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# Master Curve analysis of potentially inhomogeneous materials

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ABSTRACT

The Master Curve methodology is now widely used for ensuring the integrity of ferritic steel structures against brittle fracture. The methodology has been recently extended to the treatment of macroscopically inhomogeneous materials through bimodal and multimodal approaches. This can be of practical importance in many applications. However, the conditions of applicability of those advanced techniques remain a weak point. In this work, it is shown that a probabilistic approach can provide guidance to select the appropriate method and to measure the confidence level in statements about inhomogeneity. The method proposed is applied successfully to a practical case.



## 1. Introduction

Ensuring the structural integrity of heavy section steel structural components such as the reactor pressurized vessel is of utmost importance to avoid major accidents. Among the possible failure modes, brittle failure is critical as it occurs without warning, with extremely high crack propagation speed. It can thus be the limiting life time factor of ageing components. The development of the Master Curve test method, standardized by the American Society for Testing and Materials, ASTM, in 1997 [1], has been a milestone for the rationalization of this failure mode.

In most mechanical test methods, the result of one single test at a given temperature provides a value that is representative of the material property to be measured. Assuming a Gaussian distribution, average and standard deviation on test replicas provide sufficient information for the statistical treatment of the material property of interest. The Master Curve approach, on the contrary, requires at least six fracture toughness tests to calculate the reference temperature, $T_0$. This value allows the fracture toughness distribution to be fully characterized, under the assumption of a unique fracture toughness temperature dependence and a failure scatter following a well-defined Weibull distribution. The formal definition of the reference temperature [1] is the test temperature at which the median of the fracture toughness distribution from one inch size specimens will equal 100 MPa$\sqrt{m}$. The relative large scatter of fracture toughness tests is a consequence of the inhomogeneity at the microscopic scale, due to features such as carbides distribution, as well as to varying grain size and orientation. As multiple tests are required in the Master Curve test method, the test standard ASTM E1921-11a [1] only applies to materials that are homogeneous at the macroscopic scale. However, in practical applications, it turns out that heavy section plates, forgings and welds are not homogeneous at the macroscopic scale. Some deterministic inhomogeneities at the macroscopic scale, due for example to cooling rate differences along the thickness during the heat treatment, can be easily taken into account by specifying that the specimens should be extracted from the 1/4 and 3/4 thickness location. This ensures that the samples come from a location that is likely to be homogeneous at the macroscopic scale, but does not guarantee that they are representative for the whole structure. Thus, appropriate safety factors need to be introduced.

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**Nomenclature**

| | |
|---|---|
| ASTM | American Society for Testing and Materials |
| $C_1$, $C_2$ | constant values |
| $C_B$ | confidence that a material follow a bimodal distribution |
| $C_H$ | confidence that a material is "reasonably" homogenious |
| $C_I$ | confidence that a material is "significantly" inhomogeneous |
| $C_M$ | confidence that a material follow a multimodal distribution |
| erf($x$) | error function |
| $LB_{BM}$ | temperatures at the 100 MPa$\sqrt{}$m level of the 5% tolerance bound of the bimodal Master Curve analysis |
| $LB_{MC}$ | temperatures at the 100 MPa$\sqrt{}$m level of the 5% tolerance bound of the homogeneous Master Curve analysis |
| $LB_{MM}$ | temperatures at the 100 MPa$\sqrt{}$m level of the 5% tolerance bound of the multimodal Master Curve analysis |
| $LBM$ | measurement of the difference between the probability of the bimodal and multimodal distributions |
| LBS | Lower Bound Shift |
| $LH$ | sum over each data of the natural logarithm of the failure density function for the homogeneous Master Curve distribution |
| $LB$ | sum over each data of the natural logarithm of the failure density function for the bimodal distribution |
| $LM$ | sum over each data of the natural logarithm of the failure density function for the multimodal distribution |
| $M$ | measure of material inhomogeneity |
| $M_b$ | a measure of material inhomogeneity based on $T_a - T_b$ (bimodal distribution) |
| $M_{b^*}$ | an alternative measure of material inhomogeneity based on $T_a - T_b$ (bimodal distribution) |
| $M_c$ | arbitrary level of "acceptable" material inhomogeneity |
| $M_{LBS,b}$ | a measure of material inhomogeneity based on LBS (bimodal distribution) |
| $M_{LBS,m}$ | a measure of material inhomogeneity based on LBS (multimodal distribution) |
| $M_m$ | measure of material inhomogeneity based on $\sigma_{Tm}$ (multimodal distribution) |
| MC | Master Curve |
| $N$ | total number of data |
| NPP | Nuclear Power Plant |
| $p_a$ | proportion of the "$a$" population (bimodal distribution) |
| $p_b$ | proportion of the "$b$" population (bimodal distribution) |
| $R$ | correlation coefficient |
| $r$ | number of valid data |
| $T_0$ | reference temperature (homogeneous material) |
| $T_{0,m}$ | average reference temperature of the different populations (multimodal distribution) |
| $T_a$ | reference temperature of population "$a$" (bimodal distribution) |
| $T_b$ | reference temperature of population "$b$" (bimodal distribution) |
| $\sigma$ | standard deviation |
| $\sigma_M$ | uncertainty on the measure of material inhomogeneity |
| $\sigma_{Tm}$ | standard deviation of the reference temperature of the different populations (multimodal distribution) |

For data sets containing non-deterministic macroscopic inhomogeneities, a method has been proposed by Wallin et al. [2] and is under consideration for being included in a non-mandatory annex of the E1921 standard. This method allows the treatment of two cases of inhomogeneities, namely the bimodal and the multimodal Master Curve. The bimodal Master Curve is the combination in a given proportion of two populations in one data set, each population being characterized by its reference temperature. The multimodal Master Curve allows the treatment of data sets composed by a multitude of populations. The different populations follow a normal distribution characterized by an average reference temperature and a standard deviation. The bimodal and multimodal Master Curves are able to cover a wide range of typical inhomogeneities and have already found many applications. Some applications were directed towards materials that are notoriously inhomogeneous, such as WWER steels [3–7], the EURO data set [8,9], ferritic–martensitic steels [10] or pipeline welds [11]. In other applications, the main goal was the verification of a homogeneous behavior in particular conditions, such as dynamic loading [12,13], irradiation [14–17], or in connection with the microstructure [18]. Other research work was related to structural applications [19–21].

Three Master Curve methods are therefore currently available, that cover various possible situations: homogeneous, bimodal and multimodal materials. Yet, a few important issues concerning these methods remain open, such as:

- Which method should one select?
- What is the minimum size requirement of the data set to obtain sufficient confidence?
- When should a material be defined as inhomogeneous and, in this case, what is the probability of making a wrong statement?