UDK 669.14:620.17:669.28 ISSN 1580-2949
Original scientific article/Izvirni znanstveni članek MTAEC9, 47(5)611(2013)

# EFFECT OF A Mo ADDITION ON THE PROPERTIES OF HIGH-Mn STEEL

# VPLIV DODATKA Mo NA LASTNOSTI VISOKOVSEBNOSTNEGA Mn-JEKLA

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*Prejem rokopisa – received: 2012-12-31; sprejem za objavo – accepted for publication: 2013-01-10*

TWIP steels are a family of high-Mn austenitic steels having both high strength and high ductility used as automotive-body steels. In the present paper, the effect of an addition of Mo on the improvement of the mechanical properties of a TWIP steel (Fe-33Mn-3Si-2Al) is investigated. Different amounts of Mo were added to the chemical composition of the steel and the resulted mechanical properties, microstructure and crystallographic phases were examined after the casting, hot rolling and annealing. The results showed that an addition of Mo enhances the mechanical properties; however, the optimum strength was obtained with an addition of 1.3 % Mo. This resulted in an increase in the ultimate strength and elongation of the steel.

Keywords: molybdenum, TWIP steels, hot rolling, Mo carbide

TWIP-jekla so skupina avstenitnih jekel z visoko vsebnostjo Mn, ki imajo visoko trdnost in dobro preoblikovalnost ter se uvrščajo med jekla za avtomobilsko pločevino. V tem članku smo preiskovali vpliv dodatka Mo na izboljšanje mehanskih lastnosti TWIP-jekla (Fe-33Mn-3Si-2Al). Dodane so bile različne količine Mo v jeklo in preiskovane so bile mehanske lastnosti, mikrostruktura in kristalografske faze po ulivanju, vročem valjanju in žarjenju. Rezultati so pokazali, da dodatek Mo izboljšuje mehanske lastnosti, vendar pa je bila največja trdnost dosežena pri dodatku 1,3 % Mo. To se je izrazilo v povečanju natezne trdnosti in raztezku jekel.

Ključne besede: molibden, TWIP-jekla, vroče valjanje, Mo-karbid

## 1 INTRODUCTION

In recent decades, various kinds of steels have been developed for the automotive industry. These steels significantly enhanced various properties like safety, fuel consumption, impact resistance and other properties. But the safety issues and the necessity of welfare increment require the use of the accessories that are is in contrast with the principle of down-weighting of cars.[1]

TRIP, transformation-induced plasticity, steels are known as the steels combining high-strength and high-ductility properties, attracting the attention of the automotive industry. The phenomenon of the transformation-induced plasticity includes the formation of martensite from the remaining austenite phase under the effects of strain and deformation, which leads to an increase in the strength and ductility.[2] In TRIP steels, $\varepsilon$ (HCP) and $\alpha$ (BCC) martensites are formed in the $\gamma$ (FCC) lattice due to internal and external stresses.[2]

TWIP steels are high-manganese steels ($w$(Mn) = 17–35 %) whose microstructure remains austenite even at room temperature. For this reason, these steels are deformed through the twins within the grains. The formation of twins and its rate depend on the hardening rate of steels. A greater hardening rate will lead to a finer microstructure. Therefore, twin boundaries will act similarly to grain boundaries which, in turn, will lead to a higher strength of the steel.[3] The formation of twins, or the occurrence of a phase transformation, depends on the value of *SFE*[3] of the austenite phase ($\gamma_{fcc}$). A higher rate of *SFE* ($80 > \gamma_{FCC} > 20$ mJ/m$^2$) stimulates the formation of twins and its lower rate causes austenite to transform to e martensite and then to a martensite.[3]

Although there are no comprehensive studies on the influence of the alloy elements on the *SFE* phase of the Fe-Mn austenite phase, it was defined, with the researches carried out, that Cu and Al significantly increase the value of *SFE* of an austenite phase, while Cr decreases *SFE* of steel.[4] In this research, we study the influence of Mo on the mechanical properties of a group of TWIP steels.

## 2 EXPERIMENTAL PROCEDURE

Two heats with the chemical compositions shown in **Table 1** were prepared in an induction furnace under argon atmosphere and then cast. The homogenization treatment was conducted for an hour at a temperature of 1200 °C to remove any segregation of the alloying elements during the solidification. Hot rolling in five successive passes up to a total strain of 70 % was applied thereafter and the specimens were cooled in air (with the finishing rolling temperature of 900 °C). The treatment continued with a full annealing of the samples for 10 min at 1100 °C followed by air cooling. Uniaxial tensile tests were performed at ambient temperature and the strain rate of $10^{-3}$ S$^{-1}$, according to the ASTM E8M standard using an Instron 4486 tensile machine. Phase analyses of the samples were carried out at ambient temperature with the X-ray diffraction method using a Bruker device at the angles ranging from 35° to 100° as well as Cu-K$\alpha$ x-rays and a nickel filter.

**Table 1:** Chemical compositions of the investigated steels ($w$/%)
**Tabela 1:** Kemijska sestava preiskovanih jekel ($w$/%)

| S | Fe | Mo | Al | Si | Mn | C |
|---|---|---|---|---|---|---|
| <0.006 | Ball | – | 2 | 3 | 32.9 | 0.13 |
| <0.006 | Ball | 1.3 | 2 | 3 | 33 | 0.13 |

## 3 RESULTS AND DISCUSSION

### 3.1 Phase studies

**Figure 1** shows a phase analysis of the sample without molybdenum before and after the tensile test. We can see in this figure that after the tensile test, there is no phase change in the sample without the molybdenum alloy and it remains austenitic. In the case of the sample with 1.3 % molybdenum, after the tensile test, the microstructure consists of austenite and $\alpha$ martensite with a bcc structure.

**Figure 1b** shows this phase. As the microstructure of this steel consists of austenite and martensite, the governing deformation mechanism is the TRIP transformation occurring in the high-manganese steels with *SFE* < 20 mJ/m$^2$. This deformation is based on the following transformation:

$$\gamma_{\text{fcc}}(\text{Austenite}) \rightarrow \alpha_{\text{bcc}}(\text{bcc-Martensite})$$

This transformation is stimulated by increasing the percentage of molybdenum, which lowers the value of *SFE* below 20 mJ/m$^2$, while in the sample without molybdenum the decrease rate of *SFE* is not sufficient to change the deformation mechanism from the twinning of austenite to a martensite transformation.[5]

### 3.2 Microstructure

**Figure 2a** shows the microstructure of the sample without molybdenum before and after the tensile test. In this sample, the annealing twins are apparent in the microstructure. Also, after the tensile test, the mechanical twins were formed in the microstructure due to the deformation process. As mentioned above, this phenomenon occurs due to the *SFE* level of this steel. Also, in **Figure 2b** we see that the grain size in this sample, before and after the tensile test, is smaller than in the sample without molybdenum. It has been argued that as molybdenum is a carbide-generating element, it generates carbide in a microstructure.[6] When molybdenum is added to steel, molybdenum carbide forms at the grain boundaries.[7,8] The carbide on the grain boundaries prevents the grain growth.[9] It has been shown that the formed carbide at the grain boundaries is $(Fe,Mo)_3C$ carbide.[6,10]

We found no mechanical twins and slip bands in the microstructures of the samples after the tensile test. This indicates an occurrence of transformation in this steel through a transformation of austenite to martensite.

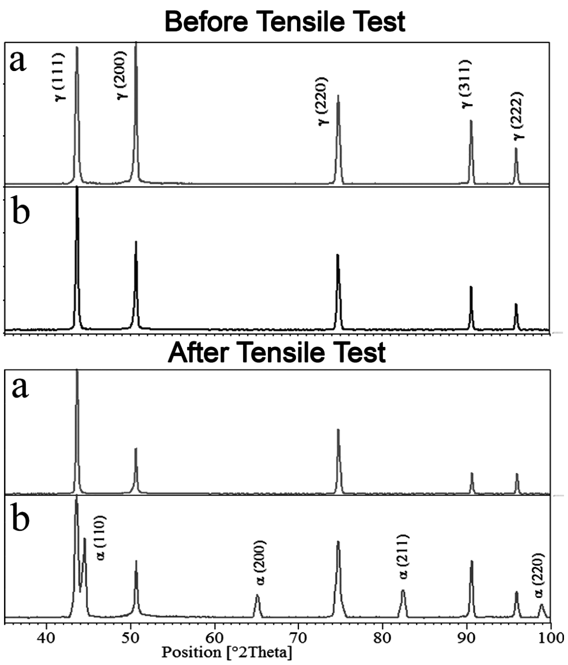


**Figure 1:** Phase analysis of the samples before and after the tensile test: a) sample without Mo, b) sample with 1.3 % Mo
**Slika 1:** Fazna analiza vzorcev pred nateznim preizkusom in po njem: a) vzorec brez Mo, b) vzorec z 1,3 % Mo

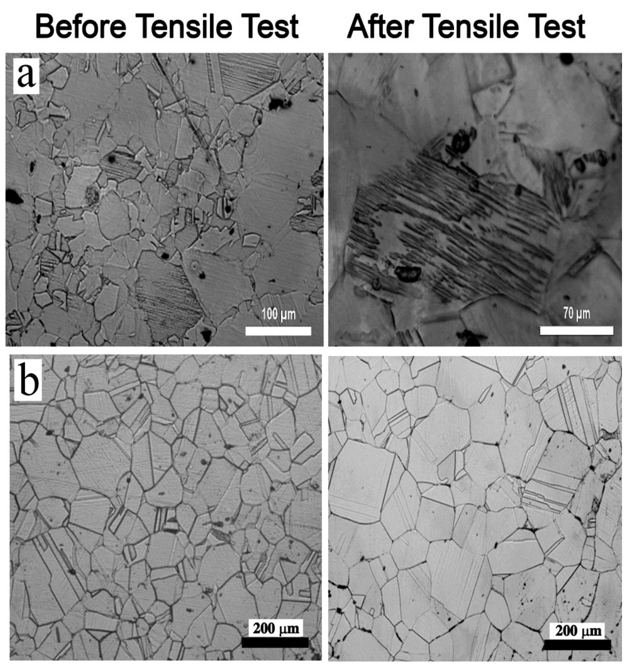


**Figure 2:** Microstructures of the samples before and after the tensile test: a) without Mo and b) with 1.3 % Mo
**Slika 2:** Mikrostruktura vzorcev pred nateznim preizkusom in po njem: a) brez Mo in b) z 1,3 % Mo

### 3.3 Estimating the results of the tensile test

**Figure 3** shows the tensile-test curves at ambient temperature. It is apparent that the sample containing molybdenum shows a higher strength and ductility compared with the sample containing no molybdenum. As mentioned above, the reason for this is the formation of molybdenum carbides. Also, it has been found that the sample containing molybdenum shows a higher ductility due to the carbides between the grain boundaries. This prevents a disintegration of the grain boundaries and increases the ductility.

**Figure 4** shows images of the microstructures of the samples after the tensile test obtained with the SEM microscope and also the results of a surface analysis of the dispersion of carbon and molybdenum. The contents of molybdenum and carbon near the grain boundaries in the sample containing 1.3 % molybdenum are increased. This increase indicates a formation of molybdenum carbide, which increases the stability of the grain boundaries. From the point analysis of the carbide precipitates in **Figure 5** the type of carbide may be recognized as $(Fe,Mo)_3C$.

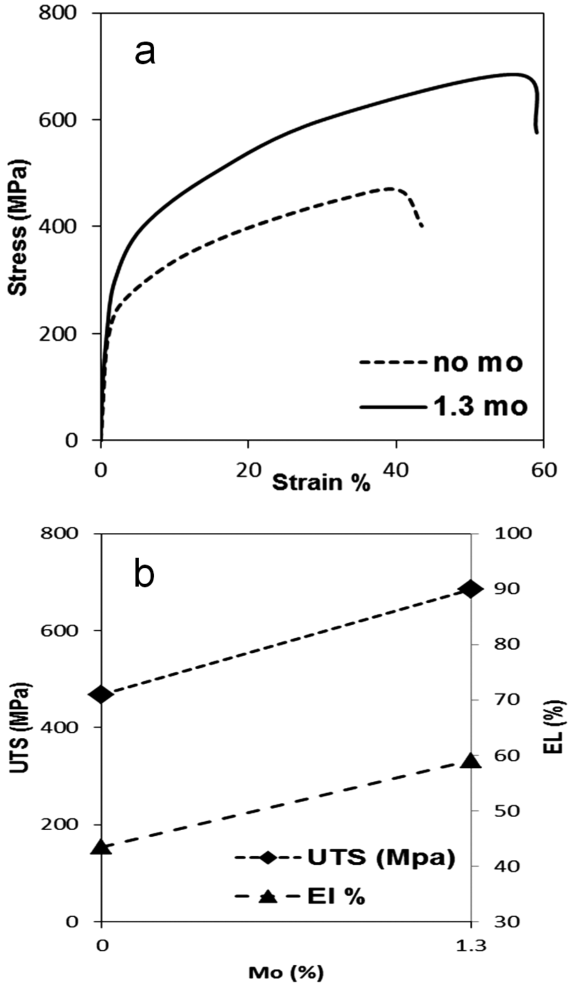


**Figure 3:** a) Engineering stress-strain curve, b) results obtained from the engineering stress-strain curve
**Slika 3:** a) Inženirska krivulja napetost – raztezek, b) rezultati, dobljeni iz inženirske krivulje napetost – raztezek

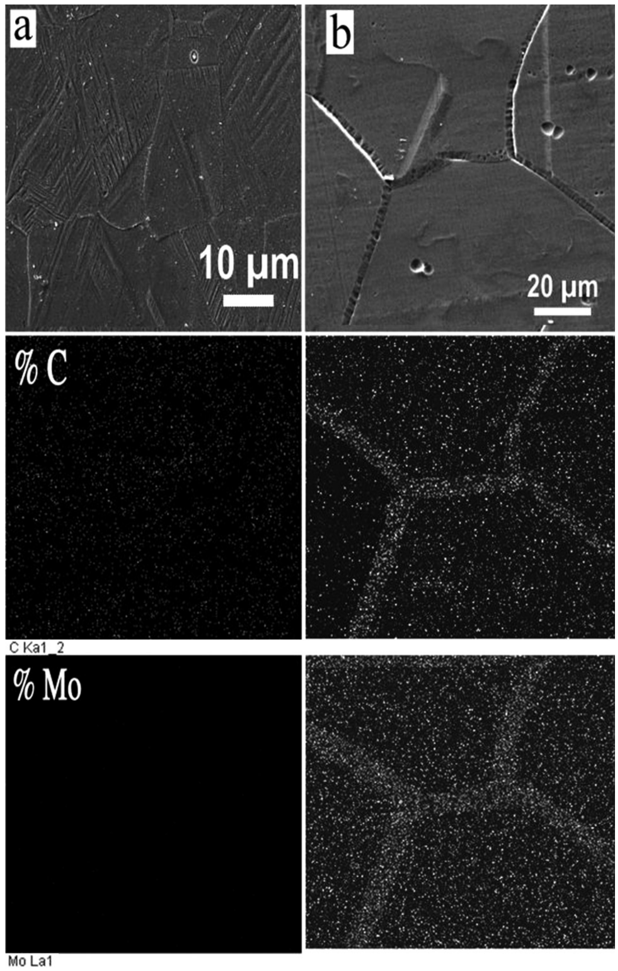


**Figure 4:** Images obtained with the SEM microscope and a surface analysis: a) sample without Mo, b) sample containing 1.3 % Mo
**Slika 4:** SEM-posnetki in analiza površine: a) vzorec brez Mo, b) vzorec z 1,3 % Mo

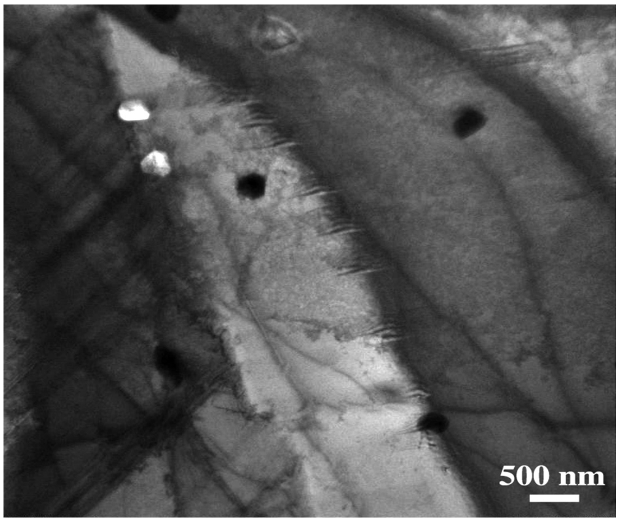


**Figure 5:** Microstructure of the sample with 1.3 % Mo and carbides
**Slika 5:** Mikrostruktura vzorca z 1,3 % Mo in karbidi

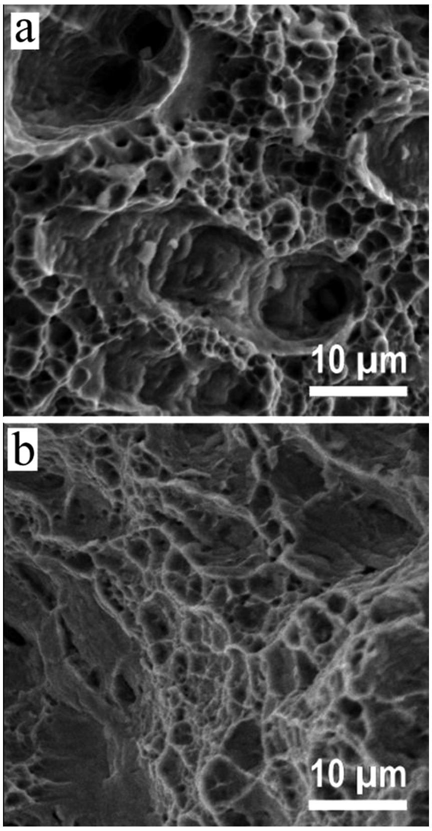


**Figure 6:** Fracture cross-sections of the estimated samples: a) sample without Mo, b) sample containing 1.3 % Mo

**Slika 6:** Prelom ocenjenih vzorcev: a) vzorec brez Mo, b) vzorec z 1,3 % Mo

### *3.4 Estimating fracture surface*

**Figure 6** shows the fracture surface after the tensile test. In the sample containing 1.3 % Mo, the size of dimples is decreased. As in the FCC metals, no brittle fracture was observed and after thorough studies we found out that these regions had been created due to the martensite generated during the transformation.[10]

## 4 CONCLUSIONS

1. Adding 1.3 % Mo increases the ultimate strength of the Fe-33Mn-3Si-2Al-0.13C steel.
2. Adding Mo to the Fe-33Mn-3Si-2Al steel up to 1.3 % decreases the grain size.
3. Adding 1.3 % Mo lowers *SFE* of the austenite phase, which prevents an occurrence of the TWIP mechanism and encourages the TRIP mechanism.

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