Tensile Testing of Steel Specimens
Using the Metal Magnetic Memory Method

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Abstract
Due to the problematic resource assessment of aging equipment at hazardous facilities currently, necessity of improve the means and methods of non-destructive testing of stress-strain state is becoming more topical. Usually to define the capabilities of the selected NDT method the tensile tests are widely used, NDT method and control devices are calibrated then simultaneously with of the sample’s simulated mechanical characteristics definition. The report considers the MMM method’s capabilities for determination of the mechanical characteristics (proportional limit, yield strength and tensile strength) on the example of tensile testing of steel specimens as well as results of tensile testing of steel specimens. Testing of the MMM method and magnetometric TSC (Tester of Stress Concentration) type instruments at expansion of steel specimens in a tensile testing machine MVK-MVO-51 was carried out at the ISD DUNAFERR Laboratory (Budapest).

Keywords: Metal Magnetic Memory method (MMM), non-destructive testing (NDT)

Currently, due to the problem of aging equipment lifetime assessment at hazardous production facilities, the need to improve the efficiency of the methods and devices of non-destructive testing (NDT) of stress-strain state (SSS) becomes more and more relevant.

To determine the capabilities of a selected SSS NDT method, tensile testing of specimens are widely used, when calibration of the method and inspection instruments is performed simultaneously with determination of the specimen’s conventional mechanical properties. Such testing results in establishing of the correlation between the physical field parameters used by this method and NDT instrument and the specimen’s strain-force parameters recorded on the “σ-ε” diagram of the test plant.

At present the metal magnetic memory (MMM) method developed by Energodiagnostika Co. Ltd. (Moscow, Russia) is more and more commonly used in practice for solution of the problems of equipment SSS NDT. Russian and international standards on the MMM method are available.

In accordance with GOST R ISO 24497-1-2009 “Non-destructive testing. Metal magnetic memory method. Vocabulary”, the MMM method is a non-destructive testing method based on recording and analysis of the distribution of self-magnetic leakage fields (SMLF) occurring on products in stress concentration zones (SCZs) and structural inhomogeneity. In this case SMLF reflect irreversible variation of magnetization in the direction of the action of maximum stresses due to work (external) loads, as well as structural and process history of products and welded joints after their fabrication and cooling in the magnetic field of the earth.

1 One should distinguish the traditional concept of “stress concentrator” from the materials science concept of “stress concentration” that occurs in areas of stable dislocations slip bands due to the effect of workloads.
The MMM method differs fundamentally from all the known magnetic NDT methods by the fact that its application does not require artificial magnetization of a product, but it uses the natural magnetization and after-effect that appears in the form of magnetic memory of the metal to actual strains and structural changes.

In 2011, under the contract between TUV Rheinland InterCert Kft. (Budapest, Hungary) and Energodiagnostika Co. Ltd. (Moscow, Russia) validation of the MMM method was carried out for the purpose of its approval for application during the examination and inspection of hazardous industrial facilities. Validation was performed through series of tests in industrial and laboratory conditions.

ISD DUNAFERR Laboratory (Budapest) conducted testing of the MMM method and TSC-type (testers of stress concentration) magnetometric instruments during stretching of steel specimens on the MVK-MVO-51 tensile-testing machine (MVK-09-SZ-65-01-03-10).

It is known that during standard tensile tests of steel specimens force (yield strength $\sigma_{0.2}$ and tensile strength $\sigma_t$) and strain (relative elongation $\delta$ and relative contraction $\psi$) characteristics of the material are obtained that are conditional. They are conditional because the prerequisites are: specific specimen shape and specific sequence of tests. In addition, such specimen testing results in obtaining of stresses ($\sigma_{0.2}$, $\sigma_t$) that are not internal stresses occurring on the specimen during the tensile strain; they only represent a conditional equivalent of stresses – an external specific force applied to the specimen of a specific shape.

Another important characteristic of the material’s mechanical properties is proportional limit - $\sigma_{p.l.}$ (or elasticity limit). This important but conditionally specified characteristic has a clear physical interpretation: there is a point the “stress-strain” curve near the conditional conventional proportional limit, which is characterized by the fact that incremental values of elastic and plastic components of longitudinal strain at low variation of the load are equal in it – derivatives of elastic and plastic strain components by stress are equal.

During the normal standard tensile testing of a steel specimen the tensile-testing machine recorder produces a “stress-strain” diagram ($\sigma$-$\varepsilon$) that shows the values of $\sigma_{0.2}$ and $\sigma_t$. It is impossible to determine the proportional limit value $\sigma_{p.l.}$ on the said diagram.

Let us consider the MMM method capabilities in determination of the said mechanical characteristics on the example of tensile testing of individual steel specimens.

Photo 1. Specimens placement for testing:
1 – specimen; 2 – sensor clamps; 3 – jaws; 4 – SMLF measuring sensors.
Photo 1 shows the specimen placement in the tensile-testing machine and mounting of the TSC instrument inspection sensors.

Figure 1 shows the measurement scheme of the normal $(H_y)$ and the tangential $(H_x)$ components of the specimen’s self-magnetic field.

![Measurement scheme of the normal $(H_y)$ and the tangential $(H_x)$ components of the specimen’s self-magnetic field](image)

1 – point of specimen fixing in the tensile-testing machine; 2 – specimen; 3 – groove for inspection area localization; 4 – sensor; 5 – electronic unit; 6 – rod for sensor mounting; $P$ – tensile load.

Figure 2 shows the specimens’ shape and dimensions. A special groove was made in the center of the specimens to localize the maximum strain in the area of inspection by the MMM method. Grooved specimens stretching was performed on the tensile-testing machine under the conditions of increasing load with varying in time strain rate.

![Shape and dimension of SK and PK specimens](image)

Figure 2. Shape and dimension of SK and PK specimens.
Thus, three specimens of steel P335JR conditionally designated as SK-1, SK-2, SK-3 and three specimens of steel P355GH conditionally designated as PK-1, PK-2, PK-3 were tested.

Figure 3 presents the “stress-strain” diagram ($\sigma$-$\varepsilon$) recorded on the specimen SK-1. The “$\sigma$-$\varepsilon$” diagram clearly shows several scallop waves characterizing the so-called discontinuous yield (DY). The “yield drop” (points $C$ and $D$) corresponding to the conditional value of yield strength $\sigma_{0.2}$ (0.2% of the relative strain of the specimen’s test portion) should be distinguished among these scallop waves. Two other scallop waves (points $E$ and $F$), recorded on the “$\sigma$-$\varepsilon$” diagram probably correspond to shear strain jumps during the developing longitudinal plastic strain of the specimen.

Figure 4 presents the magnetogram of the $H_x$ field (coinciding with the direction of the $P$ load application) variation depending on the $P$ load and test time $t$ in seconds. The “$\sigma$-$\varepsilon$” diagram and the $H_x$-$P$ magnetogram displays the points $A$, $B$, $C$, $D$, $E$, $F$, $G$, $H$ that correspond to basic characteristics of the specimen’s metal recorded during its stretching to rupture.

Figure 4. The diagram of the self-magnetic field $H_x$ variation depending on the $P$ load.
Let us consider in more detail the curve of the specimen’s self-magnetic field $H_x$ variation in comparison with the “$\sigma-\varepsilon$” diagram. It can be seen that on the section from point A (initial specimen’s state at $P=0$) to point B the $H_x$ field varies abruptly reaching its minimum in point $B$. And then, after point $B$, the $H_x$ field increases up to point $C$ that corresponds to the initial yield drop point in the “$\sigma-\varepsilon$” diagram. Then the $H_x$ field has a marked abrupt drop from point $C$ to point $D$ at the yield drop.

Coincidence of these points at the “$\sigma-\varepsilon$” diagram yield drop and on the $H_x$ field variation curve is conditional. During the comparison of points positions by the time characteristic of this specimen it was found that points $C$ and $D$, corresponding to the physical yield strength, on the $H_x=f(\varepsilon)$ magnetogram were recorded much earlier compared to positions of points $C$ and $D$ in the “$\sigma-\varepsilon$” diagram. Such results were obtained based on comparison of the variation rate of $P$ load on the tensile-testing machine with $H_x$ field values that correspond to the same load and are measured using the TSC instrument in the “Timer” mode.

Point $G$ in figure 3 and figure 4 corresponds to the conditional tensile strength $\sigma_t$, and point $H$ – to the specimen failure point. Stress drop on the $G-H$ section of the “$\sigma-\varepsilon$” curve is accompanied by the self-magnetic field $H_x$ increase on the $H_x-P$ curve due to the increase of strain in the specimen’s groove.

The time test characteristic was used in calculation of the $P$ load and of the stress $\sigma$, respectively, which correspond to point $B$ on the $H_x$ field curve. Comparison of figure 3 and figure 4 suggests that in point $C$ of the $H_x$ field curve and the “$\sigma-\varepsilon$” curve the stress level is equal to the yield strength - approximately 366MPa. At that 5400 pulses were recorded in point $C$ on the TSC instrument, and in point $B$ of the $H_x$ curve the number of recorded pulses is 1500. Then by simple calculation the stress level corresponding to point $B$ on the $H_x$ curve is obtained: $\frac{1500}{5400} \times 366\text{MPa} = 101.6 \text{MPa} \text{ (approx. } 0.28\sigma_{0.2})$.

In accordance with papers [1, 2] the specimen’s measured self-magnetic field $H_x$ represents the strain resistance energy, and the area of recorded minimum on the $H_x$ field curve (point $B$) corresponds to the minimum of the internal energy ($W_\alpha$) spent by the material on resistance to variation of the glide plane inclination. Section $AB$ of the $H_x$ curve represents the maximum variation of the initial glide planes position in the specimen. On this section the main glide planes direction is formed under the action of the applied $P$ load. The strain resistance energy of this specimen under the load of 101.6MPa (point $B$ on the $H_x$ curve) tends to minimum due to formation of the main sliding direction.

Taking into account that in accordance with [1] the sliding direction and the specimen’s self-magnetization induction vector direction coincide (while their signs may be opposite), the practical importance of this feature becomes obvious: when the external specific force reaches the value that corresponds to the internal energy $W_\alpha$ minimum, “stabilization” of self-magnetic leakage fields induction vector direction in force field space occurs. In point $B$ on the $H_x$ curve the magnetization induction force component becomes equal to the magnetic component due to the effect of a weak external field (as a rule, of the earth’s field). With further increase of the external force the magnetization induction force component begins to exceed the magnetic component, which can be observed on the $H_x$ field variation curve above point $B$. Point $B$ corresponds to the boundary, after which the energy of resistance to elastic
longitudinal strain becomes lower than that of the plastic strain. At the same time the glide planes rotation angle relative to the external load direction starts to increase facilitation the increase of longitudinal plastic strain.

Thus, based on the experimental research data, taking into account the proportional limit determination presented in papers [1, 2], it can be stated that point B on the $H_e$ curve corresponds to the physical proportional limit for the tested specimen’s material of this size.

It should be noted that characteristic changes on the $AB$ section with clear recording of time derivative $dH_e/dt$ variation in point B on the $H_e$ field curve were obtained on all six specimens of different steels tested under a similar scheme. At the same time different values of $\sigma_{p.l.}$ that fluctuated at the level of $0.3\sigma_{0.2}$ were recorded in the characteristic point B on the $H_e$ curve on various specimens even made of the same steel grade. Similar variations were obtained on the $H_e$ field normal component curve, but with less pronounced inflection of the derivative $dH_e/dt$ in point B.

As a result of the carried out studies of six specimens data, as well as based on the previously performed similar testing [1, 2, 3, 4] using the MMM method and the appropriate TSC-type instruments, a conclusion may be drawn on the principal possibility to determine the physical proportional limit $\sigma_{p.l.}$ by the MMM method during the normal tensile testing of specimens. Determination of $\sigma_{p.l.}$ using the physical MMM method provides a unique possibility to determine in this way the fatigue limit of the specimen’s material, as it can be assumed that the $\sigma_{p.l.}$ value corresponds to the limit value of the cyclic load amplitude, above which the material begins to work under the conditions of plastic strain accumulation that causes the product material fatigue. However, this assumption requires proof during performance of fatigue tests using the MMM method. Paper [5] demonstrates the principal possibility of such a study.

Due to application of the metal magnetic memory (MMM) method and the appropriate inspection sensors and instruments during the tensile testing of a specimen, determination of $\sigma_{p.l.}$, $\sigma_{0.2}$ and $\sigma_t$ becomes possible at the physical level.

References