CONTRIBUTION TO THE ASSESSMENT OF THERMAL AGEING OF STAINLESS STEEL CASTINGS AND WELDS

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ABSTRACT

Indentation tests are considered for measuring and verifying of thermal ageing of stainless steel castings and welds in service. Therefore, relations between indentation- and tensile diagrams were analyzed. Conventional tensile characteristics, deduced from the indentation diagram, should be used for fracture toughness prediction. Form of correlation of yield stress and tensile strength on one side and of fracture toughness on the other side was proposed, which is specific for austenitic-ferritic two-phase materials. Properties of castings and welds were compared and analyzed within the framework of a mesomechanical homogenization model with micromechanical effect of geometric slip distance.

Keywords: stainless steels, aging, thermal degradation, tensile properties, hardness, fracture toughness

1. INTRODUCTION

In this paper, some results of our analytical and experimental work are described, which - with the use of available literature data - are oriented to prediction of fracture toughness of stainless steel castings and welds thermally aged at water reactor operating temperatures. Obviously, prediction of fracture toughness must be based, primarily, on usual laboratory mechanical, fracture-mechanical and metallographical tests and evaluations including artificial ageing experiments or examination of actual field components after service. In addition to prediction of ageing degradation for an end-of-life or life-extension condition, it would be very useful to have the capability of measuring and verifying the severity of ageing for a given component at a given time of service; indentation diagrams measurement is an attractive possibility. Therefore, our work which is actually under development encompasses 3 specific areas, which are closely interdependent, and which - in combination with usual tests and evaluations - will permit to attain the specified goal:

1) Development of method of indentation diagrams analysis, i.e. of derivation of the conventional characteristics $R_{p0.2}$ and R_m from indentation diagrams.

2) Formulation of the correlation between $R_{p0.2}$ and R_m on the one side and fracture toughness resistance curve $J=J(\Delta a)$ on the other side.

3) Analysis and mesomechanical modeling - selection and application of the physical-mathematical model for constitutive properties "homogenization" using constitutive properties of both phases (austenite and ferrite) and their volume ratio and geometric distribution.

At present, our mesomechanical constitutive modeling of two-phase stainless steel castings and welds results in a qualitative interpretation of several characteristics of thermal ageing degradation of fracture toughness for both material types. Quantification of several characteristics is desired, is possible and is under way.

2. DEVELOPMENT OF METHOD OF INDENTATION DIAGRAMS ANALYSIS

The decision to base the fracture toughness prediction in a substantial manner on the indentation diagrams obtained from tests on field components was motivated by positive experience with indentation diagrams measurement and evaluation in connection with diagnosis of radiation hardening and regeneration annealing effects on reactor pressure vessels /1/. For stainless steel castings and welds, the ageing effects on stress-strain diagram, or on $R_{p0.2}$ and R_m, are different from the thermal treatment-, irradiation- or testing temperature effects on stress-strain diagram of ferritic steels for RPV's. For these ferritic steels, the main effect of the parameters mentioned consists in a modification of strength coefficient, preserving the shape of stress-strain curve (or strain hardening exponent). On the contrary, thermal ageing of two-phase stainless steels leaves $R_{p0.2}$ (practically) unchanged, with increasing R_m. Therefore the indentation diagrams evaluation method successfully used in the case of ferritic steels cannot be simply applied. Further development of the evaluation method is necessary.

For determination of yield stress $R_{p0.2}$ and tensile strength R_m from the indentation diagram, or of stress-strain curve $\sigma=\sigma(\epsilon)$ from Meyer hardness curve HM=HM(d/D) (here d and D are indentation- and indentor diameters, respectively), semiempirical methods are used. The most detailed data concerning analysis of indentation diagrams, which are currently available, /2/ show that the relation between stress-strain and indentation diagrams may depend on some factors, such as nonsphericity of yield surface or behaviour under nonproportional loading, which do not apply at usual tensile tests. Relation between HM=HM(d/D) and $\sigma=\sigma(\epsilon)$ may be analysed in detail only by numerical simulation of indentation test using finite element method. We used published results /3,4/ and carried out our own calculations - numerical simulation of indentation tests using a program system SYSTUS (Framasoft) with two variants of a constitutive model (isotropic, elastic/incompressible plastic solid complying with von Mises'yield condition and with isotropic or kinematic hardening). Numerical simulation of indentation diagrams based on finite element method shows that the relation between indentation diagram and the tensile diagram is - for both austenitic and ferritic steels - principially simple. Materials of both types behave according to the simplest model- flow theory with spherical yield surface and isotropic hardening. The correlation is not complicated by such phenomena as kinematic hardening or distorded form of yield surface. According to our meaning, this feature should be valid for two-phase austenitic-ferritic alloys as well. Namely, we take as sufficiently confirmed (both experimentally and by model calculations) that the "constraint factor" CF for passage from Meyer hardness HM to flow stress σ(σ=HM/CF, based on the correspondence $\epsilon_{ef}=0.2(d/D)$, where ϵ_{ef} is a characteristic strain under the indentation with dimensionless size d/D) is in certain range of (d/D)-values equal to CF=2.9.

Method of indentation diagrams is sufficiently sensitive, but its successful application to solution of our problem - diagnosis of ageing of stainless steel castings and welds - may depend on other factors. Inhomogeneity and anisotropy of materials may cause that the interpretation of results may be ambiguous. Actually, it is not possible to judge if the indentation testing method will have practical significance for welds, where the ageing influence on $\sigma=\sigma(\epsilon)$ may be small.

3. CORRELATION BETWEEN THE TWO QUANTITIES $R_{p0.2}$ AND R_m AND FRACTURE TOUGHNESS RESISTANCE CURVE

Prediction of fracture toughness on the base of measured, or from indentation diagram determined, values of $R_{p0.2}$ and R_m (or values $R_{p0.2}$ and R_m determined as a result of a physical-mathematical model of ageing, as will be described in part 4 of the paper) needs to find an appropriate form of correlation between $R_{p0.2}$ and R_m on the one side and $J=J(\Delta a)$ on the other side. To this end we used the data selected from /5/. The correlation was searched in a form $J_c=R_{p0.2}.f(R_m/R_{p0.2})$, which has some physical significance: J_c is proportional to $R_{p0.2}$, which characterize the temperature dependence or material special features in a class of materials with similar behaviour. Dimensionless factor $f(R_m/R_{p0.2})$ characterizes the influence of strain hardening.

The chemical composition of weld metal made from the material Sv04Ch19N11M3 approaches to the chemical composition of heats 74 and 75, with principal chemical composition and ferrite volume ratio as follows /6/:
heat 74: 19.11% Cr, 9.03% Ni, 2.51% Mo, 15.5% ferrite,
heat 75: 20.86% Cr, 9.12% Ni, 2.58% Mo, 24.8% ferrite.
We analysed results of tests at 25°C. From Tab. 4 we took values $R_{p0.2}$ and R_m for different thermal ageing histories, from Tab. 5 the corresponding values of fracture toughness J_c (basic variant of J-integral, named "deformation J"). The ageing temperature 450°C was not included into the analysis; at 450°C ageing processes proceed which do not correspond to processes in service of reactor components /6/, therefore according to /6/ data associated with 450°C are not appropriate for simulation of thermal ageing in service. We have further excluded from final evaluation all variants (some ageing histories for heat 75) having excessive dispersion of $(R_m/R_{p0.2})$-values. (Exclusion of values with excessive dispersion, concerning heat 75 with higher ferrite volume ratio and higher degree of embrittlement, is reasonable, as other data show /7/; it is explicitely mentioned there /7/ that at tensile testing of severely embrittled materials the specimens fail before attaining smooth load maximum. Therefore in such cases the measured tensile strength does not characterize strain hardening.) Fig. 1 shows the data after exclusion of values corresponding to initial state, which are influenced by internal stress according to /5/. It is evident that for inter- or extrapolation of the data the power relation

$$J_c/R_{p0.2}=K.(R_m/R_{p0.2})^n$$

can be used, where K depends only approximately on chemical composition and probably also on other factors, such as ferrite volume ratio and ferrite distribution. Considering the dispersion of experimental results it is not sure that the value of exponent n is constant for both heats (for both chemical compositions).

4. ANALYSIS AND MESOMECHANICAL MODELING - CONSTITUTIVE PROPERTIES, FRACTURE TOUGHNESS AND AGEING OF STAINLESS STEEL CASTINGS AND WELDS

One of the goals of our work is a more fundamental comparison of properties of two-phase stainless steel castings with those of welds, namely of their constitutive properties and fracture toughness in initial state and of their tendency to properties degradation during thermal ageing. Principially, both types of materials are similar; differences consist in ferrite volume ratio and in distribution (particle size) of ferrite in austenitic matrix. We are also attempting to elucidate relations between mechanical properties in microscale (represented by microhardness of ferrite particles) and macroscopic properties of material. (Our considerations are based on principal hypothesis, which is according to our meaning undoubtedly correct: microphysical processes causing ferrite ageing, namely the most important process of spinodal decomposition of the solid solution, are not influenced by particle size of ferrite. These microphysical processes were subjects of detailed studies by American and French teams - we give for orientation only two references to recent work /8,9/.)

For attaining this goal, it is suitable to use mesomechanical models, i.e. models for homogenization of constitutive (elastic/plastic) properties of "composite" formed by austenite and ferrite. Models of this type make possible to solve, or assess, the following problems:

a) correction of the constitutive properties on different ferrite volume ratio,
b) determination of limit values of $R_{p0.2}$ and R_m corresponding to saturated thermal ageing of the dispersed phase, and
c) influence of the phases geometry on $R_{p0.2}$ and R_m.

Comparison of fracture toughness in initial state represents a qualitatively different problem: in semiempirical relations between constitutive properties and fracture toughness a somewhat mysterious quantity figures, "characteristic size of the process zone". It is matter of fact that fracture toughness $J_{0.2}$ of weld metal in initial state /10-12/ is typically less than fracture toughness of castings with higher ferrite volume ratio, in initial state /5/. This phenomenon may be interpreted so, that the structure with more coarse ferrite dispersion leads to larger characteristic size of the process zone in front of the crack tip, and therefore has larger fracture toughness. This somewhat unusual phenomenon is, nevertheless, known with high strength steels /13,14/, and is connected with certain mechanism of crack growth, which becomes evident by characteristic symptoms. These same characteristic symptoms appear with materials in which we are interested, as Table 1 shows.

Table 1.
Mechanism of crack growth (deformation localization and failure initiation in bands, zig-zag crack growth) and characteristic features of fracture toughness

consequences expected (according to analogy with high-strength steels)	experimental observations with two-phase stainless steel castings and welds
- "anomalous" dependence of fracture toughness on grain size	- "anomalous" dependence of fracture toughness on ferrite distribution "size": lesser fracture toughness of welds /10-12/ relative to fracture toughness of castings /5/
- deviation of crack growth path, crack branching	- deviation of crack growth path, accompanied by break of resistance curve $J=J(\Delta a)$ with aged castings /5/; break of $J=J(\Delta a)$ with castings and welds in initial state and after ageing /5,10-12/

Sufficient amount of informations on homogenization of constitutive properties are available; even the experience with stress-strain curve prediction for aged austenitic-ferritic alloys /15/ was published. We decided to use this approach in solving our problem. Alternative models also exist /16,17/; these models should be mutually compared and the optimal one should be selected. Mesomechanical models are continuum mechanical ones and, consequently, they do not describe the influence of structural dimension of the modeled system dispersed phase - matrix. In comparing properties of welds and castings in different ageing states, not only different ferrite volume ratio and different conventional constitutive properties determined by actual degree of spinodal decomposition of solid solution play a role, but also the dimensional factor - geometric slip distance /18/. This dimensional factor causes that weld metal with lower ferrite volume ratio has higher yield stress compared with cast material with higher ferrite volume ratio. Mesomechanical homogenization model with micromechanical effect of geometric slip distance enable us to classify, interpret and bring into mutual relation the different facts concerning the influence of thermal ageing of castings and welds on constitutive properties, Charpy impact energy and fracture toughness, as Tab. 2 shows.

Table 2.
Mesomechanical model of homogenization of constitutive properties with micromechanical effect of geometric slip distance and qualitative characteristics of thermal ageing of castings and welds

consequences expected (according to the model)	experimental facts
- approximately linear dependence of $\sigma=\sigma(\epsilon)$ on ferrite volume ratio (for small ferrite volume ratios)	- for castings linear dependence of HV30 on ferrite volume ratio, different for different states of ageing/9/
- absence of ageing influence on initial part of $\sigma=\sigma(\epsilon)$, until ferrite does not deform plastically; ageing influence on $\sigma=\sigma(\epsilon)$ in strain interval, where ferrite in initial state deform plastically	- for castings ageing does not practically influence $R_{p0.2}$, R_m grows by ageing /5/
- when at tensile test or at Charpy impact test or at fracture toughness test specimen fractures before plastic deformation of ferrite begins, ageing of ferrite (or further ageing of ferrite) does not influence fracture	- for castings the saturation of impact energy begins before saturation of microhardness does /9/
- when ferrite is more finely distributed and, therefore,	- for welds (contrary to castings) lower ageing

lower geometric slip distance causes higher ferrite strength properties, strain interval within which ageing of ferrite does not influence mechanical-, eventually also fracture properties of "composite" grows	influence on impact energy or fracture toughness than expected according to the ferrite volume ratio; eventually on the background of internal stress relaxation the ageing embrittling influence cannot be practically detected /11/
- as a consequence of volume changes at phase transformation during cooling internal stress on a mesomechanical scale (tensile stress in ferrite) arises; internal stress can diminish fracture toughness	- with both castings and welds in the first ageing stage the effect of internal stress relaxation dominates and fracture toughness increases /5,11/

From Tab. 2 approximative comparison of behaviour of castings and welds at thermal ageing follows. More exact comparison will be attained after experimental examination of welds aged in service, after "definitive" selection and application of the homogenization model and after quantification of the micromechanical effect of geometric slip distance.

5. CONCLUSIONS

A. We intent using the indentation tests for non-destructive measuring and verifying of thermal ageing of stainless steel castings and welds in service. Therefore, the relations between indentation- and tensile diagrams were analyzed and the quantitative relation was shown, both for austenitic and ferritic steels.

B. After determination of $R_{p0.2}$ and R_m, the prediction of fracture toughness should follow. Therefore, the form of correlation of $R_{p0.2}$ and R_m on one side and of $J = C.(\Delta a)^n$ on the other side was proposed, specific for austenitic-ferritic two-phase material.

C. For the purpose of more fundamental comparisons of properties of two-phase stainless steel castings and welds we are selecting a mesomechanical model of homogenization of constitutive properties. This model enable us to classify, interpret and bring into mutual relation different facts concerning influence of thermal ageing of castings and welds on constitutive properties, Charpy impact energy and fracture toughness. It follows from the model that the sensitivity of the weld metal to thermal ageing is low, comparing with the sensitivity of the cast material.

D. Further progress in the assessment of thermal ageing of stainless steel castings and welds will be attained by experimental examination of welds after service and by further development of the homogenization model.

E. The promising diagnostic method of indentation diagrams should be verified in field. This method is principially appropriate, but - especially with welds, where large effects of thermal ageing are not expected - it is not sure if it will be possible to detect the ageing effects on the background of disturbing effects of inhomogeneity and anisotropy of properties.

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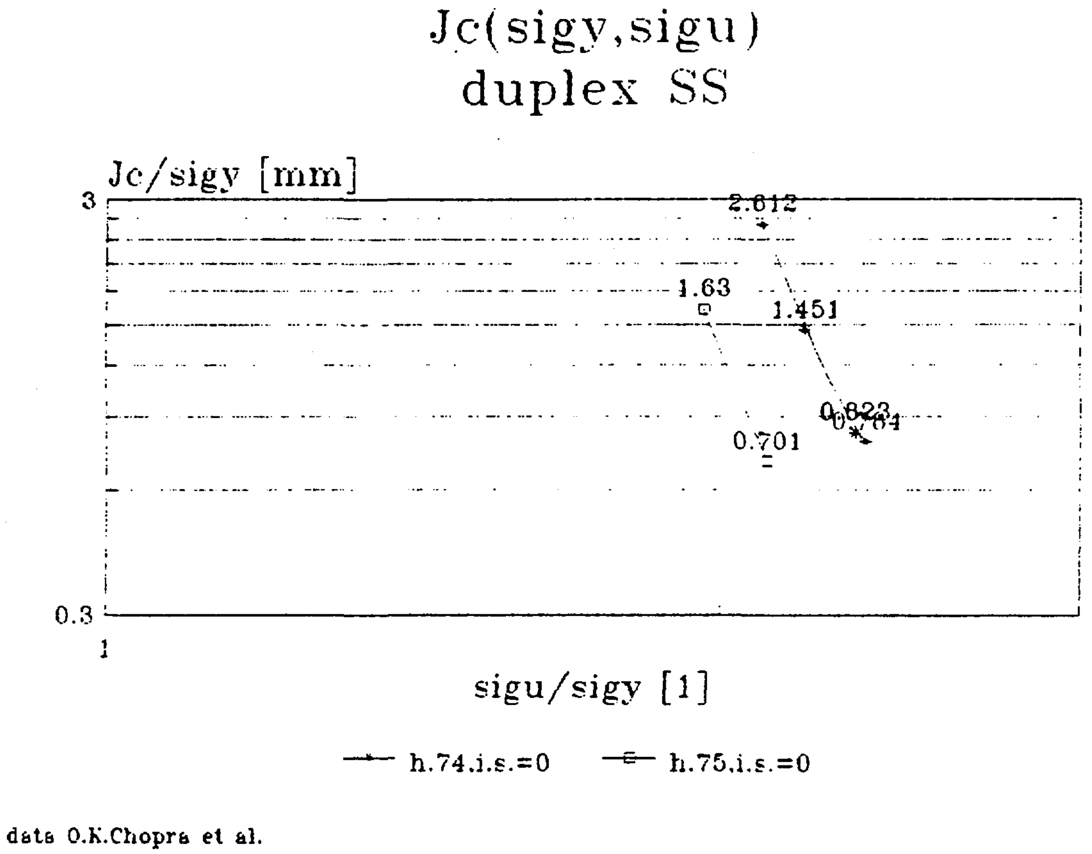

Fig 1.
Relation between J_c, $R_{p0.2}$=sigy and R_m=sigu for two heats of austenitic-ferritic steel CF-8M with different chemical composition and ferrite volume ratio, in different thermal ageing states, after internal stress relaxation.