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The study of work hardening in Fe–Mn–Al–C alloys

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Three austenitic Fe–Mn–Al–C alloys with different aluminium content from 0, 5.1 and to 8.5 wt% are chosen for the present work hardening study. Serrated stress-strain curves with pronounced work hardening were observed during tensile testing, also the serration of stress–strain curve is found to be decreasing as the increase of aluminium content. The serration can, however, still be observed even if the aluminium content is increased to as much as 8.5 wt%. According to morphology studies and electron microscopic investigations, it is found that strain-induced deformation twins are closely related to the work hardening in the present alloys. Therefore, deformation twinning is strongly suggested as a major cause of work hardening in Fe–Mn–Al–C alloys, and also plays an important role on the serration of stress–strain curve.

1. Introduction
The Fe–Mn–Al–C alloy system has been considered as a new family of high performance alloys with an outstanding combination of strength, toughness, workability, oxidation and corrosion resistance. Although the mechanical behaviour of these multi-purpose austenitic steels which include the strain hardening, strain ageing, fatigue fracture and stress corrosion cracking have been reported [1–4], the mechanism of deformation behaviour still remains uncertain. According to Kim's report [5], which indicates the low temperature mechanical properties of a series of Fe-30 Mn-5Al-0.3C-0.1X alloys, a special behaviour of increasing elongation with decreasing temperature can be observed. It is proposed that the behaviour is attributed to strain-induced mechanical twinning. Most studies [6–10] which discuss the work hardening with deformation twinning of the austenitic Fe–Mn–C alloys suggested that stacking fault–dislocation interactions are responsible for the rapid work hardening. However, some other studies [11–13] have proposed that the rapid work hardening in Hadfield manganese steel is due to the interaction of dislocations with carbon atoms in austenitic solid solution. Furthermore, the effect of aluminium content on the deformation behaviour is expected to be more complicated and important than was previously predicted in Fe–Mn–Al–C alloys.

The present study concentrates on the examination of tensile deformation curves and attempts to correlate this with the microstructure of the Fe–Mn–Al–C alloys. The final aim is to obtain a reasonable mechanism for the various work hardening phenomena of the Fe–Mn–Al–C alloys.

2. Experimental procedures
Three Fe–Mn–Al–C alloys were chosen for the present study with different aluminium content from 0, 5.1 and to 8.5 wt%. The chemical compositions of these alloys are listed in Table I. All alloys for the present studies were melted in an air induction furnace under a protective argon atmosphere. After homogenization, the cast alloys were hot forged at 1200° C. Plate-type testing specimens with a gauge length 25 mm were sectioned from the forged alloys and solution treated at 1100° C for 1.5 h. Tensile tests were carried out at room temperature with an Instron model 8031 testing machine at a strain rate of $4 \times 10^{-4}\,sec^{-1}$. After tensile testing, the fracture surface and microstructure were examined by using a scanning electron microscope (SEM) and an optical microscope. X-ray diffraction analysis was carried out on a computer-controlled diffractometer having a copper target. A thin foil for the transmission electron microscopic (TEM) investigation was prepared by using a double jet electropolisher with an electrolyte of 33% perchloric acid, 33% acetic acid and 34% ethyl alcohol. Electron microscopic studies were performed by using a JEOL-2000FX STEM operated at 200 kV.

3. Results and discussion
After solution treatment, the microstructure of all alloys was examined and confirmed by an optical microscope and an X-ray diffractometer to be fully austenitic. Fig. 1 shows the optical micrograph of alloy A where twins can be observed in the austenitic matrix. In general, it can be seen that the present

TABLE I Chemical composition of three Fe–Mn–Al–C alloys

Alloy	Composition (wt %)			
	Mn	Al	C	Fe
A	29.2	–	0.81	Bal.
B	30.9	5.1	0.88	Bal.
C	30.1	8.5	0.88	Bal.

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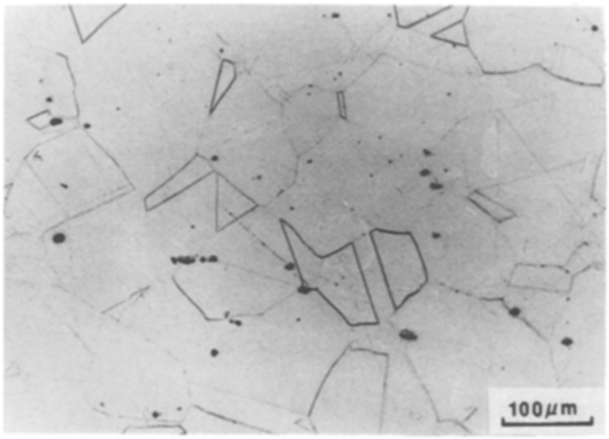

Figure 1 Optical micrograph of alloy A heat treated at 1100°C for 1.5 h and water quenched.

Fe–Mn–Al–C alloys have comparable low stacking fault energy [14]. Fig. 2 shows the tensile stress–strain curves of three alloys which were tested at room temperature. From the present results, these alloys show a very interesting behaviour that is the serrated flow in the jerky stress–strain curves. Also, the serration decreases in magnitude as the aluminium content is increased from alloy A (0%) to alloy C (8.5%). The same serrated behaviour was reported in Hadfield manganese steel [12], but it has been neglected in many previous Fe–Mn–Al–C alloys studied. The tensile properties of the three alloys are listed in Table II. The measurement of work hardening used in this study is defined as the difference in flow stress as plastic strain of 0.04 and 0.002 ($\Delta\sigma = \sigma_{0.04} - \sigma_{0.002}$). It shows that alloy A has a higher work hardening $\Delta\sigma$ than the other two alloys. Alloy A has a yield strength of 423 MPa and can reach an ultimate tensile strength of about 993 MPa. Also, among the present three alloys the work hardening $\Delta\sigma$ also decreases with increasing aluminium content. It is obvious that the aluminium atoms play an important role in the deformation behaviour of Fe–Mn–Al–C alloys under a solid solution condition. Elongation of these alloys is also shown in Table II. For all alloys, necking is very slight and sometimes it cannot be observed before tensile fracture even if the elongation is very high, and only a small necking can be observed for alloy C after tensile fracture as shown in Figs 3a and b.

TABLE II Tensile properties of three Fe–Mn–Al–C alloys

Alloy	σ_{UTS} (MPa)	$\sigma_{0.002}$ (MPa)	Elongation (%)	$\Delta\sigma$ (MPa)
A	993	423	72	168
B	841	435	59	124
C	814	440	58	106

From the tensile results, it indicates that the present Fe–Mn–Al–C alloys have a deformation behaviour with pronounced work hardening which is associated with serrated stress–strain curves, as per Hadfield manganese steel [12]. Many studies [14, 15] have shown that the increased work hardening which is associated with serrations can be attributed to an increased rate of dislocation multiplication, and the

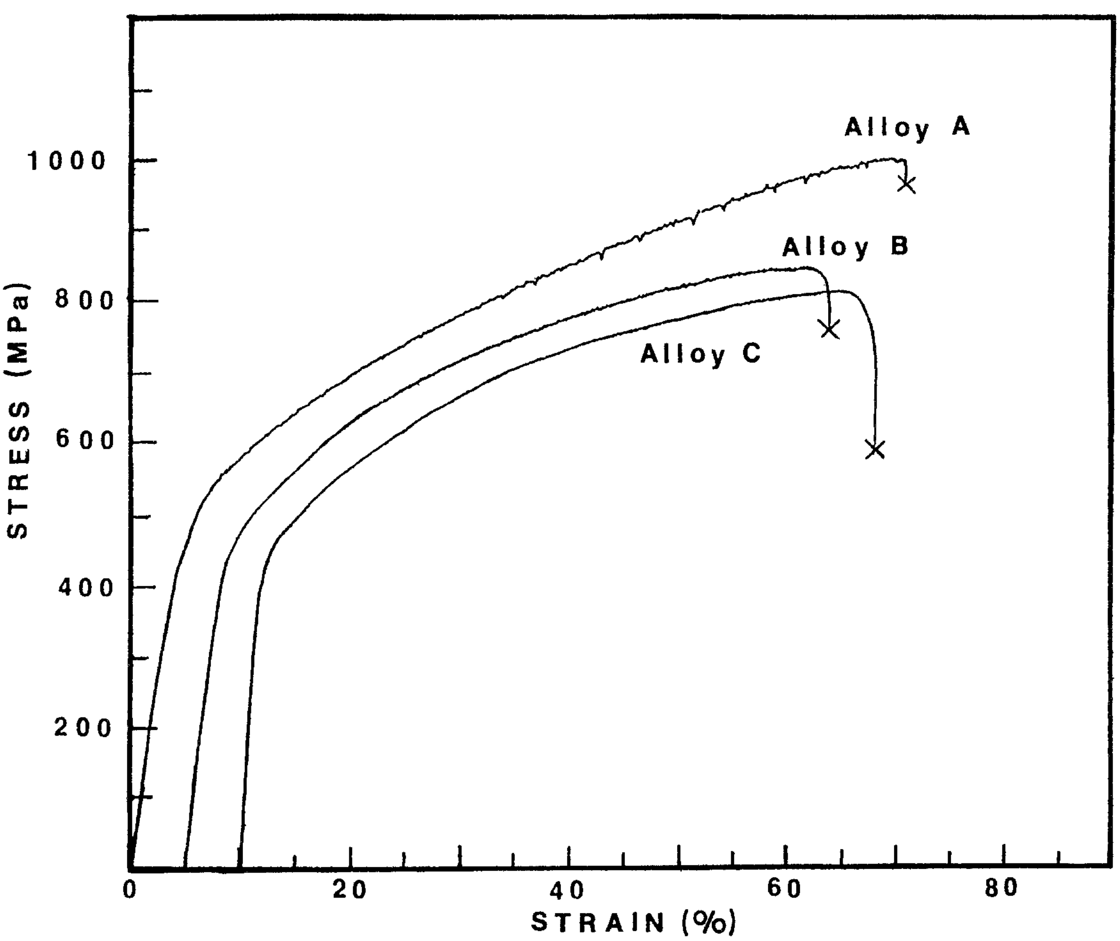

Figure 2 Engineering stress–strain curves of three Fe–Mn–Al–C alloys tested at 26°C. $\dot{\varepsilon} = 4 \times 10^{-4}\,\text{sec}^{-1}$.

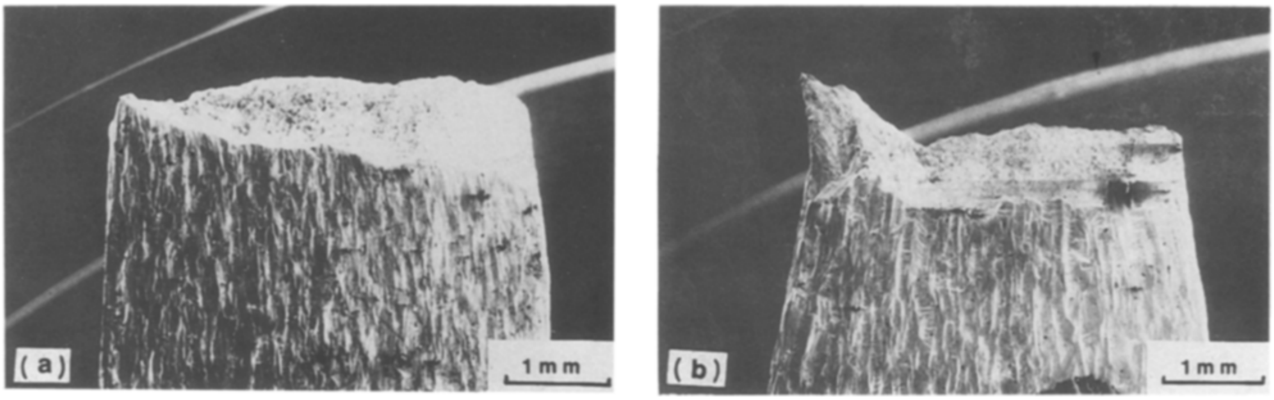

Figure 3 Necking of tensile test specimens. (a) Alloy A, (b) Alloy C.

increase of dislocation density can always offer a high stress. In detail, most studies [6–8] indicated that the work hardening is seen to be closely related to deformation twinning, and suggested that twins can act as strong obstacles to dislocation propagation. However, Dastur and Leslie [12] recently suggested that rapid work hardening is due to the dynamic strain ageing which is associated with the interactions between dislocations and Mn–C couples in a fcc matrix. As a result of the rapid pinning of dislocation and a special short-range diffusion of carbon within the cores of dislocations in a Fe–Mn–C alloy during plastic deformation, the work hardening is high. Therefore, their suggestions are concentrated on the mechanism by dynamic strain ageing instead of twinning. On the other hand, the low temperature work hardening behaviour of the Fe–Mn–C alloy which is associated with twin formation was proposed by Adler, Olson and Owen [10]; at that temperature range no dynamic strain ageing can be observed. In addition, the comparison between Fe–Mn–C alloys and low-carbon fcc alloys, such as Fe–Ni–C alloy, Co-33Ni alloy, indicated that the carbon atom did not play any special role on work hardening which was proposed by Dastur and Leslie [12].

In order to characterize the nature of the deformation behaviour of the present Fe–Mn–Al–C alloys, the specimens after a certain level of plastic deformation were further examined by using SEM and TEM. Figs 4a, b and c are the scanning electron micrographs of the free surface of fractured specimens. The strain markings and transgranular cracks can be observed. Figs 5a and b are the bright-field and dark-field TEM images of alloy A after 20% tensile

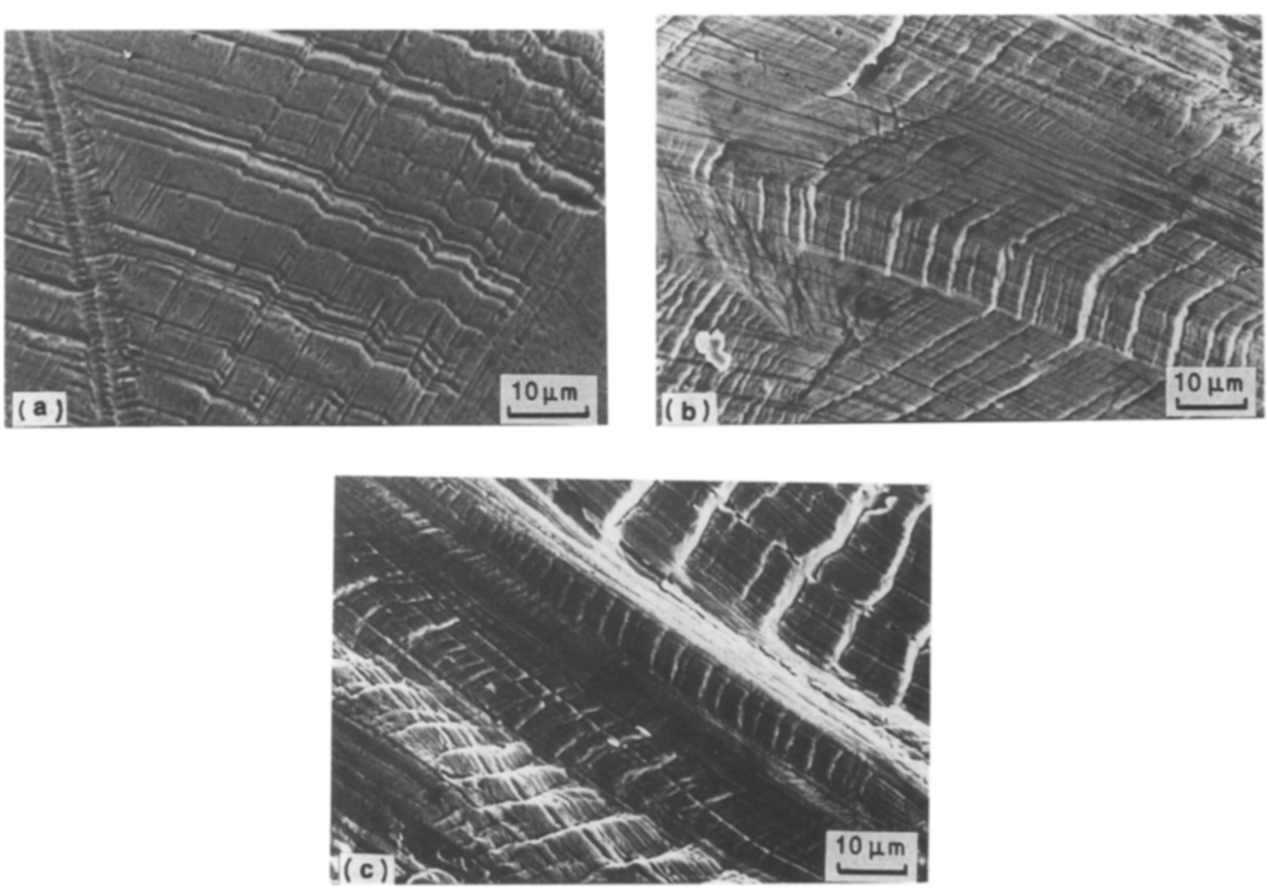

Figure 4 Scanning electron micrographs of free surface after tensile fractured. (a) Alloy A (b) Alloy B (c) Alloy C.

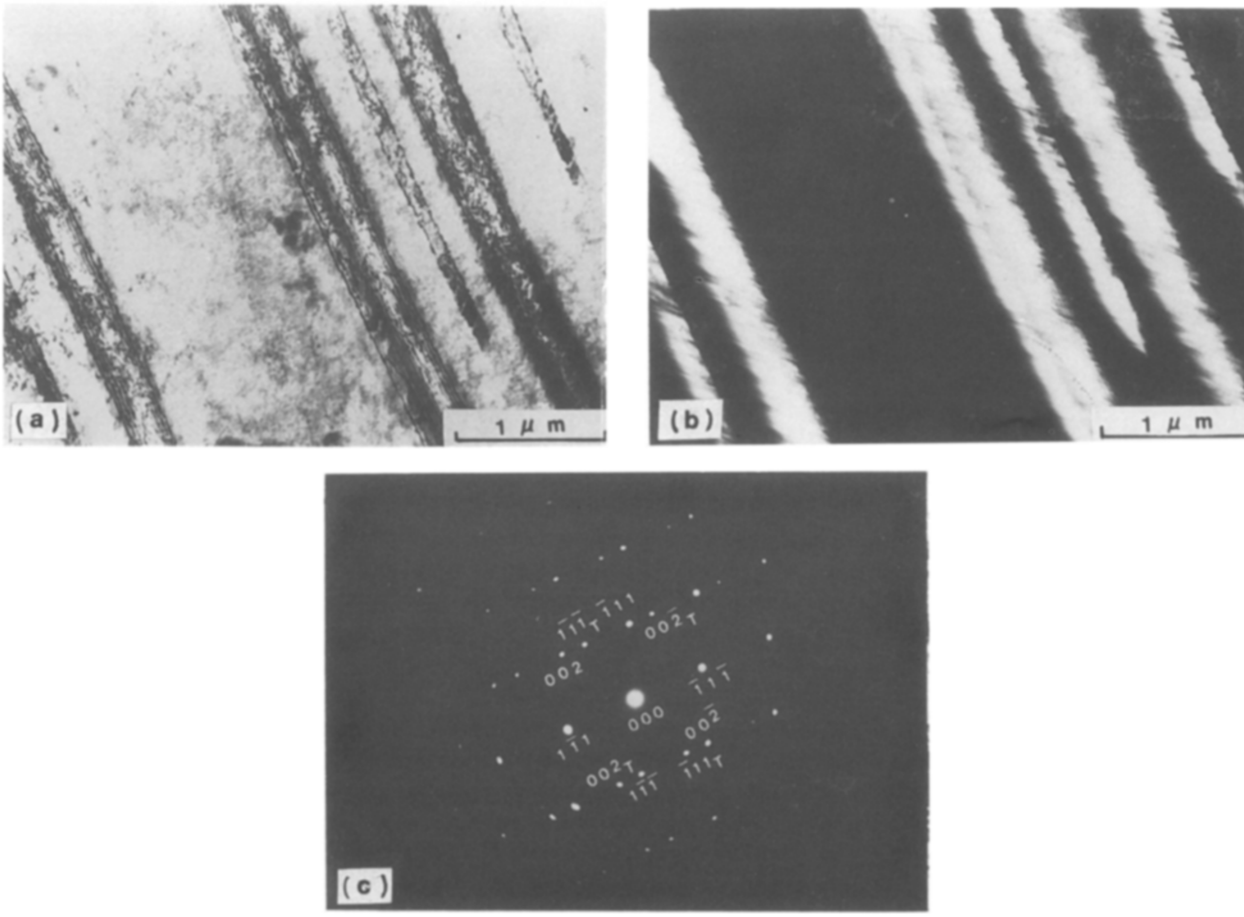

Figure 5 Transmission electron micrographs of alloy A strained 20% (a) Bright field image, (b) Dark field image, (c) Electron diffraction pattern of $(\bar{1}\,\bar{1}\,0)$ plane.

strain. There are many strain-induced deformation twins and small parallel lines can be observed. The appearance of those lines are investigated and seen to be the images of stacking fault. In general, those come from the dissociated dislocation. Fig. 5c shows a typical diffraction pattern of a twin with a twin axis $[1\,\bar{1}\,1]$ from the $[\bar{1}\,\bar{1}\,0]$ beam direction. The combinations of deformation twins with high density of tangle dislocations were also observed in alloys B and C as shown in Figs 6 and 7. It is reasonable to suggest that the formation of mechanical twins is closely related to the hardening behaviour, and it is consistent with Kim's observation [5]. The hardening contribution of twinning in fcc alloys has been modelled by Remy [7, 8], which used the role of coherent twin boundaries as slip obstacles in a manner equivalent to grain refinement. Also, the twin–slip and twin–twin interactions in fcc crystals has been discussed. In the present study, no strain-induced transformation of austenite to α' or ε martensite can be found in Fe–Mn–Al–C alloys by using an electron microscope or an X-ray diffractometer.

From the observations of high density of dislocations and deformation twins and the close relation between deformation twins and slip bands by using TEM and SEM technique, this provides a strong evidence that

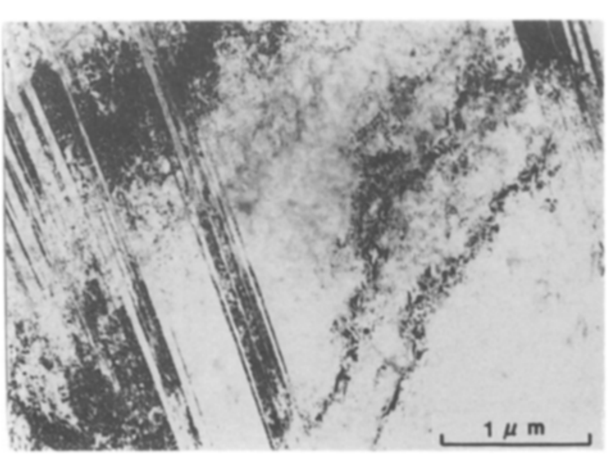

Figure 6 Transmission electron micrograph of alloy B strained 50%.

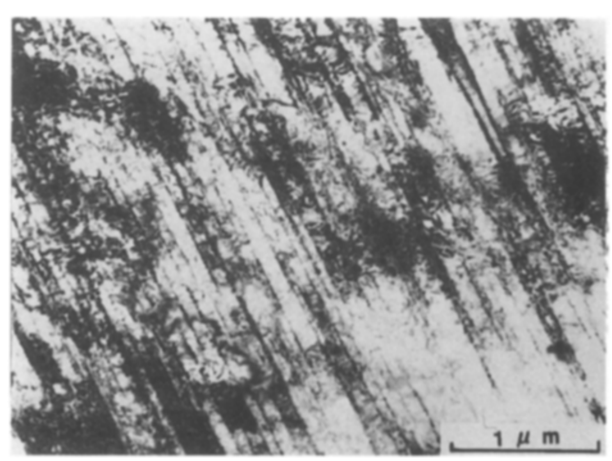

Figure 7 Transmission electron micrograph of alloy C strained 50%.

deformation twinning plays a major role in the hardening behaviour in the present Fe–Mn–Al–C alloys. However, it is still unknown how deep the mechanism of dynamic strain ageing which was proposed by Dastur and Leslie [12] is involved in the hardening behaviour of the present high-carbon Fe–Mn–Al–C alloys. More research work needs to be done to gain further understanding.

4. Conclusions

The conclusions are as follows.

(1) Serrated stress–strain curves with pronounced work hardening were observed during tensile testing in the present three Fe–Mn–Al–C alloys.

(2) Aluminium decreases the work hardening rate and the serration of stress–strain curve in the present Fe–Mn–Al–C compositions, but the serration can be still observed even the aluminium content is increased to as high as 8.5 wt %.

(3) Strain-induced deformation twins and twin–slip interactions are strongly suggested to play an important role on the work hardening behaviour in the present Fe–Mn–Al–C alloys.

(4) No strain-induced martensitic transformation can be found during plastic deformation in the present study.

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