JOURNAL OF MATERIALS SCIENCE 22 (1987) 4215–4220

# Fracture behaviour in tempered martensite embrittlement of medium-carbon alloy steels

KYO S. LEE
*Department of Die Design, Dae-Yu Technical College, Sungnam-City, Keunggi-Do, Korea*
HOON KWON, YANG C. LEE, JIN H. LEE, NAM D. CHO
*Department of Metallurgical Engineering, Kookmin University, Seoul, Korea*

The effect of alloying additions (nickel and silicon) on the fracture behaviour in tempered martensite embrittlement (TME) has been studied in commercial alloy steels. The fracture behaviour is analysed using the fractographs of the impact specimens tested at various temperatures. In 4140-Ni(4340) steel, where nickel-addition increases the intrinsic matrix toughness, the intergranular brittle type of TME is observed. In 4140-Si(4140 + 2Si) steel, where silicon-addition decreases the intrinsic matrix toughness, the intergranular brittle type of TME is also observed. The occurrence of the intergranular brittle type of TME is attributed to the activation of coarse grain-boundary carbides at the grain boundaries which the relatively high impurity content of commercial alloy steel renders impurer (i.e. weaker), despite relatively low intrinsic matrix toughness in 4140-Si steel.

## 1. Introduction

A drop in toughness after tempering in the temperature range 250 to 450° C in martensitic steels, even though the strength is decreased with increasing tempering temperature, has been referred to as tempered martensite embrittlement (TME). The brittle type of TME can be classified into intergranular and transgranular brittle types, the intergranular brittle type of TME being associated with the combined action of impurities and carbides at the grain boundaries [1–6], and the transgranular brittle type of TME being correlated with the interlath carbides [7–10]. On the other hand, TME is suggested to be dependent upon the plastic flow behaviour of the matrix with different carbide distributions [11, 12].

Recently, Kwon and Kim [13, 14] suggested that the fracture behaviour in TME, as well as the fracture behaviour itself, can be influenced by the variation in intrinsic matrix toughness with alloying additions in relatively high-purity ternary alloy steels. For the transgranular brittle type of TME, a relatively low level of intrinsic matrix toughness is necessary, at which the occurrence of transgranular brittle fracture is sensitive to the microstructural change with tempering. For the intergranular brittle type of TME, it is necessary for the intrinsic matrix toughness to reach a relatively high level at which the occurrence of intergranular brittle fracture is effectively activated in the presence of coarse grain-boundary carbides, compared to where there are few grain-boundary carbides.

If the impurity content is relatively high, however, the occurrence of intergranular brittle fracture can become relatively easy in the presence of coarse grain-boundary carbides, in spite of the relatively low intrinsic matrix toughness. Under these conditions, the intergranular brittle type of TME can occur if the intergranular brittle fracture can be effectively activated in the presence of coarse grain-boundary carbides, compared with where there are few grain-boundary carbides.

In this research, the fracture behaviour in TME with alloying additions (nickel and silicon), which can affect the intrinsic matrix toughness, has been analysed for commercial alloy steels containing a relatively high content of impurities.

## 2. Experimental procedure

The 4140-Ni(4340) and 4140-Si(4140 + 2Si) steels were prepared by alloying additions to 4140 steel. The alloy compositions are listed in Table I. Standard size Charpy V-notch impact specimens were made from the forged bar.

All specimens were austenitized at 1200° C for 1 h in a flowing argon atmosphere and then oil-quenched. The austenitized specimens were tempered in a neutral salt bath for 1 h in the temperature range 200 to 500° C, and then quenched in water.

For the investigation of fracture behaviour with test temperature, Charpy impact testing was conducted in the temperature range −196 to 15° C. The fracture surfaces were examined using Etec and Jeol scanning electron microscopes.

TABLE I Chemical compositions of alloys (wt %)

| Alloy designation | C | Ni | Si | Cr | Mn | Mo | P | S |
|---|---|---|---|---|---|---|---|---|
| 4140-Ni(4340) steel | 0.40 | 1.65 | 0.30 | 0.85 | 0.71 | 0.22 | 0.025 | 0.027 |
| 4140-Si steel | 0.41 | – | 1.96 | 0.85 | 0.71 | 0.22 | 0.025 | 0.027 |

0022–2461/87 $03.00 + .12 

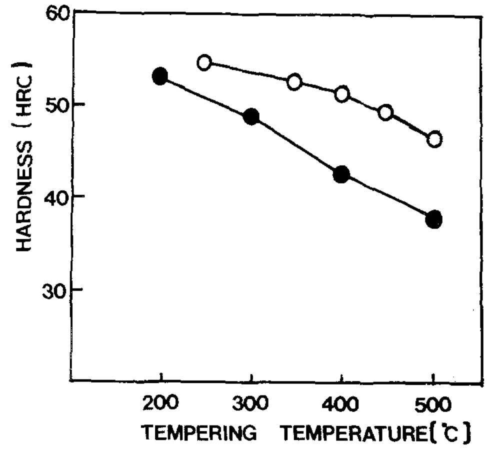



*Figure 1* Room-temperature hardness changes with tempering temperature in (●) 4140-Ni and (○) 4140-Si steels.

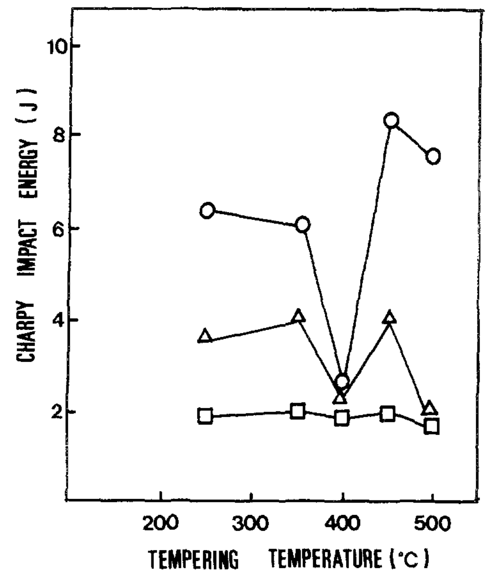



*Figure 3* Impact toughness changes with tempering temperature at various test temperatures in 4140-Si steel. (○) 15° C, (△) − 55° C, (□) − 196° C.

## 3. Results and discussion

### 3.1. Mechanical properties

Fig. 1 shows the room-temperature hardness changes with tempering temperature in 4140-Ni and 4140-Si steels. The decrease in hardness with increasing temperature in 4140-Si steel is smaller than that in 4140-Ni steel. This is attributed to the large resistance to softening with tempering in 4140-Si steel in which the addition of silicon delays the nucleation and growth of cementite.

Fig. 2 represents the impact toughness changes with tempering temperature at various test temperatures in 4140-Ni steel. The TME trough, which has a minimum impact toughness between 300 and 400° C tempered conditions, is distinctly observed at test temperatures of 15, − 55, and − 80° C. At a test temperature of − 196° C, however, a TME trough is not observed and the impact toughness stays at a low value of about 4 J with tempering temperature.

Fig. 3 show the impact toughness changes with tempering temperatures at various test temperatures in 4140-Si steel. A TME trough, which has a minimum impact toughness near 400° C tempered condition, is observed at test temperatures of 15 and − 55° C. At a test temperature of − 196° C, however, a TME trough is not observed and the impact toughness stays very low, about 2 J, with tempering temperature. In the 500° C tempered condition, there is a small drop in impact toughness at test temperatures of 15 and − 55° C, which indicates temper embrittlement.

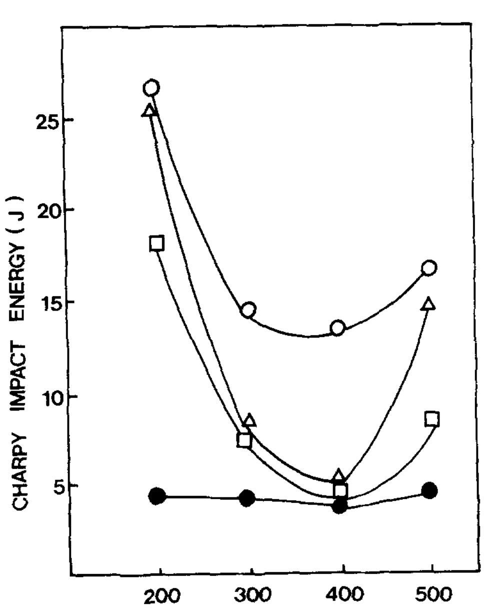



*Figure 2* Impact toughness changes with tempering temperature at various test temperatures in 4140-Ni steel. (○) 15° C, (△) − 55° C, (□) − 80° C, (●) − 196° C.

### 3.2. Fracture behaviour in TME

#### *3.2.1. 4140-Ni steel*

The fractographs at room temperature which indicate the tendency for the amount of intergranular brittle fracture to increase with increasing tempering temperature associated with TME, are shown in Fig. 4. In the 400° C tempered condition, intergranular brittle fracture mostly occurs.

Fig. 5 shows the fractographs at a test temperature of − 80° C, representing the same tendency as the fractographs in Fig. 4. Fractographs at a test temperature of − 196° C, in which the mostly transgranular brittle fracture in the 200° C tempered condition is changed to mostly intergranular brittle fracture in the 400° C tempered condition, are shown in Fig. 6. This means that the coarse grain-boundary carbides can play an important role in controlling the fracture behaviour in spite of no drop in impact toughness (i.e. no TME trough) at very low temperatures. In other words, the activation of coarse grain-boundary carbides for the intergranular brittle fracture can be effectively achieved even at very low test temperatures, because of the relatively high intrinsic matrix toughness with nickel-addition.

Thus, TME in 4140-Ni steel is the intergranular brittle type which can be produced in alloy steels having a relatively high intrinsic matrix toughness. The intergranular brittle fracture can be effectively activated by the coarse grain-boundary carbides formed in the tempering temperature range of TME, which increase the stress concentration susceptibility at the grain boundaries, compared to that at grain boundaries with few grain-boundary carbides.

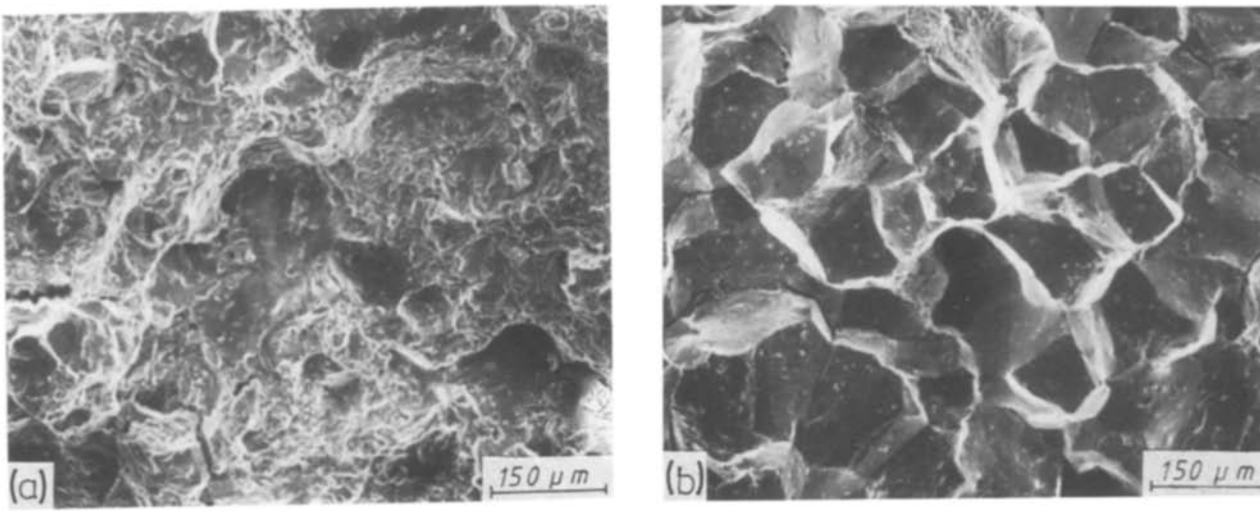



*Figure 4* Fractographs at room temperature in 4140-Ni steel. (a) 300° C and (b) 400° C tempered conditions.

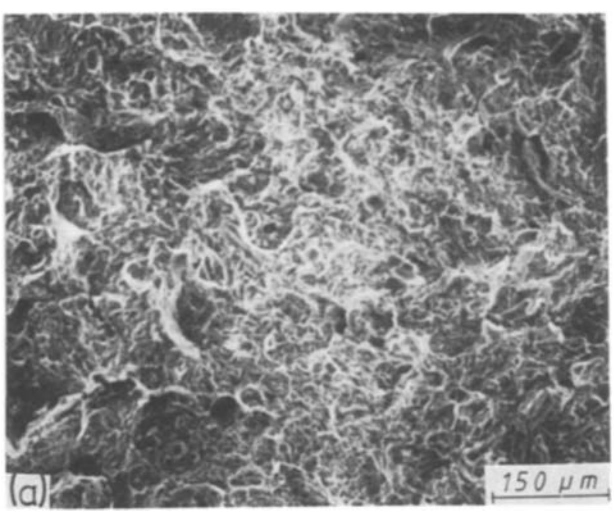
### *3.2.2. 4140-Si steel*

Fig. 7 shows the fractographs at room temperature which indicate the large increase in the amount of intergranular brittle fracture in the 400° C tempered condition where TME occurs, compared to in the 350° C tempered condition. This fracture behaviour is more clearly observed in Fig. 8, showing the fractographs at a test temperature of − 55° C.

At a test temperature of − 196° C, however, the increment in the amount of intergranular brittle fracture in the 400° C tempered condition is relatively decreased, compared with that at a test temperature of − 55° C (Fig. 9). This fracture behaviour is different from that in 4140-Ni steel. This is attributed to the relatively low intrinsic matrix toughness in 4140-Si steel.

The fractographs in the 450° C tempered condition represent mostly intergranular brittle fracture at test temperatures of 15 and − 55° C although the impact toughness in the 450° C tempered condition is higher than that in the 400° C tempered condition. Furthermore, the amount of intergranular brittle fracture in the 450° C tempered condition is rather larger than in the 400° C tempered condition, while the impact toughness in both conditions has a similarly low value of about 2 J at − 196° C. This indicates that some impurity segregation may occur during tempering.

In 4140-Si steel, the fracture behaviour which represents the integranular–transgranular brittle fracture transition with decreasing test temperature is consistent with the decrease in intrinsic matrix toughness with silicon-addition. In the presence of coarse grain-boundary carbides, of course, the intergranular brittle fracture can be activated to a considerable degree even at low test temperatures because the grain



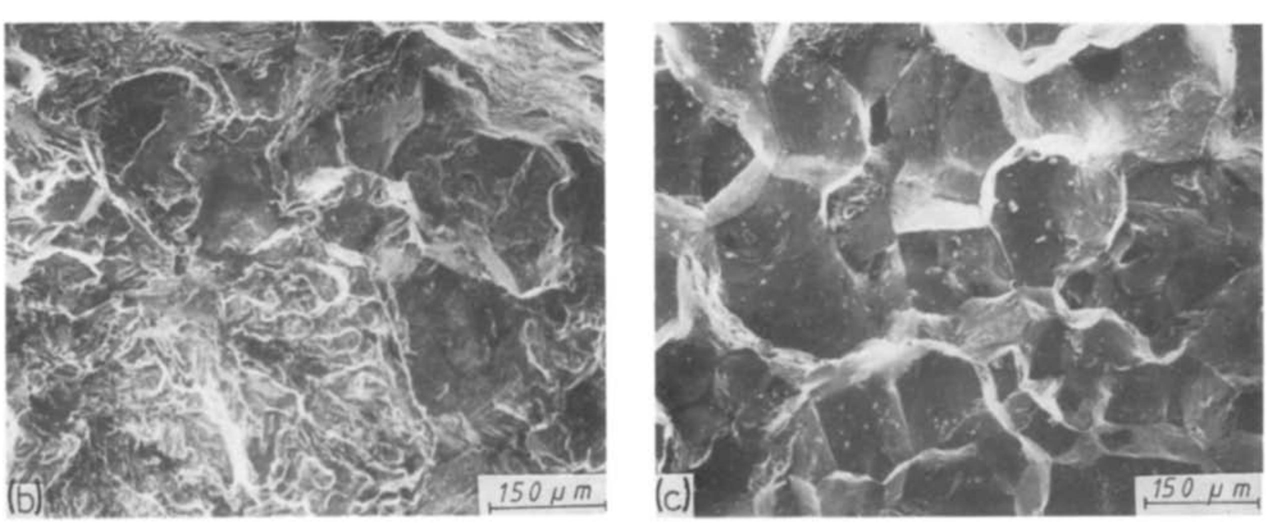




*Figure 5* Fractographs at − 80° C in 4140-Ni steel. (a) 200° C, (b) 300° C, and (c) 400° C tempered conditions.

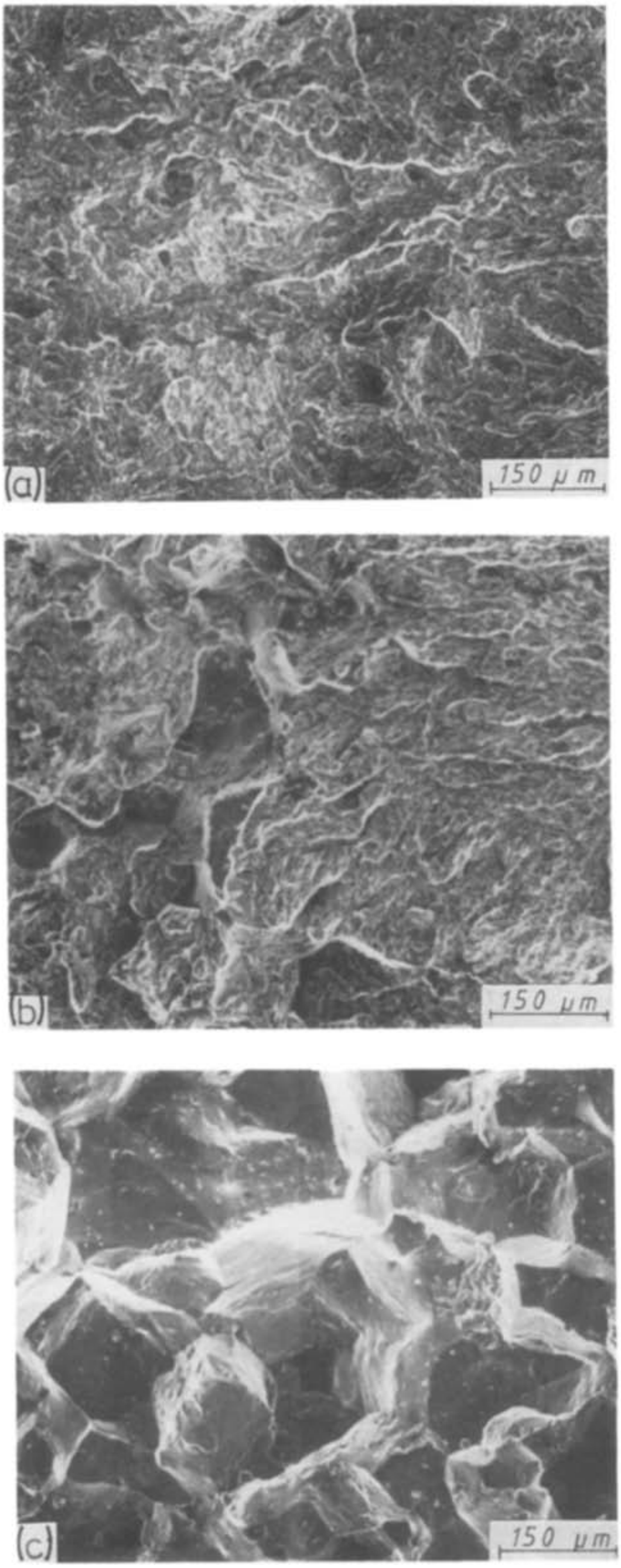



*Figure 6* Fractographs at $-196°$ C in 4140-Ni steel. (a) 200° C, (b) 300° C, and (c) 400° C tempered conditions.

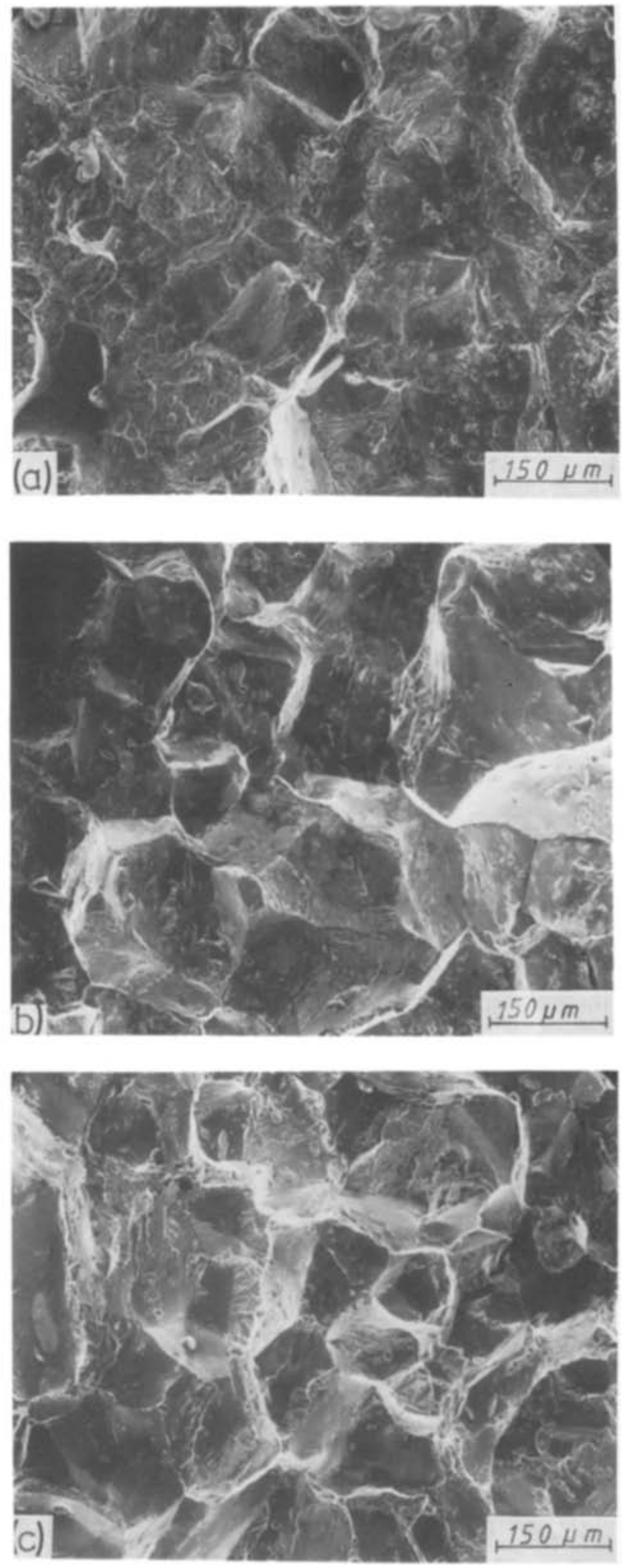



*Figure 7* Fractographs at room temperature in 4140-Si steel. (a) 350° C, (b) 400° C, and (c) 450° C tempered conditions.

boundaries will become impurer due to the relatively high impurity content in commercial alloy steel. On comparing with 4140-Ni steel in which there is no intergranular-transgranular brittle fracture transition with decreasing test temperature, however, 4140-Si steel distinctly has a low intrinsic matrix toughness.

From the fractographic observations, TME in 4140-Si steel is the intergranular brittle type, although the intrinsic matrix toughness is lowered by silicon addition. This may seem to be contrary to Kwon and Kims' suggestion [13] that the relatively high-purity ternary alloy steels having a low intrinsic matrix toughness can exhibit the transgranular brittle type of TME. In the relatively low-purity 4140-Si steel, which has a low intrinsic matrix toughness, however, the intergranular brittle fracture can be activated, with relative ease, by the coarse carbides at the grain boundaries, where more segregation of impurities will occur during austenitizing and/or tempering due to the relatively high impurity content in this steel. As the coarse grain-boundary carbides can promote more easily the stress concentrations under the conditions of

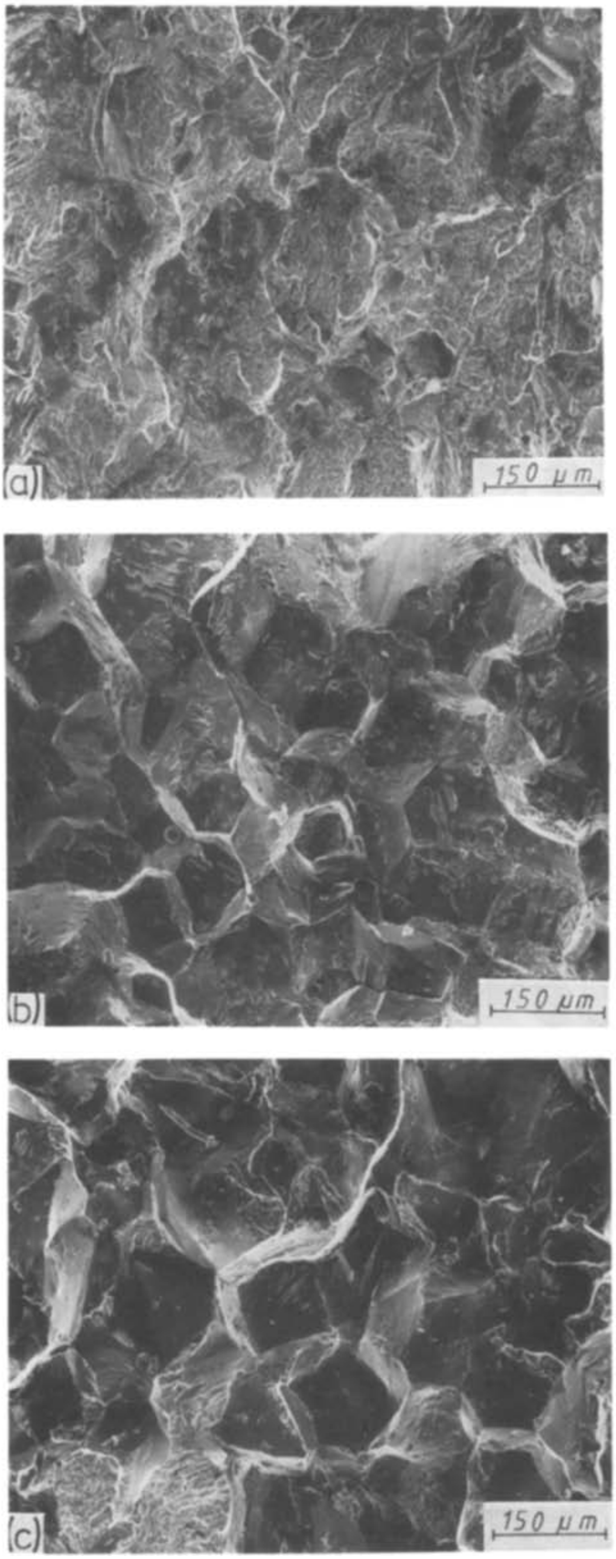



*Figure 8* Fractographs at $-55°$C in 4140-Si steels. (a) 350° C, (b) 400° C, and (c) 450° C tempered conditions.

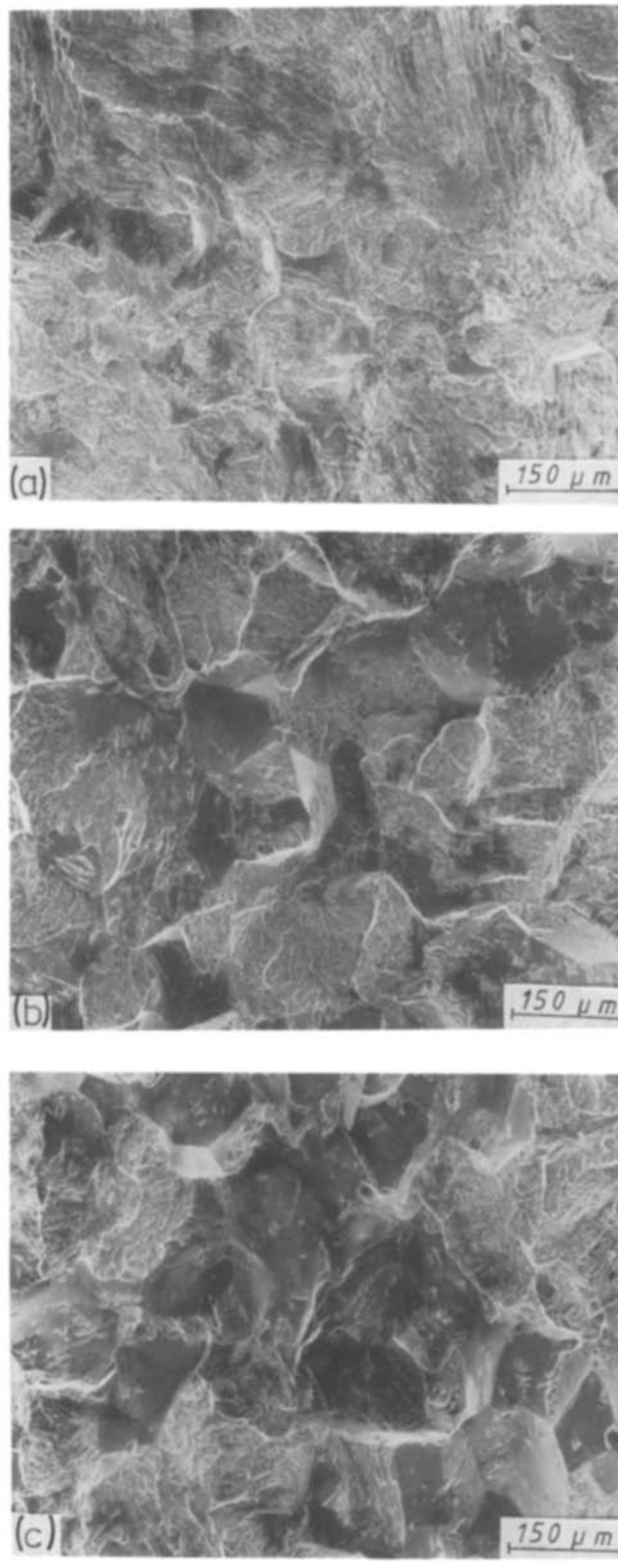



*Figure 9* Fractographs at $-196°$C in 4140-Si steel. (a) 350° C, (b) 400° C, and (c) 450° C tempered conditions.

the low intrinsic matrix toughness, the impurer grain boundaries can be easily cracked. In other words, the combined effect of coarse carbides and more impurities at the grain boundaries in an embrittled condition can induce the relatively easy occurrence of intergranular brittle fracture.

At low test temperatures, where the intrinsic matrix toughness becomes lowered, however, the degree of activation of coarse grain-boundary carbides will be smaller than that in 4140-Ni steel having a relatively high intrinsic matrix toughness. This indicates that the transgranular brittle type of TME may occur in high purity 4140-Si steel in which the transgranular brittle fracture may be easily activated compared to the intergranular brittle fracture.

Therefore, in 4140-Si steel having a relatively high content of impurities, the intergranular brittle type of TME can occur because the impurer grain boundaries in the presence of coarse grain-boundary carbides can be easily cracked, compared to those with few grain-boundary carbides, despite its low intrinsic matrix toughness.

## 5. Conclusions

1. In 4140-Ni steel where nickel-addition increases the matrix toughness, TME is the intergranular brittle type where coarse grain-boundary carbides are necessary for the intergranular brittle fracture in martensitic steels which have a relatively high resistance to the transgranular brittle fracture.

2. In 4140-Si steel where silicon-addition decreases the intrinsic matrix toughness, the intergranular brittle type of TME is observed. As the relatively high impurity content in commercial alloy steel makes the grain boundaries impurer (i.e. weaker), effective activation of the coarse grain-boundary carbides becomes possible for the intergranular brittle type of TME, despite its low intrinsic matrix toughness.

3. The intergranular–transgranular brittle fracture transition takes place in 4140-Si steel, with decreasing test temperature, because of its low intrinsic matrix toughness. Although the relatively low-purity commercial alloy steel, in which the occurrence of intergranular brittle fracture can be achieved effectively in the presence of coarse grain-boundary carbides, has a low intrinsic matrix toughness, the intergranular brittle type of TME can occur.

## Acknowledgement

This work was supported by the Korea Science and Engineering Foundation (KOSEF).

## References

1. S. K. BANERJI, C. J. McMAHON Jr and H. C. FENG, *Metall. Trans.* **9A** (1978) 237.
2. C. L. BRIANT and S. K. BANERJI, *ibid.* **10A** (1979) 1151.
3. *Idem, ibid.* **10A** (1979) 1729.
4. N. BANDYOPADHYAY and C. J. McMAHON Jr, *ibid.* **14A** (1983) 1313.
5. H. KWON and C. H. KIM, *J. Mater. Sci.* **18** (1983) 3671.
6. *Idem, Metall. Trans.* **15A** (1984) 393.
7. G. THOMAS, *ibid.* **9A** (1978) 439.
8. J. E. KING, R. F. SMITH and J. F. KNOTT, "Proceedings Fourth International Conference on Fracture", edited by D. M. R. Taplin (University of Waterloo Press, Waterloo, 1977) p. 279.
9. H. K. D. H. BHADESHIA and D. V. EDMONDS, *Met. Sci.* **13** (1979) 325.
10. H. KWON and C. H. KIM, *Metall. Trans.* **14A** (1983) 1389.
11. T. M. F. RONALD, *Metall. Trans.* **1** (1970) 2583.
12. F. ZIA-EBRAHIMI and G. KRAUSS, *Acta Metall.* **32** (1984) 1767.
13. H. KWON and C. H. KIM, *Metall. Trans.* **17A** (1986) 745.
14. *Idem, ibid.* **17A** (1986) 1173.

*Received 4 November 1986*
*and accepted 15 May 1987*