Materials Science and Engineering A 438–440 (2006) 459–463

MATERIALS SCIENCE & ENGINEERING A

www.elsevier.com/locate/msea

Transformation-induced plasticity of expandable tubulars materials

Xu Ruiping [a,*], Liu Jie [b], Zhang Yuxin [a], Guo Ruisong [a], Liu Wenxi [a]

[a] *School of Materials Science and Engineering, Tianjin University, Tianjin 300072, China*
[b] *Shanghai Tianhe Shape Memory Limited Corporation, Shanghai 201615, China*

Received 8 May 2005; received in revised form 18 January 2006; accepted 28 February 2006

Abstract

A new concept on strengthening-plasticity is presented in this paper, along with the design rules of the alloys with high expandable performance. The plasticity of expandable alloys induced by the $\gamma \rightarrow \varepsilon$ martensitic transformation, can be obviously improved. In order to enhance transformation-induced plasticity, alloys with low stacking-fault energy and high starting temperature of ε martensite $M_{s(\varepsilon)}$ should be looked for. Therefore, a formula for the calculation of $M_{s(\varepsilon)}$ of Fe-based alloys is also given in this paper in order to facilitate the design of expandable tubular materials.

Keywords: Strengthening-plasticity; Transformation-induced plasticity; Fe-based alloys; ε martensite

1. Introduction

Expandable tubular technology is an innovative technology in oil industry and has been viewed as a revolutionary well construction in the 21st century. Many papers or articles previously published have introduced its concept and applications in drilling. However, there are only few papers to introduce how to choose and design expandable tubular materials at present. This paper will present the design rules of expandable tubular materials and give a new concept, strengthening-plasticity, to express its comprehensive properties.

2. Strengthening-plasticity of materials

An idea of solid expandable tubular [1] (SET) was first put forward by the Royal Dutch Shell Technology Ventures, Inc. in 1992. Its principle [2,3] is to put the tubular into an oil well and make them expanded and deformed by pulling a specially designed grounder or pushing an expansion cone or mandrel. The main purpose of using expandable tubular is to diminish drilling dimension and widen oil-extracting pathway. SETs have been successfully installed in oil and gas fields since November 1999 [4], in a variety of environments in wells on land, offshore and in deepwater to solve a range of drilling and completion challenges. Practical field applications have shown that expandable tubular technology can reduce the overall cost of drilling greatly and shorten the construction period. Expandable tubular technology can be applied in a series of engineering technology, including petroleum drilling, fixing, completing and repairing wells. So expandable tubular technology has been viewed as a revolution in petroleum well tubular. Many petroleum companies at abroad and home have begun to develop and research this technology in recent years.

However, there are many difficulties in researching the materials of expandable tubular. Because expandable tubular are often installed in oceans or deepwater and have to bear great outside force, its materials should have high strength. Besides, the materials should also have excellent plasticity in order to meet the requirements of large deformation during the expansion process. So a new concept, which is strengthening-plasticity expressed by a parameter k, will be introduced in this paper to show its comprehensive properties. The parameter k, equals to the product of tensile strength σ_b and elongation rate δ, which are both measured under annealing condition:

$$k = \sigma_b \delta \quad (1)$$

If the unit of σ_b is MPa and δ is %, the unit of k is MPa%. A three-dimensional coordinate system can be used to show the relations among k, σ_b and δ. The value of k can be got from the upright axis of the plane of σ_b–δ, as shown in Fig. 1. From this figure, we can get the shape of this three-dimensional coordinate system looks like “hills” from top to bottom and the projection of the hills’ contour lines gives hyperbolas. The authors of this

---

[*] Corresponding author. Tel.: +86 22 27890485; fax: +86 22 27404471.
E-mail address: xuruiping99@eyou.com (X. Ruiping).

0921-5093/$ – see front matter © 2006 Published by Elsevier B.V.
doi:10.1016/j.msea.2006.02.173

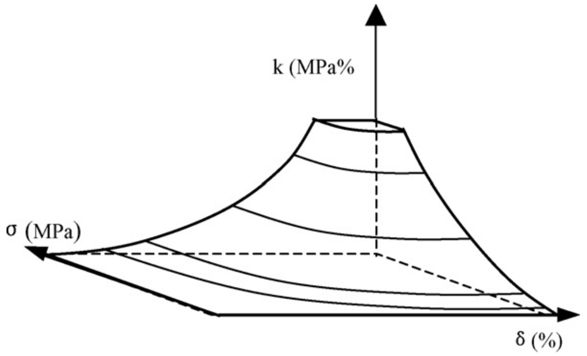

Fig. 1. The coordinates of strengthening-plasticity k.

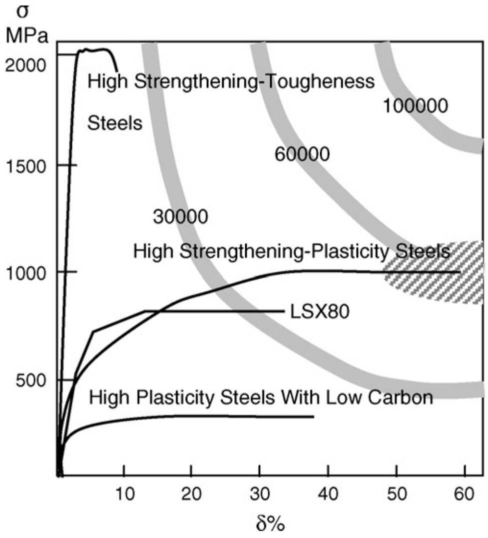

Fig. 2. The comparison of strengthening-plasticity among various types of steels.

paper have made many surface and field experiments on expandable tubular materials and compare the strengthening-plasticity of different kinds of steels. The result is as shown in Fig. 2. After many experiments, a kind of expandable alloys with excellent expandable performance was obtained at last, whose properties lies in the hatched zone in Fig. 2. This figure shows that the k of LSX80 researched by Enventure Global Technology L.L.C., is 30,000 MPa%, while the k of our expandable tubular materials reaches 60,000 MPa%, nearly two times that of Enventure Global Technology L.L.C. The measured mechanical properties of our researched expandable alloys are that σ_b is 990 MPa, σ_s 365 MPa, δ 61%, ψ 57% and work-hardened index n is 0.40, respectively. The k of high strengthening-toughness steels and high plasticity steels with low carbon seen from this figure, are both below 20,000 MPa%.

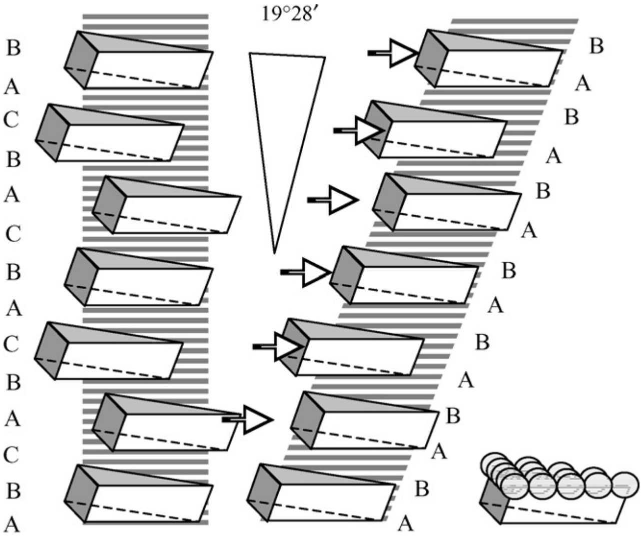

Fig. 3. The mechanism for the stress induced γ–ε transformation.

3. Design for high strengthening-plasticity steels and transformation-induced plasticity

The great trouble in designing expandable tubular materials is that the two properties of plasticity and strength are always contradictory, that is to say, the plasticity is low while the strength is high, such as the high strengthening-toughness steels. In turn, the high plasticity steels with low carbon have good plasticity, its strength is very low. In order to improve the strength and plasticity of expandable tubular materials at the same time, the mechanism of transformation-induced plasticity was used when we designed some compositions of Fe-based expandable alloys. This kind of alloy has been proven to have high strengthening-plasticity and outstanding expandable performance. The mechanism of transformation-induced plasticity is induced by the transformation from parent phase austenite γ to ε martensite when the materials are subjected to outside force. Partial plastic deformation has gone with phase transformation. Meanwhile, the double phase structure produced during the phase transformation can improve strain-hardening rate and prevent early necking phenomenon from happening. Therefore, transformation-induced plasticity can improve the strengthening-plasticity obviously. Besides, when designing expandable tubular material, it should also have high work hardening rate. The reason is to make the materials yield easily at the early period of expansion and improve their strength quickly at the later period, which can save a lot of expandable energies. The value of work hardening rate n discussed in this paper is more than 0.25, which can meet stable plastic deformation condition $d\sigma/d\varepsilon > \sigma$ [5,6]. So there are three characteristics for expandable tubular materials, i.e. high strength and high plasticity and high work hardening rate. It is important to know it when designing expandable tubular materials.

The composition of expandable alloys should lie in austenite zone according to Schaefflers figure [7]. So the addition of alloy elements should be strictly controlled to ensure that the structure of alloys is a single austenite phase. Only if the structure of alloys is an austenite, does the mechanism of transformation-induced plasticity function when expandable alloys deform under the action of stress. The mechanism of $\gamma \rightarrow \varepsilon$ martensite phase transformation is as shown in Fig. 3. The top and bottom plane of triangular prism show the place of close-packed atoms and the height of triangular prism is a planar distance between close-packed atoms. The arrowheads in this figure show the