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NONDESTRUCTIVE EVALUATION OF PIPELINES: MAGNETOACOUSTIC DIAGNOSTICS OF DEFORMATION

НЕРАЗРУШАЮЩИЙ КОНТРОЛЬ ТРУБОПРОВОДОВ: МАГНИТОАКУСТИЧЕСКАЯ ДИАГНОСТИКА ДЕФОРМАЦИИ

V.R. Skalsky, S.I. Hirnyj, R.N. Basarab

Karpenko Physical-Mechanical Institute, National Academy of Sciences of Ukraine,
Lviv, Ukraine
Ukrtransnafta JSC, Oil-trunk pipelines Druzhba, Lviv, Ukraine

Скальский В.Р., Гирный С.И., Басараб Р.Н.

Физико-механический институт им. Г. В. Карпенко НАН Украины,
г. Львов, Украина
«Магистральные нефтепроводы, филиал, «Дружба», г. Львов, Украина
ОАО «Укртранснефть», НАК «Нефтегаз Украины», г. Львов, Украина

e-mail: hirnyj@gmail.com

Abstract. The quintessential feature of the metal overload and its reaching to the ultimate strength is a plastic deformation. Great attention is paid to the search for effective methods of non-destructive testing of stress levels and strains in the materials of oil and gas pipelines. Among the NDT methods that are embedded in the oil and gas transportation industry, significant attention is given to the acoustic emission (AE) - a method that has proved effective in detecting not only brittle fracture, but the plastic shear strain at fracture of plastic materials . However, the AE method is considered effective only when diagnosed object is subjected to stresses exceeding the normal operating levels (Kaiser effect) .The effect of elastic and plastic deformation of mild steel on the intensity of magnetoacoustic emission (MAE) have been studied with a measuring MAE system that has been engineered at Karpenko Physical-Mechanical Institute of the National Academy of Sciences of Ukraine. Studies using this system NDT were the primary objective of this work, which according to the parameters analyzed for the MAE signals from elastic and plastic deformation of commercial carbon steel. The principle of operation is based on the MAE non-antiparallel dynamics of domain walls. The observed trends in decreasing the MAE signal intensity with deformation confirm information known from the literature. The conducted measurements for the elastic straining were highly reproducible with high sensitivity of MAE signal parameters to elastic straining. Studies in the plastic region exhibited relatively lower repeatability and sensitivity of the MAE parameter to the level of plastic deformation. The presented results have demonstrated that MAE could be a perspective method for nondestructive evaluation of plastically damaged parts of operated pipelines, but further studies are needed in order to discriminate the difference between the safe elastic deformation and the dangerous plastic one using MAE signals.

Аннотация. Наиболее существенным признаком перегрузки металла и его приближения к пределу прочности является пластическая деформация. Большое внимание уделяется поиску эффективных методов неразрушающего контроля уровней напряжений и деформации в материалах нефте- и газопроводов. Среди методов НК, внедренных в нефтегазовой транспортной отрасли, значительное внимание уделено акустической эмиссии (АЭ) – методу, который зарекомендовал себя в эффективном обнаружении не только хрупких разрушений, но и пластической деформации сдвига при разрушении пластичных материалов. Однако, метод АЭ считается эффективным только тогда, когда диагностируемый объект подвергается напряжениям превышающим нормальные рабочие уровни (эффект Кайзера). Влияние упругой и пластической деформации углеродистой стали на интенсивность сигналов магнитоакустической эмиссии (МАЕ) изучали с помощью измерительной системы МАЕ, разработанной в Физико-механическом институте им. Г.В. Карпенко Национальной академии наук Украины. Исследования с использованием этой системы неразрушающего контроля была основной целью данной работы, в которой проанализированы зависимости параметров зарегистрированных сигналов МАЭ от упругой и пластической деформации коммерческой углеродистой стали. Принцип действия МАЭ основан на динамике не антипараллельных доменных стенок. Тенденция к снижению интенсивности сигналов МАЕ с увеличением деформации подтверждает результаты известные в литературе. Проведенные измерения для упругой области деформирования показали высокие воспроизводимость и чувствительность параметров сигналов МАЕ к упругой деформации. Исследования в пластической области сопровождались относительно более низкими воспроизводимостью и чувствительностью параметров сигналов МАЕ к уровню пластической деформации. Представленные результаты подчеркивают, что МАЕ является перспективным методом неразрушающего контроля пластически деформированных участков эксплуатируемых трубопроводов, однако необходимы дальнейшие исследования для поиска методики, разрешающей измерять и выделять безопасную упругую и опасную пластическую деформации по сигналам МАЕ.

Key words: pipeline transport, mild steel, ageing, magnetoacoustic emission, elastic deformation, plastic deformation, nondestructive evaluation.

Ключевые слова: трубопроводный транспорт, углеродистая сталь, старение, магнетоакустическая эмиссия, деформация, неразрушающий контроль.

Introduction

As the pipeline transportation industry has reached its 150-th anniversary, it is hard to leave its undoubtedly great technological progress unnoticed. Oil and gas are effectively moved to the most distant locations so that the users are provided with necessary resources. However, with increasing demands for gaseous and liquid energy carriers and with ever-growing web of pipelines, significant part of which is being well near or even beyond its engineering lifetime, an issue of safeness of oil and gas transportation is becoming a serious problem for our generation [1].

Ageing of the oil and gas transmission and distribution pipelines is taking place simultaneously with growing demands for the quality of pipeline steels and with increasing cost of metal production worldwide. This economic condition created a well-motivated background for developments in the area of non-destructive evaluation (NDE). A quest has been accelerating for the effective physical methods that can detect and estimate a degree of metal's degradation and predict the remaining lifetime of the damaged pipeline [2].

Since the most significant signs of metal’s overloading and its nearness to its ultimate stress is plastic deformation, much attention is dedicated to the search of an effective method for NDE of the level of stress and degree of straining in the materials like oil and gas pipeline steels. Among the NDE methods approved and implemented in oil and gas transportation industry significant attention is attributed to acoustic emission (AE), which has an established record of detecting not only brittle fracture, but also plastic deformation or shear fracture of ductile materials. AE is considered effective only when a structure is subjected to the stresses exceeding the normal operational stresses (Kaiser effect) as realized, for instance, during hydrostatic testing of pressure boundaries. Additional overloading, however, contributes to degradation of the aged pipelines making closer their fatigue limit [3].

An alternative approach does not demand an excessive loading of the pipeline, but works similarly to other NDE methods. A method called magnetoacoustic emission (MAE) utilizes acoustic waves from the bulk of a ferromagnetic material. These elastic waves are generated during magnetization under the influence of external magnetic field. Discovered four decades ago, this method is becoming increasingly studied concerning aging and degradation of ferromagnetic structural materials like pipeline steels [4–9].

The principle of MAE is rooted in the dynamics of the non-180° domain walls. In strong magnetic fields MAE could originate seemingly from the irreversible rotations of the magnetization vectors through angles other than 180°, or reflect the dynamics of closure and island domains stabilized by microcrystalline imperfections. A magnetic analog to MAE, known as Barkhausen noise, is rooted in the 180° wall dynamics, though the exact nature of both has been questioned [10-14]. A major advantage of the MAE method over the Barkhausen noise is its informative depth, being 10 mm or more for the former and only 100-200 μm for the latter [15]. As to disadvantages, MAE method exhibits high sensitivity to the background acoustic and electric noises and is also sensitive to the geometry of the studied object and to the parameters of the AE system. The power of MAE signal depends on magnetostriction coefficient λ, sweep frequency f, amplitude of the external magnetizing field Ha, although its relation to magnetostriction was questioned for some materials [4, 16, 17]. Since plastic flow is the most prominent sign of metal overloading, an effective NDE method has been looked for, which would be able to evaluate the level of stress and degree of straining. MAE is one of the promising candidates for this task [4, 18].

Straining of a ferromagnetic material has a complex influence on its magnetic properties [5, 19–21]. Elastic straining has an influence on magnetocrystalline anisotropy, while plastic deformation increases the density of dislocations which serve as pinning points for domain walls [4, 22, 23]. The application of MAE for NDE seems practical since it is more sensitive to stress than to microstructure and because it is sensitive to dislocation density even at weak magnetic fields [9, 13, 18, 24–26]. The tendency of the MAE signal to decrease in intensity with increased straining could be expressed as follows [26]:

$$E_{me} \sim \lambda\, \sigma \sin^2 \Theta,$$

where λ – is the saturation magnetostriction (($\lambda 100 > 0$ for Fe), σ – stress, and Θ – the angle between the directions of magnetization vector M and σ, the application of stress to steel would cause M to align along the σ direction so that E_{me} is minimized. This would increase the total area of 180° walls at the expense of 90° walls, consequently reducing the MAE intensity.

Objective

Based on the demand of the Ukrainian pipeline transportation industry in effective NDE methods for detection and evaluation of deformation, on the one hand, and having considered the accumulated knowledge on MAE response to deformation of pipeline steels, on the other, the development of the MAE diagnostic instrument and its verification to the effects described above has been undertaken. A computer-controlled sample of MAE instrument was engineered at Karpenko Physical-Mechanical Institute (National Academy of Sciences of Ukraine) and verification of this NDE system had been the main goal of the presented study. MAE responses to deformation both elastic and plastic of commercial mild steel were recorded and overviewed.

Experimental Approach

The most effective magnetizing frequency of the experimental setup, which included an engineered MAE system and flat samples 2–3 mm thick made of mild steel was determined before MAE measurements were conducted. This frequency was found to be 9 Hz – a compromise between an increase with frequency of the intensity of the MAE signal and a decrease with frequency of the penetration depth, which is informative depth of the method. Figure 1 depicts the dependency of the principal MAE parameter, which is sum of total amplitude for the impulses of MAE signal ΣAi on the magnetizing field strength H depending on the frequency f of the sinusoidal shaped current. Thus, for the subsequent MAE study we selected the frequency of 9 Hz, as such that produced a strong MAE signals and could not contribute to the harmonic noise from industrial frequency of 50 Hz.

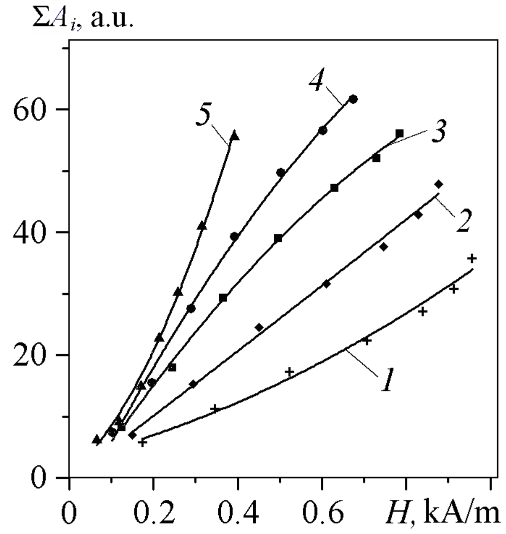

Figure 1. The dependencies of the sum of amplitude for the impulses of MAE signal ΣAi on the magnetizing field strength H for the 2 mm thick sample depending on the frequency f of the sinusoidal shaped current:
1 – 3 Hz; 2 – 6 Hz; 3 – 9 Hz; 4 – 12 Hz i 5 – 20 Hz

There were two series of magnetoacoustic measurements conducted on 3 mm thick samples made of mild steel analog to SAE 1015 type. Each testing involved a sample, which was surrounded by the magnetizing coil (solenoid) and placed into the straining machine. This loading device employed a stair-straining principle within elastic region, so that the effect of elastic deformation could have been evaluated. During these studies, in order to verify the repeatability of measurements a second sample was strained in the order loading-unloading-reloading. In other series of experiments the samples with two different thicknesses were subjected to plastic strain and unloaded before MAE measurements were made so that the effect of plastic deformation could have been evaluated. Magnetization in the strained steel sample was induced by the 6 Hz sinusoidal magnetic field with amplitude 7.1 kA/m, which is below the presaturation knee on the hysteresis loop.

A non-resonant piezoelectric transducer with a wide-band spectral characteristics was acoustically attached to the surface of the sample near the upper grip of the tensile loading device. It was electrically connected to the MAE system through a

40 dB preamplifier. Magnetoacoustic signal from the transducer was amplified to a total of 100 dB and filtered within 200-1000 kHz. For each deformation step a set of ten data samples was recorded. Consequently, a MAE parameter ΣAi , which is a sum of the amplitudes of MAE impulses measured in arbitrary units, was calculated and averaged for each step. Finally, the dependency of ΣAi on deformation ε was plotted and analyzed.

Results and discussion

Figure 2 exhibits the results from the first two series concerned with elastic straining. The dependency of MAE parameter ΣAi (sum of the amplitudes of MAE impulses) on elastic deformation can bring us to several conclusions.

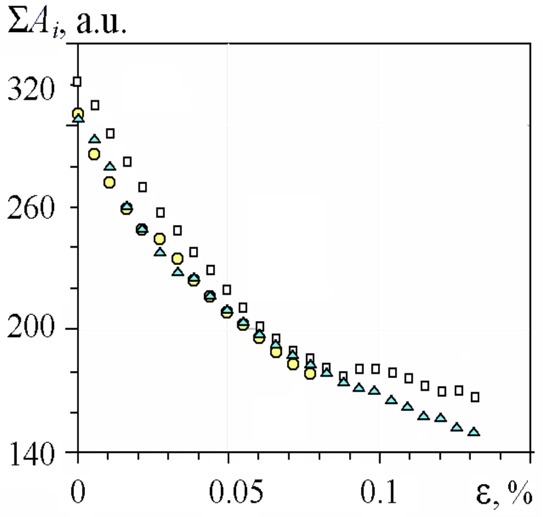

Figure 2. The effect of elastic deformation on the sum of total amplitude for the impulses of MAE signal ΣAi:
□ – 1-st run, ○ – 2-nd run, Δ – 3-rd run

Firstly, the manifestation of the effect of strain on magnetocrystalline anisotropy is very prominent, in agreement with the published reports. Within 0.13 % of elastic straining the MAE parameter decreases twofold, which is incredible sensitivity for any NDE method.

Secondly, the tendencies for both samples are very close to each other and the plots for two stair-straining runs of the second sample practically coincide with each other confirming high reproducibility of the MAE measurements. The latter is encouraging information, since the metrological issues are of serious concern especially in the magnetic and even more so in the acoustic measurements.

The results of the influence of plastic deformation of the 3 mm thick steel sample on magnetoacoustic parameter ΣAi together with a linear regression line are illustrated in figure 3. In this study one can notice a scatter in the parameter ΣAi, but the degree of scatter is relatively low (for linear regression R2 = 0.86), considering numerous acts of replacing the sample, solenoid and transducer during this series of experiments.

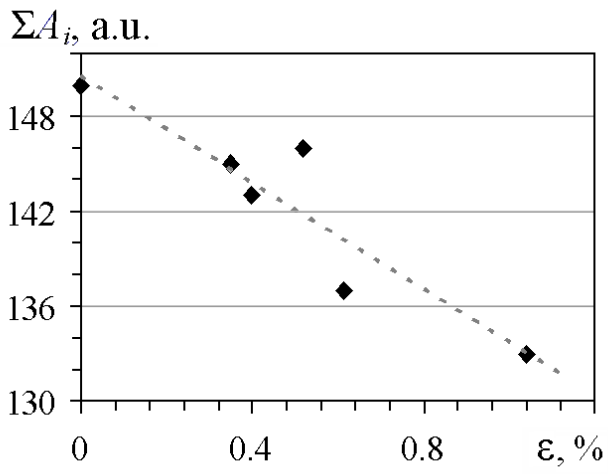

Figure 3. The effect of plastic deformation on the sum of total amplitude for the impulses of MAE signal ΣAi

In order to study the effect of plastic straining on the relationship between the magnetoacoustic parameter ΣAi and the amplitude of magnetic field strength Ha a series of experiments were conducted involving two samples of different thicknesses – 2 mm and 3 mm. The results of these studies are depicted on figure 4. Seems obvious that the parameter ΣAi decreases with plastic deformation for both differently plastically deformed samples of different thicknesses. The influence of plastic deformation, however, is not as strong as for elastic deformation, as presented in Fig. 2. For instance, even for the strongest studied magnetic field with amplitude of about Ha = 0.8 kA/m the plastic deformation resulted in the decrease from about ΣAi = 114 a.u. to ΣAi = 85 a.u. which is 25 % decrease, comparable with the decrease of ΣAi for only ε = 0.03–0.04 % of elastic straining as could be derived from Fig. 2. From this viewpoint, it might be considered that small elastic deformation, which is of little concern to industrial operators, might have similar effect on MAE parameters as a significant plastic deformation, which could precede a catastrophic failure of such environmentally dangerous objects as oil and gas pipelines.

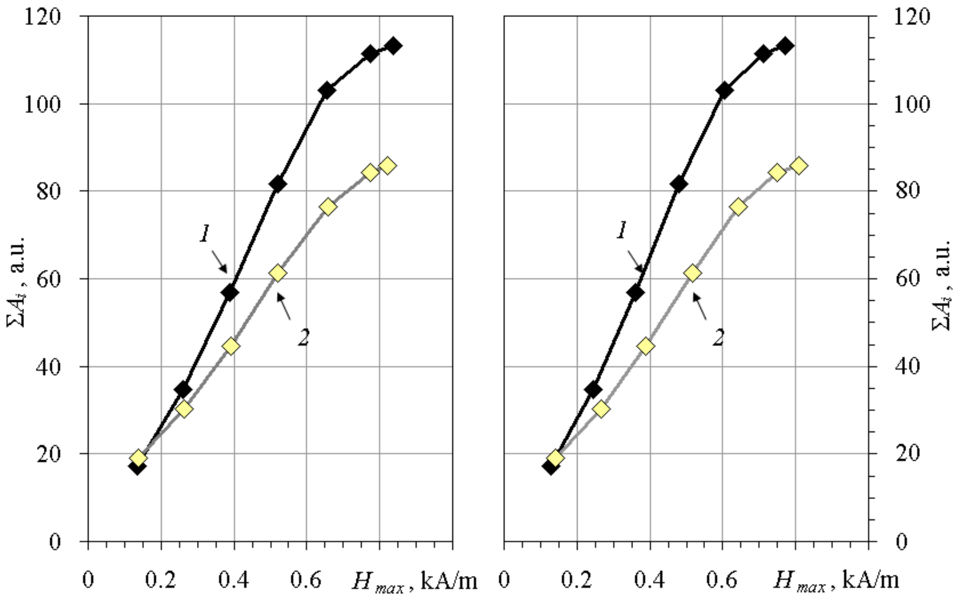

Figure 4. The effect of plastic deformation on the relationships between the MAE parameter ΣAi and the amplitude of magnetic field strength Ha for the samples 2 mm (left) and 3 mm (right) thick:
1 – non-deformed sample and 2 – the sample plastically deformed by ε = 1.7 % (2 mm thick) and ε = 7 % (3 mm thick)

The obtained results basically confirm those found in the literature [4, 9, 12, 13, 17, 27, 28]. Since plastic deformation increases the density of dislocations (generally defectiveness of the microstructure), it consequently leads to increased pinning of the domain walls. Thus, for the same magnetizing field, a smaller fraction of domain walls could overcome the pinning force and generate a "jump", which results in release of the elastic acoustic wave. As a result – decrease of the intensity of the MAE signal parameters.

The major concern, as could be derived from Fig. 4, is a comparable decrease in the MAE parameter ΣAi obtained for the two differently deformed samples of different thickness. Considering the scatter in the dependency ΣAi = f (ε), as could be noticed at figure 3, some serious metrological questions arise regarding possible application of this technique for NDE of pipelines. It is possible, however, that this issue could be resolved when moved from 2–3 mm thick samples to the thicknesses of linepipe steels for oil and gas transmission, i.e. 10–30 mm. However, more studies are needed which would have to involve powerful magnetizing electromagnets in order to achieve significant informative depth of the studied object.

As from the obtained results it is hard at this point to separate the effect of elastic deformation on the parameters of the MAE signal from the effect of plastic one. Further search into the differences in MAE signal parameters is needed to overcome this ambiguity. For instance, the spectral characteristics could be different for MAE signals induced by plastic and by elastic straining. If not, the other methods that can discriminate between elastic and plastic deformation should be employed. Besides, the routine verification of the presented dependencies on other ferromagnetic materials should be conducted.

Conclusions

The effect of elastic and plastic deformation of mild steel on the intensity of magnetoacoustic emission (MAE) signal have been studied with a measuring MAE system engineered at Karpenko Physical-Mechanical Institute. The observed decreasing trends in the MAE signal intensity with deformation confirm those known from the literature. The conducted measurements for the elastic straining were highly reproducible with high sensitivity of MAE parameters to elastic straining. Studies in the plastic region exhibited lower repeatability and sensitivity of the MAE parameter to the level of plastic deformation. The presented results have demonstrated that MAE could be a perspective method for nondestructive evaluation of plastically damaged parts of operated pipelines, but further studies are needed in order to sense the difference between the safe elastic deformation and the dangerous plastic one.

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Information about authors
Сведения об авторах

V.R. Skalsky, Karpenko Physical-Mechanical Institute of National Academy of Sciences of Ukraine, Lviv, the Ukraine

Скальский В.Р., Физико-механический институт им. Г. В. Карпенко НАН Украины, г. Львов, Украина

S.I. Hirnyj, Karpenko Physical-Mechanical Institute of National Academy of Sciences of Ukraine, Lviv, the Ukraine

Гирный С.И., Физико-механический институт им. Г. В. Карпенко НАН Украины г. Львов, Украина

R.N. Basarab, Ukrtransnafta JSC, Oil-trunk pipelines Druzhba, Lviv, the Ukraine

Басараб Р.Н., «Магистральные нефтепроводы «Дружба», филиал г. Львов, ОАО «Укртранснефть» НАК «Нефтегаз Украины» г. Львов, Украина

e-mail: rbasarab@druzhba.lviv.ua