Abstract

Materials characterized as TRIPLEX having decreased density are usually constituted on the following chemical composition: Fe-26/30Mn-10/12Al-0.9/1.1C. Their microstructure is preferentially based on the FCC arrangement. Further the microstructure of discussed alloy consists of nano-size k carbides regularly dispersed in the FCC matrix and of low ferritic particle content (approximately 8%). The strength level of this material is immediately connected with the solid solution strengthening forming the matrix basis. Besides this effect, it is useful to take into consideration process of its strengthening due to precipitated fine carbides (above mentioned nano-size k carbide particles). The preferential effect of this material is connected with its high absorption capacity (double capacity in comparison with the conventional deep drawing steels applied in automotive industry).

The formation of uniformly arranged shear bands (SIP effect) has very important influence on the realized deformation process of discussed material and the achieved beneficial technical response. This process is also influenced due to regular distribution of nano-size k carbides being coherent to the FCC matrix.

Owing to the density decrease up to 10÷12%, attained strength level (>1000 MPa) excellent formability and high resistance to dynamic loading (high absorption and achieved dynamic capacity) the presented high manganese material can be held for perspective type for the large application in automotive industry. Further, this material finds a perspective application in cryogenic technique (transport and storage of liquid gases). Besides above mentioned application examples it is possible to consider with its application for rotating machine elements.

1. INTRODUCTION

The high strength alloy constituted on the Fe-Mn-Al-C basis represents a new group of high Mn-alloys containing higher Al-content (TRIPLEX alloys). Those alloys possessing superior ductility and reduced specific weight are very attractive from point of view of their application in the automotive industry and as material for rotating electric machines, generators, due to their lower specific weight. Further, as is presented lately, the Fe-Mn-Al-C alloy has found its application domain in facilities for storage and transport of liquid gases in the cryogen technique.

The alloy under investigation covers the overall composition of Fe-18/28Mn-9/12Al-0.7/1.2C, the FCC lattice mainly, ferrite microstructure of about 8% and nano-size carbides (k carbides of 6-9 vol. %) being finally dispersed in the FCC solid solution matrix [1]. The presented contribution is devoted to give precision to achieved physical metallurgy knowledge of the investigated alloy up to present time, namely in the way of microstructural analysis inclusive the elucidation of causes leading to the specific weight reducing and the mechanism modification of plastic deformation. The aim of this work is to summarize the
2. MICROSTRUCTURAL ANALYSIS

The alloy, known under the commercial title TRIPLEX consists of the FCC matrix characterized by annealing twins and about 8 vol. % of ferrite and nano-size k-carbides regularly distributed in the FCC matrix. This carbidic phase has the ordered FCC structure (L12). To achieve the optimized properties of its microstructure, it is necessary to apply the additional aging which leads to the regular k-carbides precipitation in matrix conditioning the subsequently realized specific deformation mechanism [1]. Very important is also the characterization of the alloy resistance to the FCC decomposition in ε-martensite. The analysis shows a positive free enthalpy of the austenite-decomposition in ε-martensite (ΔGγ→ε = +1755 J.mol⁻¹) what demonstrates a very high stability of the FCC phase matrix with respect to the ε-martensite formation. The martensite transformation is also suppressed due to the relatively high SFE (Γ = 110 mJ.m⁻²). This value also shows, triplex-alloy is not prone to mechanical twinning. Recently, it has been found that the ε-martensite transformation tendency is realized if the SFE is lower than 15÷20 mJ.m⁻² [2]. In summary, it is possible to state the detected modification of the SEF level and the resistance to ε-martensite transformation corresponds to an influence of high Al content in Fe-Mn-Al-C (TRIPLEX) alloy known as element suppressing deformation twinning [3].

The evaluation of specific weight reduction in Fe-Mn-Al-C alloy is based on dissolved Al and Mn level in matrix due to their large atomic radius in comparison with Fe atomic radius. The performed determination of the specific weight demonstrates the minimum value (ρ = 6.5 g.cm⁻³) at high Al-content (cAl ≈ 12 %).

![Fig.1](image)

**Fig.1.** Density as function of the Al-concentration of diverse Fe-xMn-yAl-zC alloys containing 14-28 % of Mn. The lover dependence represents overall reduction in density with increasing Al-concentration. The upper dependence corresponds to a decrease in density due to the expansion of matrix lattice.
In solid solution the detected overall mass reduction of the FCC and BCC coexisting phases corresponds to the reducing of average molar mass of the alloy matrix and to the decrease of the atomic density of the unit cell. The matrix lattice is expanded as it results from the larger Al atomic radius \( r_{\text{Al}} = 0.147 \text{ nm} \) in comparison with the radius of the Fe atoms \( r_{\text{Fe}} = 0.126 \text{ nm} \). To the density decrease of matrix, the Mn in alloy also contributes due to its larger atomic radius \( r_{\text{Mn}} = 0.134 \text{ nm} \) in comparison with Fe.

Figure 1 shows a summarising dependence of the found specific weight on the Al content in alloy under the additional effect of different Mn content in investigated alloy group. Two dependences are presented in Fig.1, namely the dependence of total reduction in specific weight (the lower dependence which amounts to 17 % at the highest Al-investigated concentration 12 %) and the upper dependence corresponding to the partial reduction in specific weight solely due to the dilatation of the austenitic lattice parameter (at. 10 %, \( c_{\text{Al}} = 11.5 \% \)).

3. MICROSTRUCTURE

The FCC matrix of the alloy under investigation is very stable as it results from the free enthalpy value for austenite decomposition in \( \varepsilon \)-martensite \( (\Delta G^{\gamma \rightarrow \varepsilon} = +1755 \text{ J.mol}^{-1}) \). This value signifies a great FCC phase stability with respect to the formation of \( \varepsilon \)-martensite having HCP lattice. The SFE determined \[4\] for the studied Fe-Mn-Al-C alloy complex is of 110 mJ.m\(^{-2}\) of the order what demonstrates that the high Al-addition to the basic high Mn solid solution suppresses the mechanical twinning formation \[3, 5\].

![Unit cell k-carbide cell having ordered FCC lattice structure of the L1\(_2\) type.](image)

The microstructure of recrystallized Fe-Mn-Al-C alloy (TRIPLEX alloy) consists besides the FCC also of the ferritic phase (6-8 %) and the nano-size k-carbides precipitated in the FCC matrix. The k-carbide grains have the ordered FCC \((L1_2)\) microstructure (see Fig. 2). Unit cell of the carbidic phase characterized as \((\text{Fe, Mn})_3\text{AlC}\) reveals the ordered FCC-L1\(_2\) type lattice, its microstructure process dissolved carbon atoms in the centre of the unit cell. The average lattice parameter is about \( a_0 = 0.3857 \text{ nm} \) and this value depends upon the Al-content in alloy as it is found usually \[1\].

The twinning deformation and the martensitic transformation in this alloy are replaced by the formation of uniformly arranged shear bands on the \( \langle 111 \rangle \) planes being of high density within the FCC matrix. These features represent a way of important contribution to the
realisation homogeneous shear deformation to the large plastic elongation known as the SIP-effect (shear band induced plasticity). Due to above given positive value of free enthalpy ($\Delta G^{\gamma \rightarrow \varepsilon} = +1755 \text{ J.mol}^{-1}$) for a martensitic transformation (and also due to relatively high SFE being around 110 mJ.m$^{-2}$) it is possible to accept as a concluding standpoint, TRIPLEX alloys are not prone to the martensite transformation or severe mechanical twinning.

The microstructural analysis of the k-carbide precipitation morphology demonstrates the regular distribution of nano-size particles of this phase coherent to the FCC matrix (as presented in TEM-dark field image – Fig. 3) [1]. This finding confirms the important role of the above discussed k-carbide distribution in matrix by the influencing the uniformly arranged shear bands contributing to the strengthening of the investigated TRIPLEX alloy.

![Fig.3. TEM-dark field image taken from the superlattice – plane (200) of the <001> FCC zone axis – shows the regular arrangement of k-carbides coherent to the FCC matrix (20±30 nm in size).](image)

![Fig.4. Engineering stress-strain curves of TRIPLEX alloy determined at different test temperatures (distinct strain hardening behaviour and deformation mechanisms).](image)
4. SOME REMARKS TO THE RELATIONSHIP BETWEEN MICROSTRUCTURE AND THE MODIFIED DEFORMATION RESPONSE

Figure 4 demonstrates the engineering stress-strain curves of high Mn-Al Triplex alloy determined at different test temperatures lying between \(-100 \, ^\circ\text{C} \div 400 \, ^\circ\text{C}\). The presented dependences reflect different deformation mechanisms. The detected strain hardening also presents an effect of distinct deformation process realized in alloy during its loading.

In order to increase the mechanical characteristics in strength level without plastic response degradation, particularly, the investigated alloy is usually subjected to thermal aging at 550 \, ^\circ\text{C} for different isothermal aging time being from 2.1 min. to 46 min. The obtained results are summarized in Fig. 5 in a form of the engineering curves of aged samples. After the prolonged aging time, the $R_p (0.2)$ increase from 700 MPa to 1060 MPa is found (determined at room temperature). The presented stress – strain dependences are almost similar to these of the ideal elastic – plastic solid where virtual no strain hardening occurs. This result demonstrates a specific role of uniform shearing for achieving extended plastic deformation realized by moderate deformation hardening mechanism.

![Figure 5](image)

**Fig.5.** Engineering stress-strain curves of thermally aged TRIPLEX alloy. Aging was realized at 550 \, ^\circ\text{C} for different time intervals.

In Fig. 6, the specific energy absorptions ($E^{\text{V}_{\text{spec.}}}$) defined as dissipative energy per unit volume at high strain rate $10^2 \div 10^3 \, \text{s}^{-1}$ (at the conditions relevant to the crack modelling) of the chosen material types are compared. In set of the evaluated steels and alloys are indicated two variants of high Mn alloy and 4 steel types applied as deep drawing materials. The presented comparison shows the absorption energy of the conventional deep drawing steels is lower than the absorption level of TWIP and TRIPLEX of high Mn alloys (Fig. 6). The absorption capacity of these alloys is more than double in comparison with considered deep drawing steel types. These higher absorption values of the above mentioned alloys reflect a higher flow stress and beneficial plastic elongation level. In case of TRIPLEX alloy a very important role in the absorption capacity can be ascribed to the effect of sever shear band formation at high strain rate [1].
Fig.6. Specific energy absorption ($E_{\text{V} \text{spec.}}$) of the high Mn alloys and conventional deep drawing steels (crash modelling).

5. CONCLUSIONS

The presented review of TRIPLEX alloy physical metallurgy properties summarizes the results achieved up to present time by the study of these alloys aiming to form the basis for the further consecutive investigation and to contribute to the reliable engineering application of this alloy. The investigated Fe-26/28Mn-10/12Al-1.0/1.2C alloy in majority consists of the FCC microstructure possessing a dispersion of nano-size k-carbides (L1$_2$) and partially ordered $\alpha$-ferrite. The chemical composition of k-carbide is (FeMn)$_3$AlC. The achieved superior properties of this alloy can be connected with effective solid solution and precipitation strengthening.

The determined high energy absorption level ($E_{\text{V} \text{spec.}}$) of the high Mn alloys represents their very important material parameter. The deformation mechanism contribution to the achievement of enhanced ductility is connected with the realization of SIP-effect (shear band induced plasticity). The formation of homogeneous shear bands is accompanied by dislocation glide. The realization of this mechanism depends on uniform arrangement formation of nano-size k-carbides being coherent to the FCC matrix. The TRIPLEX alloy due to the reduction in specific weight, high strength and beneficial formability inclusive the superior crash resistance has large application domains e.g. in automotive industry, in cryogenic technique, facilities for the storage and transport of liquid gases and/or for weight saving constructions generally.

REFERENCES


**ACKNOWLEDGEMENT**

The authors acknowledge the Ministry of Education, Youth and Sports of Czech Republic through financial support of research design MSM6198910013.