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FEM simulation of Ductility Minimum Temperature (DMT) phenomenon in CuNi25 alloy

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Properties

ABSTRACT

Purpose: The aim of this paper was to check by three dimensional Finite Element Method simulations the possibility of existence the non-uniform deformation hypothesis as a cause of Ductility Minimum Temperature phenomenon (DMT) in CuNi25 alloy. The necessary information and mechanical properties have been collected during elevated temperature tensile tests and other research and analysis of microstructure changes in material after deformation at the range of DMT existence. Experimental results were compared with three dimensional finite element method (FEM) simulation.
Design/methodology/approach: Numerous techniques were used to characterize properties of material: high temperature tensile tests, finite element method, transmission electron microscopy, scanning electron microscopy.
Findings: During the experimental studies the course of elongation curves has been determined. The stress in material after deformation at elevated temperature was analysed by FEM simulation. It has been confirmed the possibility of existence the inhomogeneous deformation hypothesis as a cause of DMT phenomenon.
Practical implications: Understanding of material properties during high temperature deformation leads to selection of the appropriate production parameters and reductions of cost, helps to avoid destruction of material during production or operating. FEM simulations can help to reduce the costs of multiple destructive tests to determine material properties.
Originality/value: FEM simulation and investigations of this CuNi25 alloy complete knowledge about mechanical properties of this material and help us develop correct parameters for more effective technologies for material production and exploitation.
Keywords: FEM; Ansys; Metals; Copper alloys properties; CuNi25; Ductility Minimum Temperature (DMT); Elevated temperature ductility

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1. Introduction

Material engineering is very strongly correlated with research of material properties and optimization of manufacturing processes. Scientists all other the world try to optimize processes of production and get best material properties. However, there are certain phenomena that have still not been fully explained, one of them is Ductility Minimum Temperature phenomenon (DMT) [Fig. 1]. This is a common attribute of many polycrystalline metals and alloys for example copper and its alloys, steel and others [1-12]. Many studies proved existing of DMT phenomenon also on cupronickel alloys [8-10], usually it was observed as the effect of intermediate temperature ductility reduce during high-temperature plastic deformation. Various forms, conditions, and types of deformation cause different levels and temperature range of DMT phenomenon. Therefore the main problem of clarify of its existing is explanation of connections between proceeding micromechanisms and the decreasing level of ductility, which in result, leads to macroscopic lost of ductility and destruction of material. We can do an assumption that DMT is a result of specific, different for each case, combination of factors and mechanisms [1] accompanying to process of deformation at 0.3-0.7 T_m and none of them is specify responsible for DMT phenomenon. In various metals, it is possible to identify heterogeneous mechanisms responsible for the loss of ductility and often crack formation leading to destruction of material [10]. Course of plastic deformation at intermediate temperature depends on many factors, selection of appropriate conditions requires understanding of many processes and theirs causes. Identification of one mechanism responsible for intermediate temperature ductility through is difficult because of many correlations between inter alia: microstructural heterogeneity, non-uniformity of chemical composition, heterogeneous in nature process of deformation, kind and morphology of grain boundaries and grain junctions, grain boundary serrations, rate of deformation, segregation of impurities on grain boundaries, geometrical heterogeneity in each scale, shape and size of grains, the grain boundary character distribution, Strain Induced Grain Boundary Premelting, character of the grain boundary connectivity, combination of strain rate and its influence to the mechanisms of plastic deformation, thermal activated internal dynamic transmutation, recrystallization, temperature and its local changes, type of deformation environment, differences in quantity and type of crystalline building defects, diffusion processes, the course of stress relaxation process and others. Because of mentioned factors deformation each time operated differently and none of them is alone responsible for DMT [13-24].

Based upon literature studies of DMT phenomenon and in CuNi25 alloy can be accepted, as in brass, hypothesis of non-uniform deformation [1]. Existing of Ductility Minimum Temperature phenomenon is the effect of concentration of deformation in a small volume of material which is a result of deformation's localization and its excitation by thermal activated processes at the temperature range close to the beginning of recrystallization temperature. Localization of deformation can run just as the other different processes, like non-uniform deformation of crystalline structures as their specific feature, non uniform deformation connected with insufficient accommodated grain boundary sliding, non-uniform deformation as a result of chemical heterogeneity, local temperature differences as a result of inhomogeneitie of structure, stress concentration and so on. In material below temperature of thermal processes activation, where localization of deformation is occurring, usually is observed hardening of material and increase of deformation stress up to moment when deformation can start in other volumes of material. At the temperature of operation of thermal activated processes for example close to the temperature of recrystallization in high deformed areas (hardened regions), starts the recrystallization process, and it is locally created situations for softening of materials. It is connected with decrease of deformation stress and continuation of deformation in those materials volumes, what in consequence is a reason of cracking of materials on a borderline of soft and hard areas. While temperature rises, thermal activated processes take place in more areas, after reaching suitably high temperature, almost in whole volume of sample, forming stress relaxation leading to increase of material ductility [10-22].

Described mechanism is particularly effective when deformation occurring (is located) in very small volume of material. Although in those areas the level of strain are very high, in spite of the macroscopic behavior of material showing its embrittlement. Stress concentration occurs in deformed areas and when the numbers of cracks across critical value cause a formation of fracture and destruction of material. Described process has typical stochastic feature. In the DMT range change of activation energy of deformation process are observed, which is connected with beginning of thermal activated processes like recrystallization and dynamic recovery and others. In the range of temperatures higher than DMT, more areas with high volumes are ready for softening, and therefore, tendency to crack formation is smaller. Deformation process in the range of DMT can be modeled by concept of polycrystalline material with “soft” and ”hard” areas [2], simulated and computed in a macro scale using model of material continuum and Finite Element Method simulation adopted to the elastic-plastic scope.

2. Material and experimental procedure

The single-phase copper nickel alloy seems to be an ideal material for investigations on DMT effect because of lack of phase transformations which exclude a number of material inhomogeneities. The CuNi25 alloy was used as the basic material for experimental studies. The chemical composition of investigated alloy has been shown in Table 1. Material has been delivered in the form of ingots with measurements of 250x400x600 mm. It was hot forged and cut, after this the material has been dragged to rods onto the diameter of 15 mm and then cut into sections of 300 mm. After heat treatment the structure of the material was rather homogeneous, and the average grain size of the material was 400 μm. The results of measuring the size of the grain, were made by light microscopy image analyzer.

Table. 1.
Chemical composition of CuNi25 alloy [%]

Cu	Ni	Mn	Pb	Fe	Zn	C	S
rest	25.1	0.3	0.005	0.3	0.3	0.05	0.01

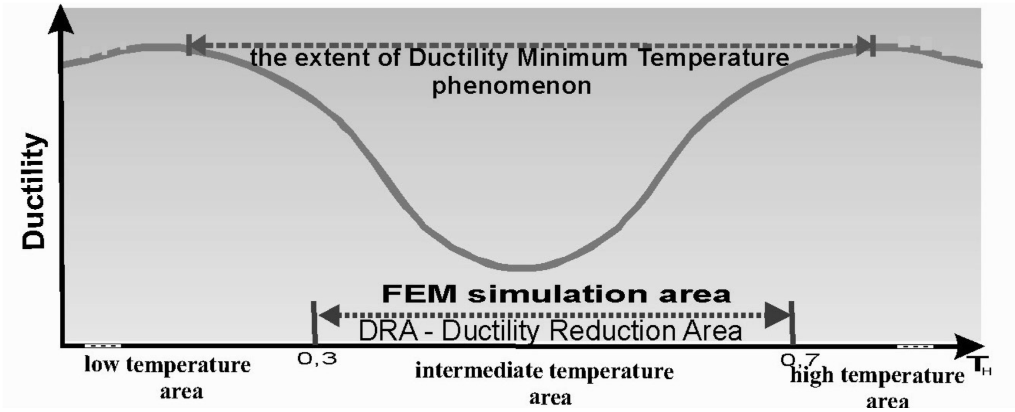

Fig. 1. The range of Ductility Minimum Temperature phenomenon occurrence

The tensile test was carried out in at elevated temperatures and it was conducted on the testing machine INSTRON 4505. The samples was deformed with strain $4{,}2\cdot10^{-3}\cdot s^{-1}$.

The proper tensile temperature was ensured by the electronically controlled resistance furnace equipped with a thermocouple Pt-PtRh13 and electronic temperature controller with an accuracy of ± 2°C. After the static tensile test, the samples for the preservation of their structure were immediately cooled in water. After determining the scope of occurrence of the DMT effect, the temperature interval was set on 25°C in order to indicate accurately course elongation in Ductility Reduction Area (DRA).

In order to investigate the microstructure of deformed samples, the metallographic, scanning electron microscopy study and transmission electron microscope study was conducted.

3. Model of soft and hard areas

Modeling of polycrystalline metal was started from the define of the geometry of the virtual sample. It was assumed that it will have a cuboid shape (Fig. 2). To fill the space completely for the equivalent of the grain was selected Kelvin's 14-hadrons.

To reflect the structural heterogeneity of virtual grains it was assumed that a single model grain consists of a core and mantle (Fig. 3). The individual core and mantle was given respectively properties of hard or soft material. It was assumed that the entire sample volume is filled with grains of a fixed shape and size. According to the hypothesis of non-uniform deformation the following assumptions were taken for this purpose: (1) thickness of mantle layers is function of temperature; (2) grain size and grain shape is constant; (3) at a temperature 350°C, in the grains soft layers not exists; (4) at 600°C full grains are filled by soft materials as a result of soft layer increasing and; (5) loading acts for sample dose not develop large deformation, while stresses develop which exceed yield point in boundary layers. Material properties were taken for investigated CuNi25 alloy from experiment.

This model works for all metals and alloys, because the mechanisms that occur in them do not depend strictly on the particular chemical composition and deformation conditions. The process of plastic deformation takes place earlier, locates itself and causes deformation of soft areas leading to the accumulation of stress, until they reach the critical value reflecting the loss of material plasticity reserve.

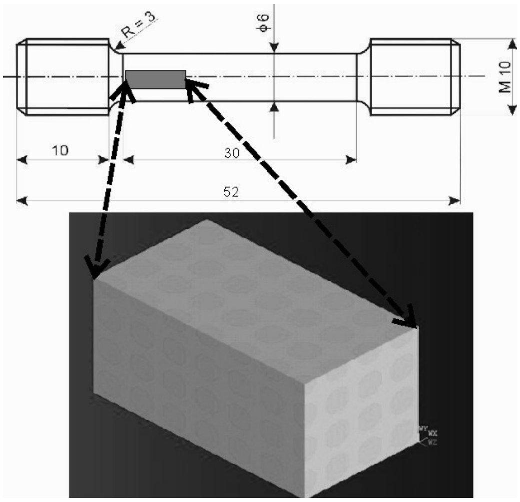

Fig. 2. The real sample and the model of virtual polycrystalline sample of material with "hard core" and "soft mantle" areas used for FEM simulation, based on Kelvin's 14-hedrons

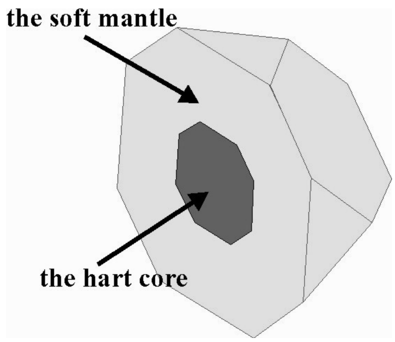

Fig. 3. Model of virtual grain with a hard core and soft mantle shell in single 14-hadron used for FEM simulation

It allows for simplification of the model and enable the assumption that at a given temperature, the inhomogeneities occurring in the material cause macroscopically the existence and the occurrence of two categories of areas, in which a local combination of various material properties and other factors, determines different level of critical stress (σ_{cr}) necessary to initiate the course of one of the mechanisms of plastic deformation. The study adopted the following fragmentation of these areas: SA - soft areas in which the level σ_{crSA} is sufficient for the location and course of plastic deformation and HA - hard areas characterized by the presence of higher level of critical stress σ_{crHA}.

$$\sigma_{crSA} < \sigma_{crHA} \tag{1}$$

Macroscopically the course of the plastic deformation in the scope of the occurrence of the DMT effect is a result of mutual coexistence of deformation in the both soft and hard areas. Due to the difference in the level of threshold value of deformation activation of the both soft and hard areas the macroscopic level of ductility depends on location of deformation. After reaching an adequate value of strain for reasons of its mechanical level of stress and may cause in a macro scale local loss of plasticity reserve. It leads to macroscopic changes in plasticity and local destruction of material. In order to confirm qualitatively the validity of the thesis, finite element method software ANSYS was used. The three dimensional numerical verification of “soft and hard places" model for CuNi25 alloy was held on the basis of real experiment results.

4. Results and discussion

For CuNi25 alloy deformed with strain $4.2 \cdot 10^{-3} \cdot s^{-1}$ in high temperature tensile test results revealed that elongation and reduction of area for analyzed materials shows strong dependence on the test temperature and Ductility Minimum Temperature phenomenon was found (Fig. 4). The existence of reduced ductility area was indicated between 350-600°C. The course of elongation line show that the minimum of DMT effect for CuNi25 400μm alloy obtained at 525°C level of 15% for elongation.

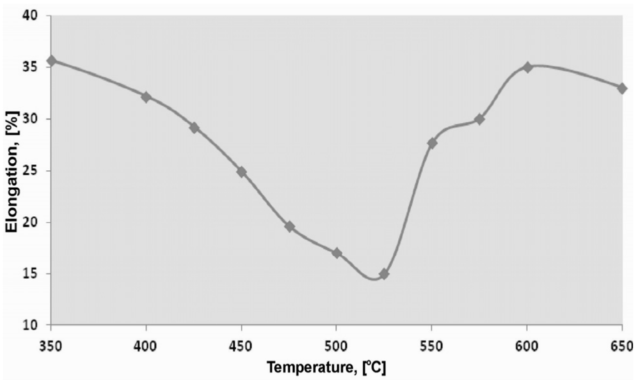

Fig. 4. Elongation versus test temperature for CuNi25, after deformation during high temperature tensile tests with strain rate $4.2 \cdot 10^{-3} \cdot s^{-1}$

The results of conducted simulations with the use of “soft and hard areas” model was shown on chart (Fig. 5) seem to confirm that the of non uniform deformation reflects qualitatively the behavior of the material during deformation in the range of DMT phenomenon existence. Obtained results are qualitatively reflected with the results obtained for elongation in the tensile test of CuNi25 alloy (Fig. 4). The calculations made and their comparison with the results of actual research in DRA indicates the possibility of functioning of the concept of the model of “soft and hard areas” in reality, at least in a qualitative way. In the numerical model, the areas in which the concentration of stress was observed, are the border areas between the soft and hard areas (Fig. 6) and points of triple virtual grains connection (TJ). The same conclusions can be drawn from the observations carried out on TEM as evidenced [9] and on the (Fig. 7) observations on thin films made of all samples deformed in the range of ductility reduction area show similar regularity. Places having a tendency to accumulation of point and linear defects are inclusions and especially privileged areas are grain boundaries, particularly the TJ. These sites generate or accumulate dislocations leading to increase of local stress and changes in mechanical properties of these areas.

This can be considered further circumstantial evidence of the occurrence of persistent distortion localization during deformation. It provides a sense of the rightness of the proposed thesis of non-uniform deformation, confirming the heterogeneous plastic deformation process in real polycristals deformed in the DRA.

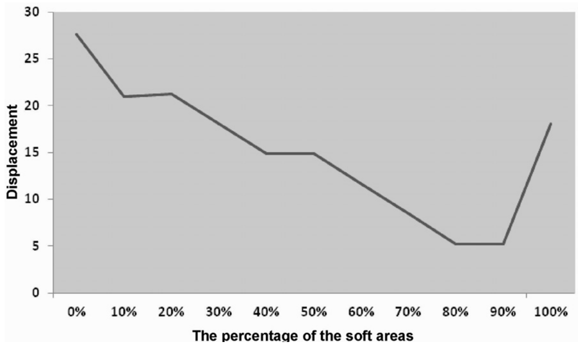

Fig. 5. The results of FEM simulations, displacement of virtual sample versus percentage of the soft areas

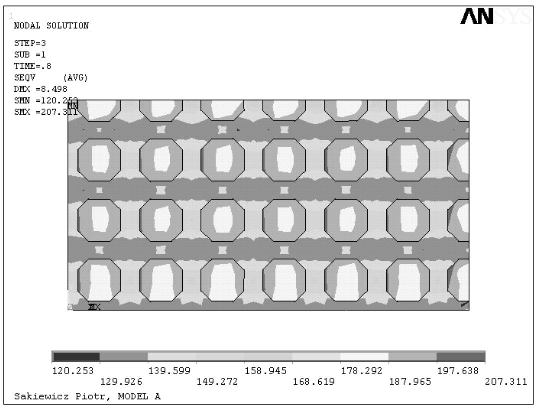

Fig. 6. Stress distribution in the model of 70% of soft areas in the volume of the virtual sample

The TEM observations revealed zones of different saturation of dislocations within grains and also the border areas. In the vicinity of wide angle grain boundaries the deformation structure is characterized with high heterogeneity in terms of density, shape and size of dislocation cells. In these zones the presence of elongated deformation cells was often observed. The samples of CuNi25 alloy after being deformed above 400°C, show area of local dislocation agglomeration, partially in the cellular system, characterized by different levels of dislocations density (Fig. 7). Segregation and dispersed spherical emission on dislocations are most probably visible. In all of the studied materials deformed in DRA was observed the presence of border zone of complex dislocation structure characterized by the occurrence of the areas of different density of crystalline structure defects.

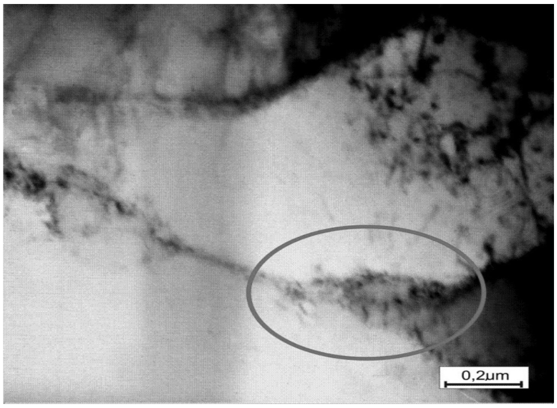

Fig. 7. The structure of CuNi25 alloy sample after deformation at 475°C (TEM)

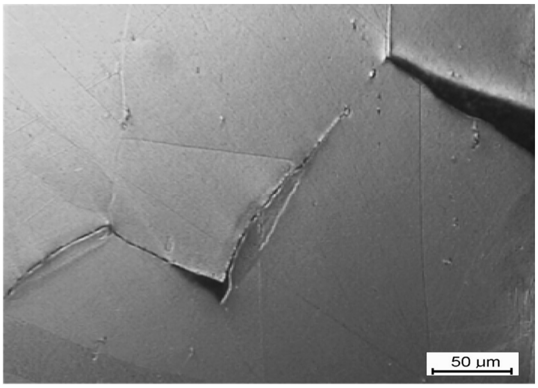

Fig. 8. The structure of CuNi25 alloy sample after deformation at temperature 500°C

After deformation in the range of DRA, in grains boundaries occurs two types of voids and cracks which runs along the grain boundaries (Fig. 8). First type of voids is probably a result of non-enough accommodation of grain boundaries sliding or cavitation. Second type is usually long cracks, which are located also along the grain boundaries and are and exist near the small grains which ”decorate” original grain boundaries (Fig. 9). With increasing temperature in samples after deformation the processes of rebuilding the microstructure, probably dynamic recovery and dynamic recrystallization are observed. This was revealed by the presence of grain boundary serrations and cellular dislocation structure of subgrains and local existence of undefected areas, as well as small new grains. Traces of dynamic recrystallization in the samples of CuNi25 alloy are relatively less visible than in brasses and copper due to the higher value of stacking fault energy [1,23]. CuNi25 samples for the preservation of its structure, immediately after the deformation, were cooled in water, which probably caused the freezing of recrystallization nucleation.

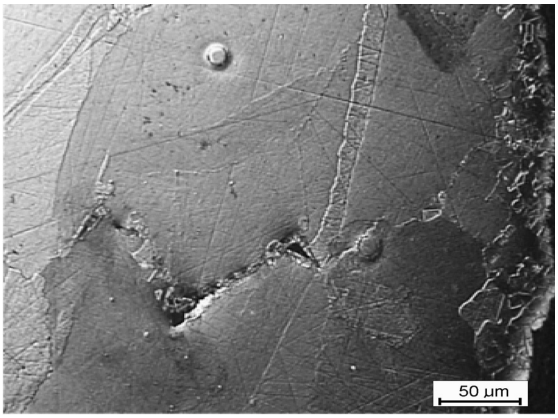

Fig. 9. The structure of CuNi25 alloy sample after deformation at temperature 600°C

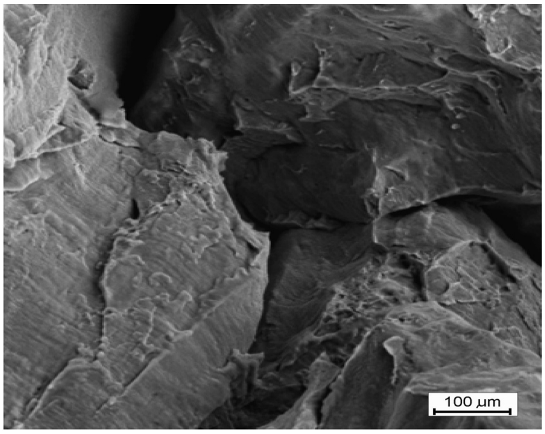

Fig. 10. The fracture of CuNi25 alloy sample after deformation at temperature 525°C (SEM)

The result of fractography examinations shows the influence of the deformation temperature on the character of the fracture in CuNi25 alloys. The examined copper-nickel alloy showed after the tensile test in the temperature below 350°C and above

650°C transcrystalline ductile fracture. In the range of DMT type of existing fracture has been changed, we can notice mixed both brittle and ductile, in some areas intergranular and others transcrystalline. The most intercrystalline brittle fracture was noticed at samples deformed at the 525°C, therefore at the minimum of DRA. Even on those brittle fractures, it has been noticed locally small areas of plastic deformation (Fig. 10), which may indirectly indicate correctness of the non-uniform deformation hypothesis.

5. Conclusions

The verification of the non-uniform deformation hypothesis carried out by the use of the finite element method showed that the proposed non-uniform deformation hypothesis as a cause of Ductility Minimum Temperature phenomenon (DMT) in CuNi25 alloy and the "soft and hard areas" model seem to be correct. Simulations and computer calculations showed that the reduction in displacement as well as elongation in a real material is temporary. The results of the conducted simulation with regard to the actual results of ductility research conducted on the CuNi25 alloy seem to confirm the rightness of the concept. The adopted model of the course of the DMT phenomena appears to accurately reflect the behavior of the material during deformation in the scope of reduces ductility area. The results are qualitatively consistent with the results obtained during the tensile test of CuNi25 alloy. Based upon literature studies, observation and analysis of plastic deformation processes and their influence on range and level of, hypothesis of non-uniform deformation. The location of deformation process in small volume of heterogeneous material causes the formation of stress between "soft" and "hard" areas. The critical level of non-homogeneity is causing concentration of stress in whole volume of material causing nucleation and growth of cracks. Resulting in further influence of strength, to reduced surface cause growth of stress provoking lowered ductility and destruction of material. The "soft and hard areas" model, based on difficult to measure and define concept of heterogeneous deformation reflects in macro scale the process of plastic deformation in the range ductility reduction area. Therefore, quantity description of this phenomenon in structural scope is very difficult and explanation of DMT phenomenon has only a character of the hypothesis.

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