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Experimental Identification of the Degree of Deformation of a Wire Subjected to Bending

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Abstract:

This study provides experimental verification of analytical results on maximum strain ε_{max} in elements fabricated by bending a stainless steel wire around a cylinder with given dimensions. The method of measuring the thermal electromotive force (TEMF) of a thermocouple formed by joining the deformed metal specimen to a copper (Cu) conductor showed an increase in the thermal electromotive force coefficient (TEMFC) during heating with increasing degree of plastic deformation. For known values of plastic deformation produced by straining X5CrNi1810 stainless steel wire specimens of ∅2.8 mm diameter, the TEMF was determined as a function of the extent of deformation of the thermocouple consisting of the deformed steel wire specimen and the copper conductor. Based on the correlation (calibration curve), it was shown that the relative strain of the element fabricated by bending the same wire (made of X5CrNi1810 stainless steel, ∅2.8 mm in diameter) around the cylinder of ∅10 mm diameter is 23.8 %.

Keywords: *Thermal electromotive force; Relative strain; Degree of deformation; Steel wire.*

1. Introduction

Cold working of a metal involves work hardening i.e. increasing the strength and hardness of the metal while decreasing its ductility. An increase in the degree of deformation increases the dislocation density and the number of barriers to dislocation motion. Moreover, plastic deformation leads to an increase in electrical resistance and a decrease in the density of the metal accompanied by a change in the potential field of the lattice and hence a change in the electron density of states near the Fermi level. As the cold-worked metal is in a metastable structural state i.e. a state of higher free energy compared to the non-deformed metal, it will show a spontaneous tendency to return to its non-deformed state which is closer to a state of equilibrium. However, the metal cannot generally undergo a spontaneous transition to a non-deformed state due to the complexity of the deformed state. Activation energy is required for the processes occurring in the crystal lattice of the metal at an atomic level, such as the creation and motion of vacancies, diffusion, a positive and negative climb of dislocations, transverse sliding of dislocations, etc. [1, 2]. As all these processes can be thermally activated, the deformed material should be heated in order that it can restore the properties that existed before deformation [3-5]. During gradual heating of the deformed material, the atoms gain energy that enables their transition to a more stable energy state [6-10], consequently leading

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to reduced potential in the material and increased electron density of states near the Fermi level [11]. The deformation-induced changes in the electron density of states produce changes in the TEMF and TEMFC of the deformed metal – another metal thermocouple [12, 13].

This physical phenomenon was used for the identification of the degree of deformation in elements formed by bending a stainless steel wire around a cylinder with given dimensions. To this end, a ***thermocouple*** was constructed by mechanically joining the deformed steel wire to a copper conductor.

2. Measurement methodology

In this investigation, X5CrNi1810 stainless steel wire specimens of *∅2.8 mm* diameter were tested. The specimens were subjected to plastic deformation by bending the wire around a ∅10-mm-diameter cylinder into the shape presented in Fig. 1.

Fig. 1: The wire profile after the bending operation.

A calibration curve was obtained using straight wire specimens of the same diameter and made of the same material as the bent wire specimens. The straight wire specimens were subjected to tension load and plastic deformation up to different values of relative strain (ε). The mechanical joining of the as-prepared specimens to copper conductors resulted in ten thermocouples.

TEMF measurements of the as-formed thermocouples led to the experimental determination of TEMF as a function of temperature for differently deformed straight wire specimens (Fig. 2), and TEMF as a function of the relative strain at a temperature of 40 °C – calibration curve (Fig. 4).

Using the same procedure, by heating from 0 to 300 °C, temperature dependence of TEMF was determined for the thermocouple formed by joining the circularly bent wire (Fig. 1) with an unknown degree of deformation to the copper conductor (Fig. 3).

The as-obtained temperature dependence of TEMF and the calibration curve were used to determine the relative strain of the wire bent into a loop at a temperature of 40 °C.

3. Results and discussion

According to ***Fick's law***, [14] when two materials having different concentrations of conduction electrons ($n_1 > n_2$) are brought into contact, the conduction electrons diffuse into both directions. A substantial number of electrons are transferred into the other material which consequently becomes negatively charged, while the first material assumes a positive charge. The electric field thus created opposes the diffusion process. When these two effects are balanced, the flow of electrons through the contacting surface becomes balanced as well. A ***contact potential difference*** occurs between the contacting materials:

$$U = \frac{kT}{2e}\left(\frac{n_1}{n_2} - \frac{n_2}{n_1}\right) \tag{1}$$

where:
$k = 1.3806505 \cdot 10^{-23}$ J/K – Boltzmann's constant;
$e = 1.60217653 \cdot 10^{-19}$ C – the elementary charge.

If such two materials are joined to form a thermocouple the contacting surfaces of which are kept at different temperatures ($T_2 > T_1$), a ***thermal electromotive force*** E_{temf} is generated:

$$E_{temf} = \frac{k}{2e}\left(\frac{n_1}{n_2} - \frac{n_2}{n_1}\right)\left(T_2 - T_1\right) = \alpha \cdot \Delta T \ \left[\mathrm{V}\right] \tag{2}$$

where: α – the thermal electromotive force coefficient (TEMFC) which is dependent only on the properties of the contacting materials.

The objective of this research was to determine the correlation between the TEMFC and the degree of deformation of the materials [15-20], and use it to identify the relative strain of the metal specimens tested.

Fig. 2. presents measurement results of the temperature dependence of TEMF for the thermocouples formed by joining Cu conductors to straight steel wire specimens ∅2.8 mm in diameter which have undergone plastic straining to different values of the relative strain (ε).

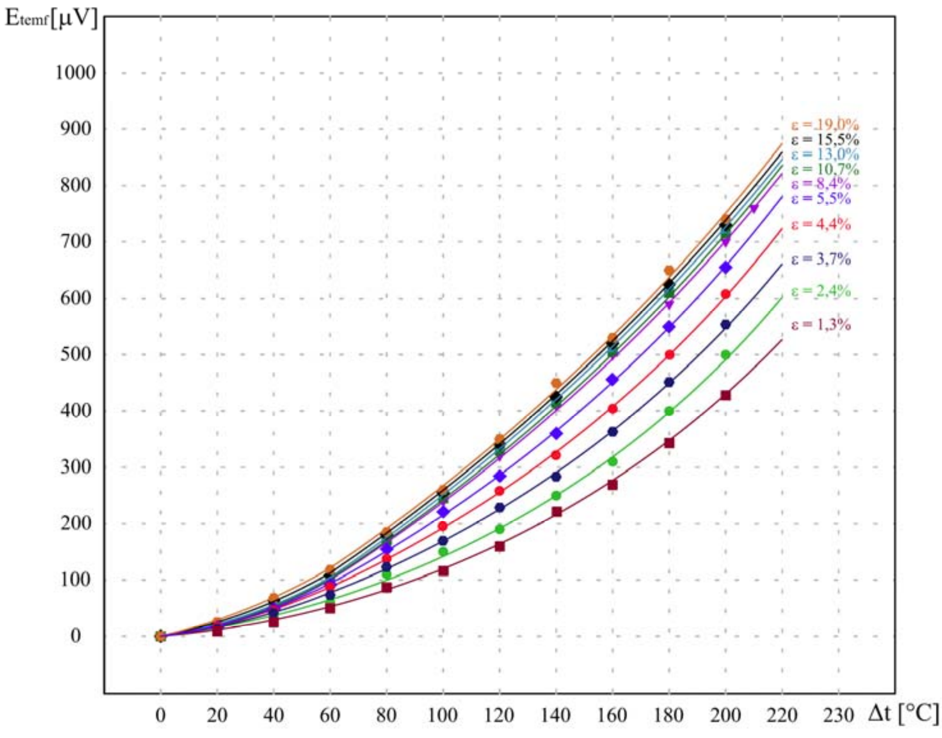

Fig. 2. Temperature dependence of thermal electromotive force, E_{temf}, for the thermocouples formed by joining Cu conductors to straight steel wire specimens of ∅2.8 mm diameter, which have undergone plastic straining to different values of the relative strain (ε).

The analysis of the experimental results in Fig. 2. clearly reveals an increase in the TEMFC during heating in all specimens. In addition, as the degree of deformation increases, there is a more rapid increase in the TEMFC during thermocouple heating. The increase in the TEMFC during heating can be explained by expression (2) which defines the TEMFC (α):

$$\alpha = \frac{k}{2e}\left(\frac{n_1}{n_2} - \frac{n_2}{n_1}\right) \quad (3)$$

where:
n_1 – the electron density of states near the Fermi level in the deformed steel wire part of the thermocouple; n_2 – the electron density of states in the copper part of the thermocouple.

The copper part of the thermocouple is structurally stable during heating; therefore, the electron density of states in copper n_2 does not change during heating up to 400 °C.

The cold-worked section of the thermocouple (the steel wire) is in a metastable structural state. During heating, the deformed part of the thermocouple is recovered. This is accompanied by a decrease in the density of chaotically distributed dislocations and a decrease in mechanical microstress, which causes an increase in the electron density of states near the Fermi level n_1 in the deformed steel wire portion of the thermocouple. According to relation (3), the increase in n_1 value leads to an increase in the TEMFC.

The analysis of the experimental results presented in Fig. 2. suggests that the TEMFC at all temperatures is proportional to the extent of plastic deformation.

In the initial heating step, the two ends of the differently deformed thermocouples are at the same temperature (0 °C). As experimentally determined, the electron work function in the steel alloy is lower than that in copper. Accordingly, the density of free electrons in the steel alloy (n_1) is higher than in copper (n_2). However, as the degree of deformation increases, the density of free electrons n_1 in the alloy decreases. [5] As a result, the contact potential difference between the alloy and copper decreases with increasing degree of deformation of the tested elements. The lower contact potential difference facilitates the diffusion of free electrons as the temperature of the heated contact increases. This causes the TEMF during heating to be proportional to the degree of deformation of the wire specimen in the junction (Fig. 2).

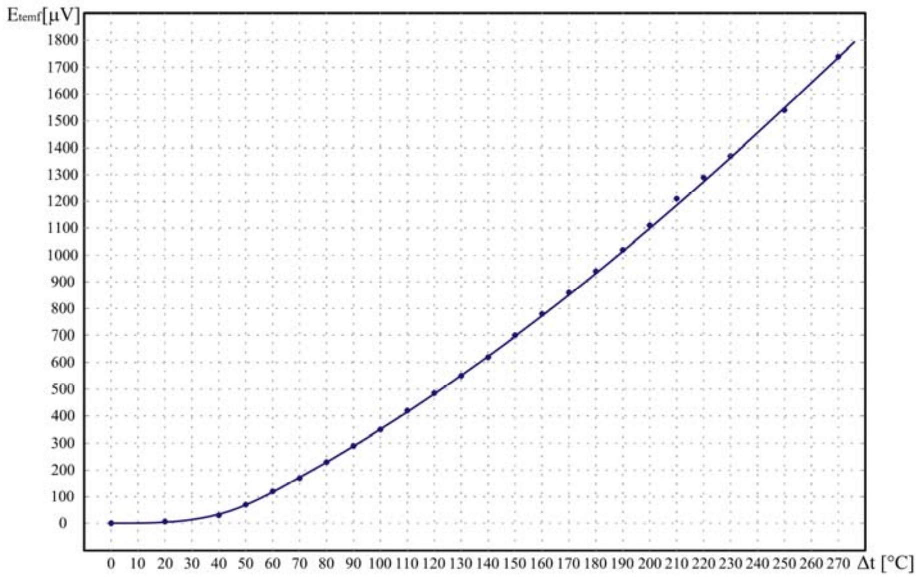

Fig. 3. TEMF as a function of temperature of the thermocouple formed by joining the copper conductor to the deformed loop-shaped wire specimen (Fig. 1) ∅2.8 mm in diameter.

The experiment showed that at the same temperature difference between the two thermocouple ends different TEMF values correspond to different degrees of deformation of the axially loaded steel wire joined with the copper conductor to form a thermocouple (Fig. 2). Therefore, a particular degree of deformation of the wire element joined with the copper conductor to form a thermocouple is matched to the corresponding TEMF value which is always the same for a particular temperature when the same measurement parameters are used (the same heating pattern, the same atmosphere, etc.).

The experimental results of TEMF measurement for the thermocouple formed by joining the copper conductor to the deformed loop-shaped wire specimen (Fig. 1) of ∅2.8 mm diameter are given in Fig. 3.

The analysis of the results presented in Fig.s 2 and 3 shows that the temperature dependences of TEMF are similar in shape for wire specimens deformed by different types of load - tensile and bending.

Based on the results in Fig. 2, the TEMF was determined as a function of relative strain (ε), at a temperature of 40 °C, (Fig. 4) – the so-called ***calibration curve.***

The idea is to use the diagram to identify an unknown degree of deformation of the wire element forming a thermocouple with the copper conductor, at the same difference in temperature between the ends Δt = 40 °C.

The TEMF value reading obtained from the diagram presented in Fig. 3 (for the thermocouple joining the copper conductor to the deformed loop-shaped specimen) was E_{temf}=34.5 μV. For this TEMF value, the deformation degree value of 11.9 % was read from the calibration curve (Fig. 4).

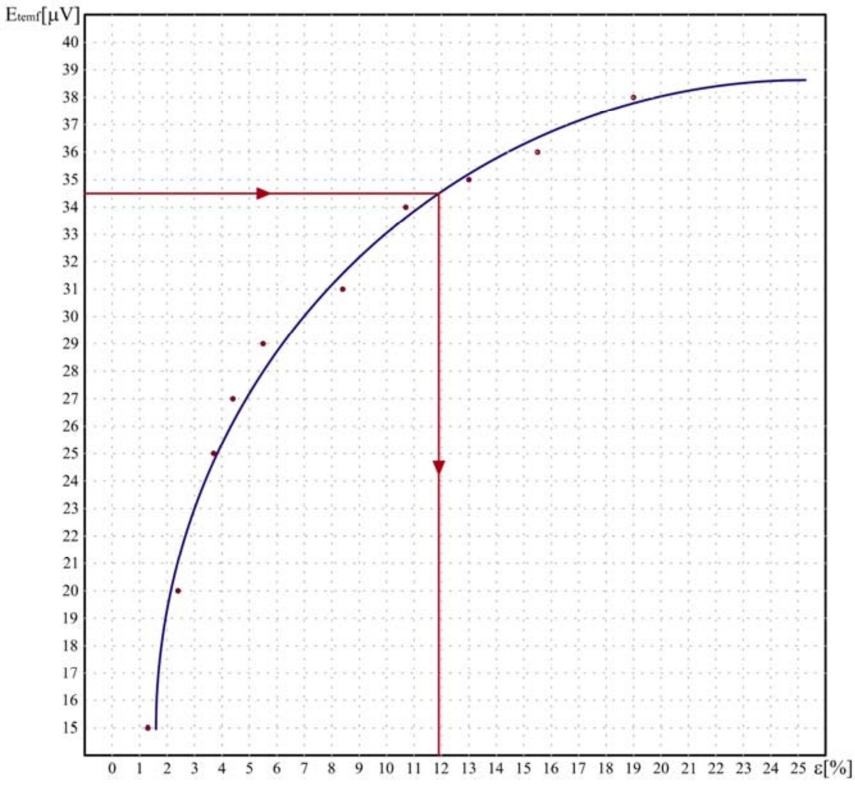

Fig. 4. Thermal electromotive force (E_{temf}) as a function of relative strain (ε), at a temperature of 40 °C, for a wire of ∅2.8 mm diameter – calibration curve.

As opposed to the axial stress involving an almost constant strain distribution along the cross-section of the wire (ε=ε_{max}), the strain distribution along the cross-section during pure bending is ***linear*** [21-27], and maximum deformation (ε_{max}) is reached by the fibers farthest from the neutral surface, whereas all fibers at the neutral surface are non-deformed (Fig. 6). It is assumed that in case of pure bending the hypothesis of plane section is valid for strains, that exceed the strain of proportional limit [21-23]. Therefore, strain distribution in the cross-section of the element fits the scheme presented in Fig. 6. The model can be used in all the applications where the material behaviour of the wire guarantees that plane cross sections of the wire will remain plane after rotation due to bending. This hypothesis is commonly accepted because it is a good approximation of the real behaviour of many engineering materials. The material shows a symmetric tension–compression behaviour, and the neutral axis of the wire will not change its position. It follows from the assumptions, and general elastoplastic behaviour of isotropic steels. [24, 25].

From this assumptions it can be deduced that longitudinal strains are proportional to the distance y from the neutral surface: [21-27]

$$\varepsilon_z = \frac{y}{R} \tag{4}$$

where:
R – neutral surface curvature radius,
y – distance from neutral surface.

The maximum strain in longitudinal direction has the fibers which are farthest from the neutral surface (Fig. 5), and is calculated according to (4):

$$\varepsilon_{\max} = \frac{y_{\max}}{R} = \frac{1,4}{6,4} = 0,219 = 21,9\%$$

All wire material points located at an identical distance from the neutral surface form the so-called *equipotential surface* along which free electrons are evenly distributed. Therefore, the value of deformation plotted in Fig. 4 is the ***mean value of relative strain*** (ε_m) of the bent wire. Given the strain distribution along the cross-section of the wire presented in Fig. 6, **the results show that the maximum strain is twice the mean value of relative strain** i.e. ε_{max} = 23.8 % for the ∅2.8-mm-diameter wire.

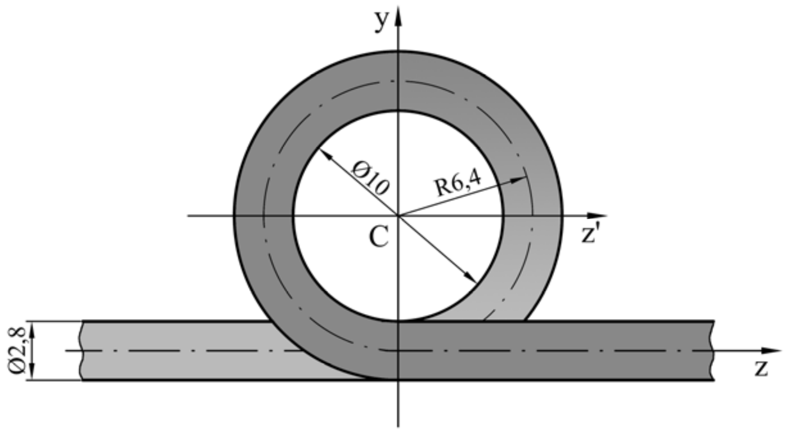

Fig. 5. Geometry of bended wire, ∅2.8 mm diameter.

The comparison with the theoretical value for maximum strain of ε_{max} = 21.9 % computed for the ∅2.8-mm-diameter wire revealed a deviation of about 8% for the values obtained.

In the experimental measurement described above, the maximum strain value was somewhat higher than the calculated value due to the assumptions that are made and because the effect of twisting the cross-sections around the longitudinal axis during wire loop formation was neglected when raising theoretical considerations.

For the wire ∅5 mm in diameter, the same experiment was performed, yielding similar results i.e. somewhat higher values of maximum strain compared to the theoretically calculated ones, as in the case of the ∅2.8-mm-diameter wire.

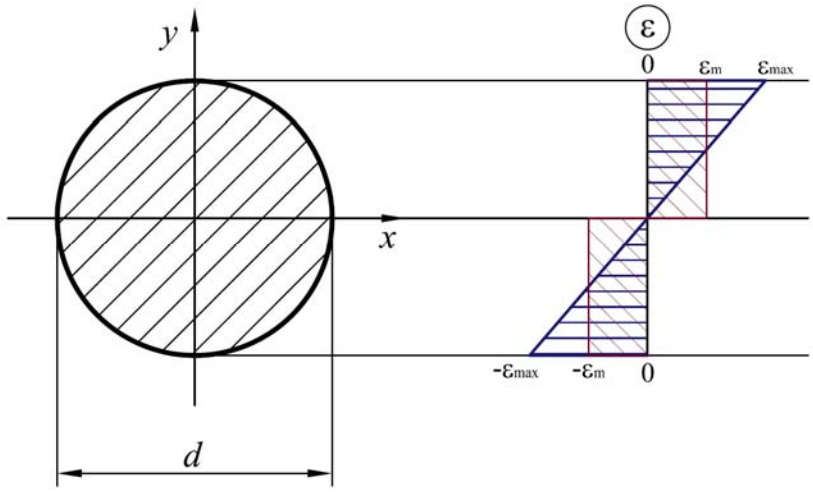

Fig. 6. Strain distribution along the cross-section of the wire undergoing pure bending.

Although the wire tensioning operation for calibration curve design and the bending of the wire into the shape presented in Fig. 3 were performed at room temperature, due to the insufficient sensitivity of the voltmeter used for the measurement, the TEMF values used were those measured for all samples at 40 °C. This could have resulted in no substantial error, given that the heating time until the temperature difference was reached was relatively short and the same for all measurements, thus suggesting that until that particular moment the recovery of the deformed material practically did not even start. Nevertheless, even higher levels of accuracy could be obtained by a voltmeter having a sensitivity of 0.1 μV for measurements performed at the same temperature as wire deformation temperature.

4. Conclusion

The TEMF measurement method used in this study showed a strong correlation between the degree of deformation of a steel wire and the rate of change in the electron density of states near the Fermi level in the wire.

It was found that during heating the TEMFC of the deformed metal - copper conductor thermocouple increases proportionally to the degree of deformation. The more rapid increase in the TEMFC with increasing degree of deformation is caused by the more rapid generation of free electrons during the recovery process under heat treatment in samples subjected to a higher degree of plastic deformation.

Based on the correlation between the TEMF and the relative strain (calibration curve), an unknown degree of deformation of the material was identified in the elements fabricated by bending the stainless steel wire around the cylinder of given dimensions.

This has resulted in the development of an original method for the experimental identification of the degree of deformation of wires which can have a much wider significance than when applied in these particular experimental settings i.e. it can be used for testing certain machine elements subjected to loading of unknown intensity.

The method described provides exceptional reliability in identifying deformation degrees in machine elements subjected not only to axial stress and bending but also to other types of straining, as well as to combined straining, provided that strain distributions along the cross section are previously determined.

Acknowledgments

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5. References

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Садржај: *У овом раду извршена је експериментална провера аналитички добијених вредности максималне деформације* ε_{max} *код елемената израђених савијањем жице од нерђајућег челика око ваљка одређених димензија. Методом мерења термоелектромоторне силе (ТЕМС) термопара добијеног спајањем узорака деформисаног метала и бакарног (Cu) проводника показано је да са порастом степена пластичне деформације температурни коефицијент термоелектромоторне силе (ТКТЕМС) током загревања расте. За познате вредности пластичних деформација добијених истезањем узорака жице од нерђајућег челика X5CrNi1810 пречника - 2,8 mm добијена је зависност ТЕМС од величине деформације термопара деформисани узорак челичне жице – бакарни проводник. На основу добијене зависности (калибрационе криве) показано је да величина релативне деформације код елемената израђених савијањем исте жице (од нерђајућег челика X5CrNi1810 пречника -2,8 mm) око ваљка пречника - 10 mm износи 23,8 %.*
Кључне речи: *термоелектромоторна сила, релативна деформација, степен деформисаности, челична жица.*