CONTRIBUTION TO PHYSICAL METALLURGY OF NEW HIGH STRENGTH Mn MATERIAL

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PŘÍSPĚVEK K FYZIKÁLNÍ METALURGII NOVÉHO Mn MATERIÁLU O VYSOKÉ PEVNOSTI

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Abstrakt

V automobilovém průmyslu byl dosažen pokrok ve zvýšení bezpečnosti a ekonomice pohonných hmot. Materiály o vysokém obsahu Mn tvoří perspektivní generaci vysoce pevných, tvárných slitin. Mimořádné vlastnosti těchto slitin nazývaných FeMnTWIP1100 (dvojčatově indukovaná plasticita) vykazují dva hlavní rysy: a) materiál je tvořený při všech uvažovaných teplotách zcela mřížkou KPC; b) hlavním deformačním mechanismem je dvojčatění. Slitiny FeMnTWIP1100 vykazují nízkou energii vrstevné chyby (SFE), která vede k možnému vícenásobnému, případně sekvenčnímu deformačnímu mechanismu. Vedle dislokačního skluzu jsou jak mechanismus dvojčatní, tak i tvorba ε-martensitu konkurenčními deformačními procesy a jsou založeny na velikosti energie vrstevné chyby. Mezní kritická hodnota těchto parametrů je 18mJm^{-2}. Při vyšší hodnotě energie vrstevné chyby než je uvedená kritická hodnota (okolo 20 ÷ 25mJm^{-2}) nedochází ke vzniku ε-martensitu. Naopak, v případě nižší energie vrstevné chyby než je výše uvedená hodnota, tvoří se přednostně ε-martensit. Dvojčatová deformace působí jako rozhodující mechanismus, který přispívá k dosažení vysokých mechanických vlastností. V případě procesu deformace dvojčatěním dosahuje mez kluzu 500MPa, hodnota pevnosti odpovídá 1100MPa a celkové prodloužení se rovná 50÷ 60%, a to prakticky při stejné úrovni rovnoměrného prodloužení. Tvorba krčku je v daném případě potlačena. Výše zmíněných parametrů je dosaženo při pokojové teplotě. Dále významnou vlastností slitiny FeMnTWIP1100 charakterizovanou rázovou odolností je vysoká absorpční energie definovaná jako pohlcená energie na jednotku objemu. Hodnota detekovaná pro sledovaný typ vysoko manganové slitiny odpovídá zhruba 0,50Jmm^3, zatímco konvenční typy materiálů (hluboko tažené oceli) dosahují pouze úrovně okolo 0,20 ÷ 0.22Jmm^3.

Abstract

In the automotive industry significant process has been achieved concerning safety and fuel economy. New types of materials are used in the vehicles to assure higher parameters High manganese materials form perspective generation of ductile high strength alloy. Extraordinary mechanical properties of these alloys named FeMnTWIP1100 (twinning induced plasticity) basically come from two main features: a) material is fully formed with the FCC structure at all considered temperatures; b) twinning is the main deformation mechanism. The FeMnTWIP alloys possess low stacking fault energy (SFE) leading to the possibility of multiple

simultaneous and/or sequential deformation mechanisms. In addition to dislocation slip, both mechanism twinning and ε-martensite formation are concurrent deformation mechanisms linked to the stacking fault energy. The critical boundary value of those parameters is $18mJm^{-2}$. At the stacking fault energy level, being higher than presented critical value (around $20 \div 25mJm^{-2}$ usually) ε-martensite is not initiated. On the contrary, in case of lower stacking fault energy than above given value the ε-martensite is formed preferentially. The twinning deformation acts as the decisive mechanism contributing to the achievement of high mechanical properties. In case of twinning deformation process yield strength reaches 500MPa, ultimate tensile strength value corresponds to 1100MPa and total elongation equals 50 ÷ 60% by practically the same level of uniform elongation. The necking formation is suppressed in this case. Above mentioned parameters are reached under the room temperature. Further, an important property characterizing the impact resistance of the FeMnTWIP1100 alloy is high energy absorption defined as dissipation energy per unit volume. The value detected for investigated high manganese alloy is $0.50Jmm^3$ approximately, while the conventional material types (deep drawing steels) only attain the level about $0.20 \div 0.22Jmm^3$.

Key words: mechanical twinning, ε-martensite, stacking fault energy, necking formation, twinning induced plasticity (TWIP)

1. Introduction

In the automotive industry a significant progress has been achieved concerning the safety and fuel economy. New material types are used in the vehicles to fulfil the above given goals. High manganese alloys having the FCC structure could form the next generation of ductile high-strength material. Extensive studies have been conducted on the mechanical engineering characteristics of new developed high Mn-alloys family. The material type is named FeMnTWIP1100 alloys. The achieved extraordinary mechanical characteristics basically come from two main factors: a) the full FCC microstructure at all applied temperatures; b) twinning is the main deformation mechanism. The applied very high Mn content (usually of 20 ÷ 25% approximately) assure a fully FCC microstructure at carbon content in the range of 0.5 ÷ 0.7%. The above presented chemical constitution stabilizes FCC microstructure and simultaneously contributes to the matrix strengthening owing to solute solution hardening. The chemical composition of the investigated alloy type is optimized with the aim to offer, besides the beneficial formability for given strength level also a very stable mechanical behaviour over the range of required temperature.

2. Analysis of physical metallurgy parameters

The fulfilment of parameters having a decisive influence on the level of found properties of the FeMnTWIP1100 alloys can be summarized in the following criterion principles [1]:

1) The final composition should be the 100% FCC at all working temperatures (-100 °C ÷ 300 °C).
2) No martensite formation (in investigated alloy ε-martensite is formed preferentially. The probability of the α-martensite formation is negligible) under cold rolling or deep drawing condition.

3) Optimization of mechanical properties (YS, UTS, TEL, UEL) at room temperature.
4) No carbide formation during conventional processing conditions.
5) Must be compatible with the conventional continuous casting/hot rolling process.

The high Mn-alloys (Fe-Mn-C types) having the FCC crystallographic structure possess low stacking fault energy (the SFE) leading to the possibility realization of two concurrent deformation mechanisms (in addition to the dislocation slip) can be taken into account. In this case, the mechanical twinning and/or martensite formation come into consideration. These effects are independent both on chemical composition and the deformation temperature. Outside this domain, the TWIP mechanism is limited. It leads to the dislocation gliding process preferentially and/or to the plasticity assisted by martensite formation (TRIP effect). However, these mechanisms are less effective than above described TWIP process. Dislocation gliding does not provide a sufficient hardening rate to reach high strength. The TRIP mechanism does not results in so high elongation and it disappears when all the residual austenite has transformed into martensite [2].

The comparison of the TWIP and TRIP effects demonstrates, the first given mechanism results in continuous strengthening process while the TRIP effect successively disappears with development of the austenite decomposition into martensite.

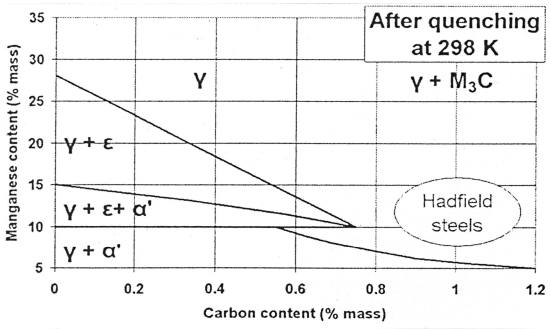

Fig.1 Fe-Mn-C phase stability diagram after tensile testing at room temperature [3]

3. Microstructural evaluation

Mechanical twinning and ε-martensite formation are competitive deformation mechanisms being very similar from the point of view of morphology and physical metallurgy origin. Both mechanisms are strongly linked to the SFE controlling the energetic cost for formation of such defects. Experimentally, it is found that the ε-martensite formation (hexagonal crystallographic structure) can replace the mechanical twinning when the SFE is reduced under certain level. It can be seen (Fig. 1) that in the Fe-Mn-C alloys the SFE increases with increasing carbon and manganese contents. This figure shows a modified diagram of the Fe-Mn-C phase stability at room temperature according Schumann's data [3], simultaneously with the defined demand of the optimum mechanical twinning corresponding to the greatest kinetics of the twin formation [1].

The lower SFE prefers the stress induced ε-martensite formation, while the higher SFE (considered to be around 20 ÷ 25 mJm^{-2}) leads to the mechanical twinning as it can be deduced from the SFE map elaborated for room temperature evaluation [1, 4]. Martensite transformation is realized if the SFE is lower than $18mJm^{-2}$. In case of the SFE being higher than $18mJm^{-2}$ no ε-martensite transformation will occurs.

On the basis of obtained experimental results, the peformed analysis is devoted to the Fe-22Mn-0.6C alloy evaluation. This chemical composition is corresponding to the intense mechanical twinning domain as it is indicated in the Fig. 1 for room temperature straining.

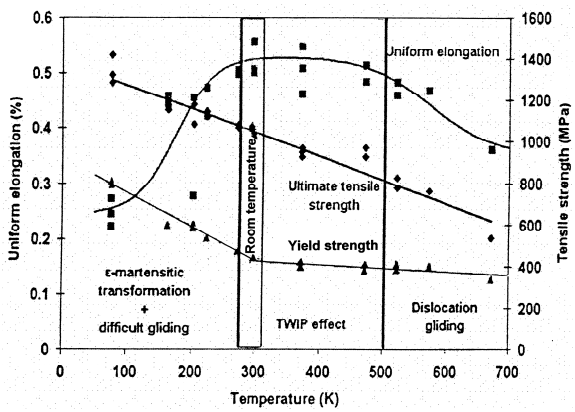

Fig.2 Results of the tensile tests realized at different temperatures on cold strips (grain size of 3μm). The domains of different deformation mechanisms are defined [1]

4. Achieved mechanical properties

Figure 2 summarizes results of tensile testing at temperature range lying between 77K and 673K. The SFE of the investigated alloy changes in large extent. At 673K this value equals 80mJm^{-2} and at this condition the realized deformation process corresponds to dislocation gliding (twinning formation is eliminated). At 293K, the SFE is 20mJm^{-2} and observed mechanical twinning is a deformation mechanism. At very low temperature (e.g. 77K), the SFE being around 10mJm^{-2} leads to ε-martensite transformation [4]. Irrespective of grain size the material behaviour demonstrates following: a) low uniform elongation and tensile strength occur at temperature about 500K, b) the high uniform elongation occurs at room temperature when the strain hardening rate -n- is higher than 0.40, c) the highest UTS is found at low temperatures but with lower total elongation. On the other hand, the UTS depends both on the strain hardening rate and the thermal activation of dislocation movement.

Figure 2 shows the maximum of the TWIP effect can be found in temperature range of 270 ÷ 500K approximately. At temperatures higher than 500K the twinning deformation is suppressed, so that planar dislocation slip only becomes an active deformation mechanism. The necking appears rapidly in tensile specimen what causes a suppressing of the uniform elongation. The experimental results confirm the best mechanical properties are observed when intense twinning activity occurs at room temperature. Under these conditions, the compromise between ductility and strength values takes place and the mentioned parameters are in balanced stage.

At low temperatures the SFE is decreasing and the mechanical twinning is replaced with ε-martensite formation. The ε-martensite plates act as strong obstacles for dislocations. The high hardening rate is still possible nevertheless dislocation movement is difficult at this temperature. The hardening process is less effective as a consequence of this behaviour. The strain hardening is lower than at room temperature and the total elongation is decreasing [1, 2].

The modification of twinning microstructure has been investigated after different deformation conditions. The TEM observation reveals the twin formation is characterized with

micro twin generation. Twins are gathered into stacks which become strong obstacles for dislocation movement. The individual micro twin thickness is only a few tenths of nanometers whereas the stack thickness reaches up to a few tenths of a micrometer. During tensile loading, two secant twinning systems can be activated sequentially. The second twinning (micro twins) system can be found in the microstructure after 15% deformation (at room temperature). This micro twin system mainly influences the work hardening process what is connected with the shortening of free paths of mobile dislocations.

5. Practical application of investigated alloys

The excellent formability and the achieved very high mechanical properties of the FeMnTWIP1100 alloys show a promising perspectives for their application in automotive industry inclusive of vehicle lightening [2, 5]. The obtained results have high lightened influence of the FeMnTWIP1100 alloys in-use properties.

The contribution is devoted to the analysis of conditions influencing the chemical application of twin alloy constituted on the Fe-Mn-C basis. After cold rolled and annealed materials the composition of this Mn-alloy provides the best compromise between the UTS (>1000MPa) and total elongation (>50-55%). The austenitic matrix is exempt from cementite or other carbide phases. The yield point of cold rolled strips is controlled in the range from 450MPa to 600MPa by attainment of fine grain size (1.5-5μm). Particular attention has been paid to austenite stability during cold straining. The complete suppression of strain martensitic formation has been confirmed up to temperature lying higher than 110 °C. Finally, the excellent formability and the attainment of very high mechanical properties of this alloy type have been verified. The obtained results have confirmed position of described material in vehicle lightening [2, 5].

The obtained results have explained influence of the FeMnTWIP1100 alloy prestraining on their in-use properties. It is essential to take into account to assess vehicle crashwothiness. The high rates of work hardened provide a very high capacity of energy absorption thus offering significant opportunities for major safety of vehicles and/or for their weight reduction. The investigated high Mn alloy exhibits remarkable combination of formability, strength, ductility and strain hardening characteristics enabling major weight reduction while improving crash safety [2]. Figure 3 demonstrates the excellent position of the FeMnTWIP1100 alloy. Mentioned figure shows the level of the specific absorption energy $E^{V}_{spec.}$ per unit volume of the two high Mn alloy variants (FeMnTWIP1100 and TRIPLEX) in comparison with conventional deep drawing materials at the crash relevant strain rate $10^{2}s^{-1}$ [6, 7]. The crash resistance of the two given Mn alloys is more than double in comparison with the conventional structural materials. In high Mn alloys the absorption energy attains 0.48-0.50Jmm^{-3}, while in the conventional material types the absorption level is only around 0.20-0.22Jmm^{-3}.

6. Conclusion

In safety and fuel economy significant progress has been achieved in the automotive industry. To assure these parameters new material types has been developed. High Mn alloys form a perspective generation of ductile high strength material. The family of high Mn alloys, characterized as the FeMnTWIP1100 materials, fulfil the technical requirements. Austenitic Fe-Mn-C alloys possess low stacking fault energy (SFE). It leads to the realization possibility of multiply simultaneous and/or sequential deformation mechanisms. In addition to dislocation slip

both mechanical twinning and ε-martensite formation are concurrent deformation mechanisms. They are linked to the SFE. In case of lower SFE, the ε-martensite is formed, preferentially, but after the getting over the ε-martensite is not initiated and the twinning formation is realized. The optimized mechanical properties are found in Fe-22Mn-0.6C alloys in temperature range between 80K and 500K, approximately.

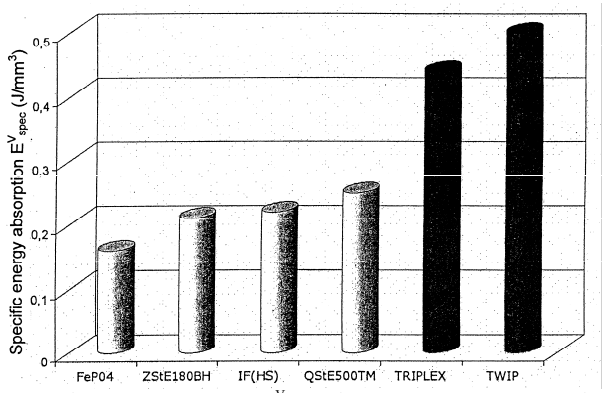

Fig.3 Diagram presents the specific energy absorption ($E^V_{spec.}$) of the FeMnTWIP1100 and of TRIPLEX. Compared data were obtained by testing of conventional deep drawing steel [6]

At temperatures higher than 500K, the SFE is sufficiently high and suppress twin formation. The active deformation mechanism is planar dislocation slip. The achieved optimized values are followed: R_p = 500MPa, R_m = 1100MPa, total elongation equals 50-55% practically by the same level of uniform elongation (the necking formation is suppressed by tensile testing). An important property characterizing the impact resistance of the FeMnTWIP1100 alloy is high energy absorption defined as dissipation energy per unit volume. The value detected for investigated high Mn alloy is 0.50Jmm^{-3}approximately, while the conventional material types (deep drawing steels) only attain the level about 0.20-0.22Jmm^{-3}

Acknovledgement

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