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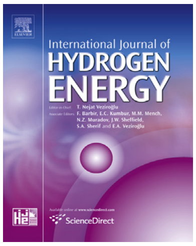

Short Communication

Determination of hydrogen compatibility for solution-treated austenitic stainless steels based on a newly proposed nickel-equivalent equation

Setsuo Takaki [a,*], *Shigenobu Nanba* [b], *Kazunari Imakawa* [c],
Arnaud Macadre [d], *Junichiro Yamabe* [e,g,**], *Hisao Matsunaga* [f,g],
Saburo Matsuoka [g]

[a] *Department of Materials Science and Engineering, Kyushu University, 744 Moto-oka, Nishi-ku, Fukuoka 819-0395, Japan*
[b] *Materials Research Laboratory, Kobe Steel, Ltd, 1-5-5 Takatsukadai, Nishi-ku, Kobe 651-2271, Japan*
[c] *Steel & Technology Development Laboratories, Nisshin Steel Co., Ltd, 4976 Momura Minamima-chi, Sunan, Yamaguchi 746-8666, Japan*
[d] *International Institute for Carbon-Neutral Energy Research (WPI-I2CNER), Kyushu University, 744 Moto-oka, Nishi-ku, Fukuoka 819-0395, Japan*
[e] *International Research Center for Hydrogen Energy, Kyushu University, 744 Moto-oka, Nishi-ku, Fukuoka-shi, Fukuoka 819-0395, Japan*
[f] *Department of Mechanical Engineering, Kyushu University, 744 Moto-oka, Nishi-ku, Fukuoka 819-0395, Japan*
[g] *Research Center for Hydrogen Industrial Use and Storage (HYDROGENIUS), Kyushu University, 744 Moto-oka, Nishi-ku, Fukuoka 819-0395, Japan*

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ABSTRACT

The nickel-equivalent equation for the materials selection of solution-treated austenitic stainless steels in present Japanese regulations does not consider nitrogen, which can improve resistance to hydrogen embrittlement. For the authorization of various austenitic stainless steels for use in high-pressure hydrogen gas and based on investigations of eight types of solution-treated austenitic stainless steels, this paper presented a newly proposed nickel-equivalent equation considering nitrogen. After tensile testing to the true strain ε of 0.3 in air at both room temperature (RT) and 228 K, the strain-induced martensite content V_M was measured by a saturation magnetization technique; the V_M correlated well with the proposed nickel-equivalent equation. For slow strain rate tensile (SSRT) testing in hydrogen gas at RT, the relative reduction in area (RRA) was consistently lower with increased V_M for $\varepsilon = 0.3$ at 228 K. This suggests that the austenitic phase stability is crucial in determining the RRA of the present

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* *Corresponding author*. Department of Materials Science and Engineering, Kyushu University, 744 Moto-oka, Nishi-ku, Fukuoka 819-0395, Japan. Tel.: +81 92 802 2983.

** *Corresponding author*. International Research Center for Hydrogen Energy, Kyushu University, 744 Moto-oka, Nishi-ku, Fukuoka 819-0395, Japan. Tel.: +81 92 802 3247.

E-mail addresses: takaki@zaiko.kyushu-u.ac.jp (S. Takaki), yamabe@mech.kyushu-u.ac.jp (J. Yamabe).

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Reduction in area
Martensitic transformation

austenitic stainless steels and the RRA was successfully quantified by the proposed equation.

Introduction

For the safety and reliability of metallic components used in high-pressure hydrogen gas, the susceptibility of the materials to hydrogen embrittlement (HE) must be determined precisely; thus, the components should be designed with consideration for the detrimental effects of hydrogen [1–3]. Slow strain rate tensile (SSRT) testing is a conventional method for characterizing the HE of metallic materials. In the SSRT test, a relative reduction in area (RRA) [4–10] has often been used to classify materials as appropriate for use in high-pressure hydrogen gas. Yamada and Kobayashi [7] proposed the following relational expression for qualifying 300-series austenitic stainless steels, e.g., Types 316 and 316L, for their use in hydrogen gas:

$$\begin{aligned}&(\text{RA obtained via tensile testing in inert gas or RA as reported in an inspection certificate}) \times \text{RRA}\\&\quad \geq (\text{Minimum requirement for RA specified in JIS standard})\end{aligned} \tag{1}$$

where RA is the reduction in area.

In most of the materials analyzed by Yamada and Kobayashi [7], RA in air exceeds 75%. However, the minimum requirement for RA in 300-series austenitic stainless steels is 60% as stipulated by the Japanese Industrial Standards (JIS); hence, 300-series austenitic stainless steels satisfying RRA $\geq$ 0.8 (or 60/75) are required. Yamada and Kobayashi also analyzed a series of RRAs for Type 304, 316, and 316L steels that revealed a relationship between the RRA and the nickel-equivalent content, Ni_{eq}, in 70-MPa hydrogen gas at 233 K. The relationship is successfully fitted by the following equation [7]:

$$\mathrm{RRA} = 0.6 + 0.4 \tanh\left(\frac{Ni_{eq} - 27.76}{1.339}\right) \tag{2}$$

where Ni_{eq} [mass %] is calculated by Ref. [11]:

$$Ni_{eq} = Ni + 12.6\,C + 1.05\,Mn + 0.65\,Cr + 0.98\,Mo + 0.35\,Si \tag{3}$$

where the unit for each element is mass percent. From Eq. (2), RRA $\geq$ 0.8 is equivalent to $Ni_{eq} \geq 28.5$ mass%.

From the aforementioned materials selection criterion based on the nickel-equivalent content, together with experimental results under various hydrogen pressures and temperatures, the present Japanese regulation permits the use of Types 316 and 316L with the following Ni_{eq} in hydrogen-gas environments at pressures of 20–82 MPa: $Ni_{eq} \geq 28.5\%$ at temperatures of 228–263 K; $Ni_{eq} \geq 27.4\%$ at temperatures of 263–293 K; and $Ni_{eq} \geq 26.3\%$ at temperatures of 293–523 K. Steel use is not limited in hydrogen gas at pressures lower than 20 MPa.

Materials regulated based on Ni_{eq} are often referred to as nickel-equivalent materials. As can be seen in Eq. (3), however, the present set of nickel-equivalent materials contains only six elements of nickel, carbon, manganese, chromium, molybdenum, and silicon. It does not contain nitrogen, which can often improve the RRA [10,12]. In order to enable the authorization of various solution-treated austenitic stainless steels for use in high-pressure hydrogen gas, a new nickel-equivalent equation considering nitrogen should be developed.

This study investigated an alternative nickel-equivalent equation that can determine the hydrogen compatibility of solution-treated austenitic stainless steels containing nitrogen, using data from experiments on eight types of such steels. After tensile testing to the true strain ε of 0.3 in air at room temperature (RT) and 228 K, the strain-induced martensite content V_M of the strained steels was measured by a saturation magnetization technique [13]. SSRT testing of the steels was also performed in hydrogen gas at pressures ranging from 78 to 115 MPa at RT. The collected experimental evidence permitted discussion of the relationship among the RRA, V_M, and Ni_{eq}.

Proposed nickel-equivalent equation

The nickel-equivalent equation in current use, Hirayama's equation [11], was derived to consider the effect of additive elements on the difference in free energies at RT between the ferrite and austenite phases of steel. The present study used the equation derived by Sanga et al. [14], because this formula is derived from thermodynamics functions, similar to Hirayama's equation. The effects of new elements can be considered by revising the thermodynamics function without experiments, which differs from the nickel-equivalent equation based on the M_{d30} parameter, which defines the temperature at which 50% of austenite has transformed to martensite after tensile extension to $\varepsilon = 0.3$ [12,15]. Regarding the effect of grain size on Ni_{eq}, Matsuoka et al. reported that V_M for Fe–16Cr–10Ni alloys with grain sizes of 1, 8, and 60 μm was not significantly affected by