<td>4.854</td>
<td>0.218</td>
<td>1.107</td>
<td>0.034</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>26.969</td>
<td>-0.077</td>
<td>0.047</td>
<td>-14.419</td>
<td>0.318</td>
<td>0.909</td>
<td>-0.096</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>1.605</td>
<td>-4.112</td>
<td>-0.874</td>
<td>-20.674</td>
<td>0.843</td>
<td>0.447</td>
<td>-0.106</td>
</tr>
<tr>
<td>500</td>
<td>0.01</td>
<td>0.435</td>
<td>11.188</td>
<td>0.002</td>
<td>27.310</td>
<td>4.678</td>
<td>1.823</td>
<td>0.138</td>
</tr>
<tr>
<td></td>
<td>0.1</td>
<td>29.677</td>
<td>0.344</td>
<td>0.606</td>
<td>11.562</td>
<td>0.441</td>
<td>2.858</td>
<td>0.080</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>24.713</td>
<td>-0.248</td>
<td>-0.007</td>
<td>-22.072</td>
<td>0.831</td>
<td>3.356</td>
<td>-0.144</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>-20.197</td>
<td>0.845</td>
<td>-14.470</td>
<td>-40.809</td>
<td>5.7801</td>
<td>5.041</td>
<td>-0.170</td>
</tr>
</tbody>
</table>

Fig. 3  True stress–strain curves of as-forged 7075 aluminum alloy.
The parameter $\eta$ is power dissipation efficiency factor. So the instability map based on Murthy instability criterion can be plotted based on the processing map data in Table 2, as shown in Fig. 5(b).

(3) Gegel instability criterion

Gegel\textsuperscript{22} proposed three instability criteria which are called Gegel A, Gegel B and Gegel C in this work:

Gegel A:

$$\frac{\partial n}{\partial \ln \varepsilon} > 0$$

(6)

Gegel B:

$$\frac{\partial \alpha}{\partial \ln \varepsilon} > 0$$

(7)

Gegel C:

$$s = \frac{1}{T} \left\{ \frac{\partial \ln \sigma}{\partial (1/T)} \right\}_{\varepsilon_0} < 1$$

(8)

The parameter $s$ is temperature sensitivity. So the instability maps based on the Gegel A, Gegel B and Gegel C instability criteria can be plotted based on the processing map data in Table 2, as shown in Fig. 5(c)–(e), respectively.

(4) Malas instability criterion

Malas and Seetharaman\textsuperscript{23} proposed another instability criterion expressed by

$$\frac{\partial n}{\partial \ln \varepsilon} > 0$$

(9)

So the instability map based on Malas instability criterion can be plotted according to the processing map data in Table 2, as shown in Fig. 5(f).

In Fig. 5, the points (A–E) represent the deformation conditions under which the compressed samples produce cracks as shown in Fig. 6. This indicates that unstable plastic flow occurs under the deformation conditions represented by those points (A–E).

From Fig. 5(a) and (b), we can see that the red point $A$ locates in stable areas of the instability maps based on Prasad and Murthy instability criteria. But the unstable plastic flow occurs under the deformation condition represented by red point $A$ because the compressed sample produces crack, as shown in Fig. 6(a). This indicates that the instability maps based on the Prasad and Murthy instability criteria cannot predict unstable plastic flow under the deformation condition represented by red point $A$. For the same reason, the instability map based on Gegel A cannot predict the unstable plastic flow under the deformation conditions represented by red point $E$ (Fig. 5(e)); the instability map based on Gegel B cannot predict the unstable plastic flow under the deformation condition represented by red point $E$ (Fig. 5(d)); the instability map based on Gegel C cannot predict the unstable plastic flow under the deformation conditions represented by points $A$, $B$, $C$ and $D$ (Fig. 5(c)); the instability map based on Malas cannot predict the unstable plastic flow under the deformation conditions represented by points $A$, $B$, $C$ and $D$ (Fig. 5(f)).

From the above analysis, we can know that the instability maps based on Prasad, Murthy and Gegel B instability criteria have better abilities of predicting unstable plastic flow due to least instability points (only point $A$ or $E$) locating in their stable areas. Considering that the theoretical derivation of Murthy instability criterion is stricter than Prasad instability criterion,\textsuperscript{20} we have established instability map of as-cast 7075 aluminum alloy, as shown in Fig. 7, by the superposition of the instability maps based on Murthy and Gegel B instability criteria. In the stable area of the developed instability map of as-cast 7075 aluminum alloy, all instability points are removed, so it has more comprehensive ability of predicting unstable plastic flow.

3.2.3. Processing map

The hot processing map of as-cast 7075 aluminum alloy based on DMM with a strain of 0.7 has been established by a superimposition of the power dissipation map (see Fig. 4) and instability map (see Fig. 7), as shown in Fig. 8.

3.3. Analysis of processing map of as-cast 7075 aluminum alloy

According to the microstructure characteristics and whether plastic flow is stable or not, the hot processing map of as-cast 7075 aluminum alloy can be divided into five areas: stable area with as-cast grain ($A'$), stable area with homogeneous grain resulting from dynamic recovery ($B'$), instability area with as-cast grain ($C'$), instability area with the second phase ($D'$), and instability area with mixed grains ($E'$).

In the stable area ($A'$) of the processing map, the typical metallographic microstructure, obtained at a temperature of 400°C and strain rate of 0.1 s\textsuperscript{−1}, is shown in Fig. 9. We can see that it still remains dendrite network structure like the initial as-cast microstructure. So, it is not suitable to deform the alloy under the deformation conditions located in area $A'$, because the as-cast microstructure cannot be eliminated effectively although unstable plastic flow cannot occur.

In the stable area $B'$ of the processing map, the typical metallographic microstructures of the deformed alloy, obtained at the temperature of 450°C and strain rates of 0.01, 0.1, 1 s\textsuperscript{−1}, are shown in Fig. 10. We can observe that (1) the as-cast dendritic microstructures have been fully eliminated; (2) the microstructure and grain boundaries are clear; and (3) the
dynamic recrystallization phenomenon seems not apparent, but the microstructure presents typical dynamic recovery characteristics and the grain size is uniform. The alloy deformed in area \( B \) of the processing map not only can get uniform microstructure but also has the as-cast microstructure defects eliminated effectively by dynamic recovery.\(^1\) Therefore, the stable area \( B \) with homogeneous grain resulting from dynamic recovery, namely the temperatures at 425–465 °C and the strain rates at 0.01–1 s\(^{-1}\), is suitable processing area for the as-cast 7075 aluminum alloy.

In the instability area \( C \) of the processing map, the typical metallographic microstructure of the deformed alloy, obtained
at the temperature of 400 °C and strain rate of 10 s⁻¹, is shown in Fig. 11(a). We can see that it still remains dendrite network structure like the initial as-cast microstructure. Fig. 11(b) shows the deformed compression sample, which has a plicated and rough surface indicating a cracking trend. The reason is that the as-cast 7075 aluminum alloy is easier to generate damage for high deformation resistance at the temperature of 400 °C and strain rate of 10 s⁻¹ as shown in Fig. 2(d). Thus it is not suitable to deform the alloy under the deformation conditions locating in the instability area D₀ of the processing map due to the as-cast microstructure like the initial billet and possible plastic flow instability.

In the instability area D₀ of the processing map, the typical metallographic microstructure (see Fig. 12) of the deformed alloy, obtained at the temperature of 450 °C and strain rate of 10 s⁻¹, illustrates that no obvious recrystallization phenomenon occurs. A large amount of the second-phase presenting gathered state is distributed along grain boundaries. These unevenly distributed second phases not only lead to uneven microstructure of the deformed alloy but also become stress

at the temperature of 400 °C and strain rate of 10 s⁻¹.
concentration area and crack source during deformation, which will reduce the plasticity and toughness of alloy and generate plastic flow instability. The evidence is that the compressed sample under the same deformation condition produces crack, as shown in Fig. 6(e). Thus it is not suitable to deform the alloy under the deformation conditions locating in the instability area $E$ of the processing map.

In the instability area $E$ of the processing map, the typical metallographic microstructures (see Fig. 13) of the deformed samples illustrate that obvious recrystallization phenomenon occurs because the fine dynamic recrystallization grains can be observed clearly in grain boundaries. But the degree of the dynamic recrystallization is small, so the microstructure of the deformed samples is very uneven due to the mixture of fine dynamic recrystallization grains and original coarse grains of the billet. This will reduce the formability of the materials and lead to unstable plastic flow easily. The evidences are that the compressed samples under the same deformation conditions produce cracks, as shown in Fig. 6(b) and (d). Thus it is not suitable to deform the alloy under the deformation conditions locating in the instability area $E$ of the processing map.

On the basis of the above analysis of the microstructure characteristics of the samples deformed in the five areas of the established processing map, the stable area with homogeneous grain resulting from dynamic recovery, namely the temperatures at 425–465 °C and the strain rates at 0.01–1 $s^{-1}$, is
suggested to be the suitable processing window for the as-cast 7075 aluminum alloy.

4. Conclusions

(1) The true stress–strain curves at temperatures of 300–500 °C and strain rates of 0.01–10 s⁻¹ are obtained by the isothermal compression tests, providing a data basis for the establishment of hot processing map of as-cast 7075 aluminum alloy. Compared with as-forged 7075 aluminum alloy, the peak stress and the corresponding strain of as-cast 7075 aluminum alloy are smaller under the same deformation temperature and strain rate.

(2) The prediction abilities of cracks of different instability criteria are compared by compression tests. The results show that the Murthy and Gegel B instability criteria have better crack prediction abilities. Thus the instability map of as-cast 7075 aluminum alloy with comprehensive crack prediction ability has been developed by the superposition of the instability maps based on Murthy and Gegel B instability criteria.

(3) The hot processing map of as-cast 7075 aluminum alloy has been established by superimposing the instability map on the power dissipation map. According to the microstructure characteristics of compressed samples and whether plastic flow is stable or not, it can be divided into five areas: stable area with as-cast grain, stable area with homogeneous grain resulting from dynamic recovery, instability area with as-cast grain, instability area with the second phase, and instability area with mixed grains.

(4) In terms of the microstructure characteristics of the samples deformed in the five areas of the established processing map, the stable area with homogeneous grain resulting from dynamic recovery, namely the temperatures at 425–465 °C and the strain rates at 0.01–1 s⁻¹, is suggested to be the suitable processing window for the as-cast 7075 aluminum alloy.

Acknowledgments

This work was financially supported by the National Science and Technology Major Project of China (No. FP7-People-2012-IRSES-318968) and the “111” Project of China (No. B08040).

References

9. Yan J, Pan QL, Li B, Huang ZQ, Liu ZM, Yin ZM. Research on the hot deformation behavior of Al–6.2Zn–0.70Mg–0.3Mn–0.17Zr alloy using processing map. J Alloys Compd 2015;632:549–57.


Guo Lianggang is an associate professor at Northwestern Polytechnical University. He mainly focuses on some special forming processes such as ring rolling and extrusion for difficult-to-deform materials which are widely used in the aerospace industry. In addition, his research interest is intelligent modeling and simulation of an entire manufacturing process for core aerospace components with key fundamental materials.

Yang He is the President of China Society for Technology of Plasticity, “Cheung Kong” Chair Professor, Professor and Chairman of the Department of Materials Forming and Control Engineering at Northwestern Polytechnical University. His main research interests include control of unequal deformation via local-loading, precise/high-efficiency/load-saving plastic forming of difficult-to-deform materials, precision forming for large-scale complex and lightweight components, and digital precision plastic forming based on multi-scale modeling and simulation.