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EVALUATION AND UNCERTAINTY ESTIMATES OF CHARPY-IMPACT DATA*

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ABSTRACT

Shifts in transition temperature and upper-shelf energy from Charpy tests are used to determine the extent of radiation embrittlement in steels. In order to determine these parameters reliably and to obtain uncertainty estimates, curve fitting procedures need to be used. The hyperbolic tangent or similar models have been proposed to fit the temperature-impact-energy curve. These models are not based on the actual fracture mechanics and are indeed poorly suited in many applications. The results may be falsified by forcing an inflexible curve through too many data points. The nonlinearity of the fit poses additional problems.

In this paper, a simple linear fit is proposed. By eliminating data which are irrelevant for the determination of a given parameter, better reliability and accuracy can be achieved. Additional input parameters like fluence and irradiation temperature can be included. This is important if there is a large variation of fluence and temperature in different test specimens. The method has been tested with Charpy specimens from the NRC-HSST experiments.

INTRODUCTION

Shift in transition temperature and upper-shelf energy from Charpy tests are used to determine the extent of radiation embrittlement in steels and to construct trend curves in order to predict the safe operating limits of reactor pressure vessels over the lifetime of the reactor. These parameters are obtained from temperature-impact-energy curves which summarize

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the results of Charpy tests under varying test temperatures. Eyeball fitting is at present the most widely used procedure for obtaining these curves. This method contains a large measure of arbitrariness and is not suited to determine uncertainty bounds for the test results. It has therefore been suggested to apply least squares fitting procedures which allow a complete uncertainty analysis of the test data. Such an analysis is particularly important if the number of test specimen is relatively small as it is the case in pressure vessel surveillance capsules and in most materials irradiation experiments. One such method has been developed by the author and is published in Ref. 1. This paper gives a brief description of the procedure and a typical application.

DESCRIPTION OF THE METHOD

Each Charpy test is characterized by a number of test parameters. Impact energy and test temperature are the most important ones; in addition there are lateral expansion, fibrosity, irradiation fluence and temperature, and chemical composition, e.g. copper content. A set of k parameters may be selected for the analysis, x_{ij} being the value of the i-th parameter for the j-th experiment. These parameter values are considered random variables, normally distributed with known variances σ_{ij}. The parameters are fitted to a linear model

$$C_0 + \sum_{i=1}^{k} C_i \bar{x}_{ij} = 0, \; j = 1, 2, \ldots n \quad . \qquad (1)$$

The coefficients are determined through a procedure which minimizes the differences between the measured values x_{ij} and the adjusted values $\bar{x}_{ij}$ in the sense of minimum χ^2, i.e.

$$\chi^2 = \sum_{i=1}^{k} \sum_{j=1}^{n} (x_{ij} - \bar{x}_{ij})^2 / \sigma^2_{ij} = \min \quad . \qquad (2)$$

There are no dependent and independent variables as in the conventional least squares curve fitting procedures. Instead there is an arbitrary scale factor which permits to fix one of the coeffients, say c_k, to

$$c_k = 1 \quad . \qquad (3)$$

The other coefficients are themselves random variables whose variances and covariances can be determined by standard statistical methods.[2]

The test parameters $\bar{x}_{ij}$ cannot always be expected to fit adequately a linear model (1) but there are usually not enough data available to distinguish between the simple linear model and a more complex nonlinear one. Indeed any linear model is valid locally, that is for a range of parameter values which is sufficiently restricted. Most importantly, data from the upper shelf region should be separated from data obtained in the transition zone since the determination of upper shelf energy should not influence the determination of the 30 ft-lb or 50 ft-lb transition temperature and vice versa.

Instead of restricting the parameter values a nonlinear transformation may be applied to fit a wider range of different conditions. Empirical trend curves can be tested in this manner.

NUMERICAL EXAMPLE

The method was applied to a series of weldments which had been irradiated in the second and third series of the BSR-HSST metallurgical experiments.[3] The Charpy specimen in these experiments received widely differing amount of fluence (between 4 and 12 $\cdot$ 10^{18} n/cm^2 Φ > 1.0 MeV), irradiation temperature (500° - 600°F), and had different chemical composition (0.2% - 0.4% copper content). In each group with the same chemical composition there was also a set of unirradiated control specimen.

The specimen were grouped into sets with similar irradiation conditions and chemical composition. However the number of specimen in each group was usually too small to determine reliably the transition temperature and upper shelf energy. Next specimen with the same chemical composition but different irradiation conditions were combined. The common temperature-impact-energy curve for one set is shown in Fig. 1. This graph contains not only the linear approximations in the transition and the upper shelf region but also their 1 σ uncertainties, both for irradiated and control specimen. The calculation gives also the coefficients for the dependency of the transition temperature on fluence unirradiation temperature together with their standard deviations. The values for the 63W series were

30 ft-lb transition temperature = 184°F ± 19°

irradiation temperature coefficient = -0.54 ± 0.44 (°F transition temperature per °F irradiation temperature)

fluence coefficient = 8.6 ± 8.1 (°F transition temperature per 10^{18} n/cm^2 > 1.0 MeV)

The temperature and fluence coefficients have reasonable values but the large variances render them not statistically significant. By combining all irradiated specimens one obtains

irradiation temperature coefficient = -0.78 ± 0.09

fluence coefficient = 14.9 ± 1.7

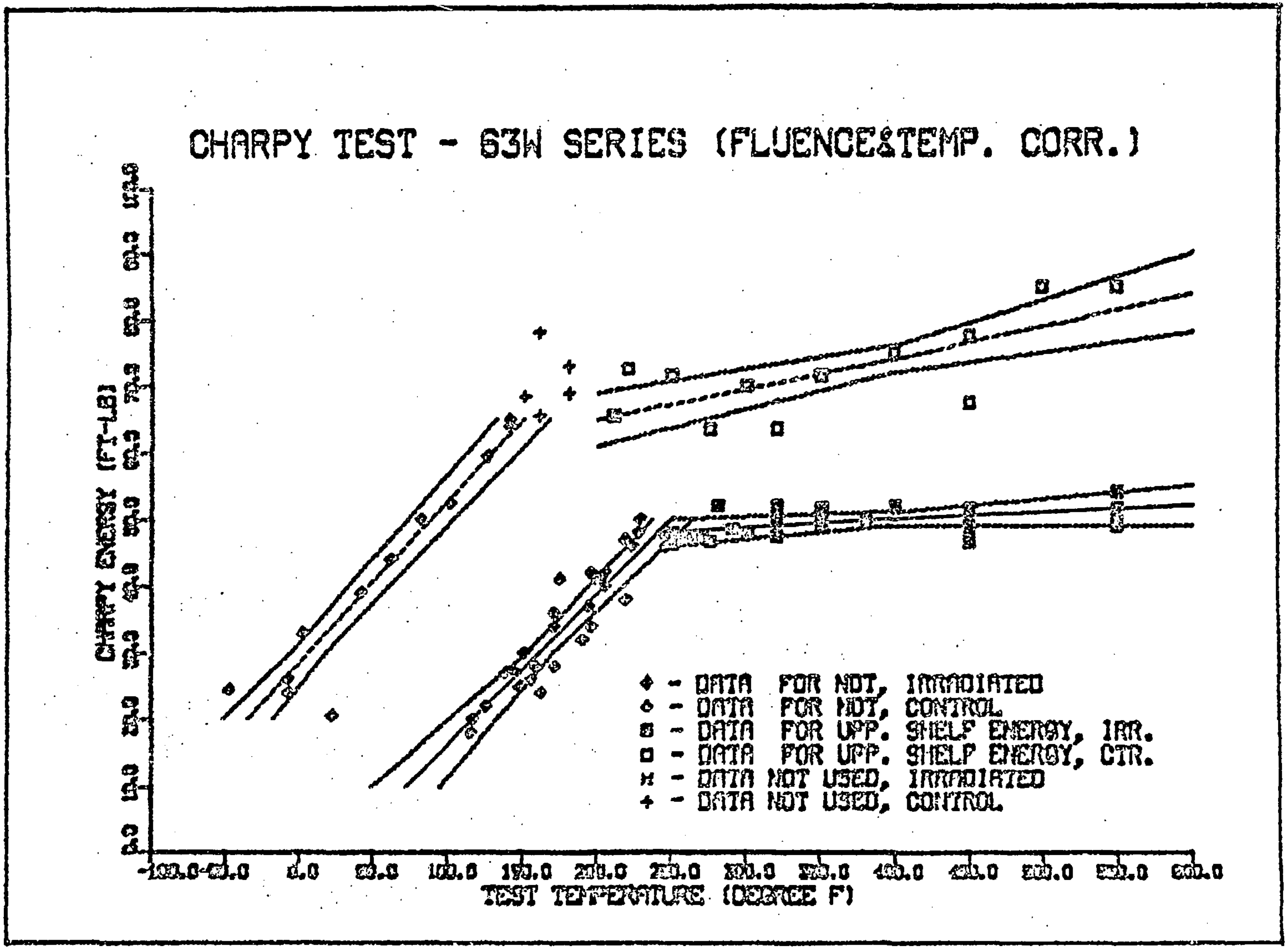

Fig. 1. This graph represents the Charpy test results of the 63W series of weldments. The transition and upper shelf regions are fitted to straight lines. The upper and lower broken lines are the 1σ uncertainty bounds. The open symbols on top represent unirradiated controls.

copper coefficient = 77.7 ± 6.6 (°F transition temperature per 0.1% copper content)

These values are certainly significant.

The linear model implied in these coefficients differs from the customary 0.5 or 0.3 power model for the relation between fluence and shift of transition temperature. Work is in progress to modify the present computer code to accept the corresponding non-linear transformation of the test parameters. The basic algorithm remains the same.

CONCLUSION

A statistical analysis of charpy test data is necessary to obtain reliable uncertainty bounds for the determination of transition temperature and upper shelf energy. A generalized linear least squares fitting method can be an effective tool for the determination of these parameters and their variances. It can also be used to determine the dependency of these parameters on irradiation conditions and chemical compositions. Modifications of the existing computer code are in progress in order to investigate non-linear models.

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