Adiabatic shearing behavior of different steels under extreme high shear loading
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Carbon steel is widely applied for a diverse range of applications within a variety of different fields, including the structural elements, the automotive industry and the nuclear power plants, for example. Typical applications in nuclear power plants include the reactor, the cooling water system, metallic containers and piping systems. Shear band formation is a complex function of strain, strain rate and temperature. Shear bands have been observed in many practical applications involving high-speed deformation, including machining, ballistic penetration, and high-speed forming. Hence, many investigations into adiabatic shear band formation have been published over the past 20 years or so. Since steel is the most widely used of all metals and finds application in a huge number of fields, developing a detailed insight into the formation of adiabatic shear bands in steel materials is highly desirable.
The carbon steels investigated in the present study were all received in plate form with a thickness of 32 mm. The compositions of the three steels satisfy the JIS code for S15C, S50C and SKS93, and are similar to AISI 1015, AISI 1050 carbon steels and AISI W4 tool steel, respectively. The current hat-shaped specimens were machined from the annealed plates with the dimensions shown in Fig. 1(a). As in the compressive SHPB experiment presented in by the current authors, the specimens were sandwiched between the incident and transmitted bars of the SHPB apparatus, as shown in Fig. 1(b). In the current tests, the specimens were deformed at strain rates of $5.0 \times 10^4 \text{s}^{-1}$, $1.0 \times 10^5 \text{s}^{-1}$ and $2.0 \times 10^5 \text{s}^{-1}$, respectively, under a fixed displacement of $D= 0.7 \text{ mm}$, resulting in the formation of shear bands in the shear zones. As shown in Figs. 1(c) and 1(d), specimen fracture (i.e. cracking) is constrained to the region immediately ahead of the tail ends of the adiabatic shear bands.

Fig. 2(a) presents the stress-displacement curves of the S15C, S50C and SKS93 steels under strain rates of $5.0 \times 10^4 \text{s}^{-1}$ and $2.0 \times 10^5 \text{s}^{-1}$, respectively. The curves show that each steel is work softened after it initially yields, but subsequently work hardens until a stress drop is induced by adiabatic heating. The abrupt increase in stress observed at the final stage of the deformation process is caused by the impact of the incident bar on the spacer ring. It is apparent that the flow stress of each steel increases with increasing strain rate. Moreover, it can be seen that an increased carbon content leads to a more significant strengthening effect during the dynamic shearing deformation process. Regarding the increased shear stress induced at higher strain rates, it is found that the steel with a higher carbon content is more sensitive to the strain rate. Fig. 2(b) plots $\Delta T$ as a function of the nominal shear strain for the three tested steels. According to the present experimental data, the duration of the deformation process is less than $100 \mu\text{sec}$. Therefore, the deformation of the steel within the shear band generates a huge temperature rise over a very short period of time. From Fig. 2(b), it can be seen that $\Delta T$ increases with increasing carbon content, strain rate and strain.

![Fig. 2](image.png)

**Fig. 2** (a) Stress-displacement curves of three carbon steels under strain rates of $5.0 \times 10^4 \text{s}^{-1}$ and $2.0 \times 10^5 \text{s}^{-1}$, respectively; (b) calculated average temperature rise within shear band.

Table 1 summarizes the width and average hardness of the shear bands formed in the three specimens.
under each of the loading conditions. It is observed that the bandwidth decreases with an increasing carbon content and strain rate, whereas the average hardness increases. The optical micrographs presented in Figs. 3(a) and 3(b) show that the shear bands formed in the S15C and S50C specimens at a strain rate of 1.0×10^5s^-1 are broadly similar. However, the microstructure of the shear band formed in the SKS93 steel specimen at the same strain rate is markedly different (see Fig. 3(c)). Specifically, the shear flow slip lines are not so well developed, and the higher carbon content results in a proliferation of microcracks and micropores, which grow and coalesce, prompting a higher degree of cracking.

Comparing the shear band morphologies of the three carbon steels shown in Fig. 3, it is seen that the S50C and SKS93 specimens contain both deformed and martensitic transformed bands, while the S15C specimen has only a deformed band. In Fig. 3(a), the elongation and distortion of the ferrite grains in the S15C specimen become more pronounced towards the center of the shear band. The distortion angle (θ), defined and plotted on the micrograph, increases from 40° to 84° as the measurement point is shifted from B to A. A similar phenomenon is also found in the S50C and SKS93 specimens, as shown in Figs. 3(b) and 3(c), respectively. The local shear strain (γ) can be defined as γ=\tanθ. Applying this definition, the maximum local strain, which occurs near the center of the transformed band, of the S50C and SKS93 steel specimens is found to exceed 70. Similarly, the maximum local shear strain in the S15C specimen, located in the center of the deformed band, is approximately 10. Mechanical twins are observed in the S15C low carbon steel specimen sheared at a strain rate of 2.0×10^5s^-1, as shown in Fig. 4. In Fig. 4(a) several twins (indicated by the arrows) are evident; located at approximately 60 μm from the center of the shear band. Figure 4(b) presents a high-magnification view, while Fig. 4(c) shows the TEM diffraction pattern of the twins (T) shown in Fig. 4(a). It is known that a small grain size limits the development of twins. The ferrite grain sizes of low carbon steel, medium carbon steel and high carbon steel are approximately 35 μm, 25 μm and 18 μm, respectively. Thus, twins are found only in the S15C low carbon steel specimens.

Table 1. Width and average hardness of shear bands in three steel specimens.

<table>
<thead>
<tr>
<th>Steels</th>
<th>5.0×10^4s^-1</th>
<th>1.0×10^5s^-1</th>
<th>2.0×10^5s^-1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Width μm</td>
<td>Hardness Hv</td>
<td>Width μm</td>
</tr>
<tr>
<td>S15C</td>
<td>242</td>
<td>265</td>
<td>213</td>
</tr>
<tr>
<td>S50C</td>
<td>219</td>
<td>310</td>
<td>196</td>
</tr>
<tr>
<td>SKS93</td>
<td>171</td>
<td>351</td>
<td>154</td>
</tr>
</tbody>
</table>
Fig. 3 Micrographs of adiabatic shear bands in: (a) S15C, (b) S50C and (c) SKS93 steel specimens under strain rate of $1.0 \times 10^5 \text{s}^{-1}$.

Fig. 4 (a) Micrograph of mechanical twins in S15C specimen under strain rate of $2.0 \times 10^5 \text{s}^{-1}$; (b) high-magnification view of specimen shown in (a); (c) TEM diffraction pattern of twins shown in (a).

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