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# SERRATED YIELDING: PHYSICAL MECHANISMS, EXPERIMENTAL DATA, MACROPHENOMENOLOGICAL MODELS

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## ABSTRACT

Jump-like deformations as a phenomenon of plastic deformation instability is found for a wide range of ductile materials within certain temperature and strain rate ranges. It is known that temperature and strain rate are the most important parameters of inelastic deformation. For most polycrystals, in the absence of phase transitions, the increase of temperature and decrease of deformation speed leads to a reduction of stresses of inelastic deformation resistance. At the same time there is an inverse dependence of the flow stress for a great number of alloys in some ranges of temperatures and strain rates. Many researchers think that the main reason of this anomalous behaviour is a diffusion process and interaction of dislocations with solute atoms. The Portevin-Le Chatelier effect is one of the best known manifestations of the influence of diffusion processes on the behaviour of deformable materials. At the moment it is an urgent problem to identify ranges of actions, within which serrated yielding is implemented in order to exclude them from manufacturing modes of metal processing.

It is preferable to use methods and approaches based on mathematical modelling for the analysis of serrated yielding, determination of optimal processing modes and design of new materials, as experimental methods are very resource intensive and applicable only for existing materials. It is not possible to build mathematical models of the studied processes with a required degree of sufficiency without a thorough study of available empirical data and establishment of leading physical mechanisms.

In the first part of the review we consider the works devoted to the description of physical mechanisms and experimental studies of serrated yielding. The main mechanism is considered to be dislocations pinning with solute atoms during delays of motion of dislocations with barriers of different nature. Three main types of the Portevin-Le Chatelier effects have been allocated based on the experimental data of uniaxial loading, in real experiments, different combinations of these three types can be found. Different approaches and models (macrophenomenological, structural mechanical, physical) are used for the theoretical description of serrated yielding; only phenomenological models are analyzed in the present review.

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## 1. Introduction

Serrated yielding (SY), also called jump-like deformation, is a phenomenon of plastic deformation instability which is found almost in all alloys at certain temperature and strain rate ranges. Serrated yielding is revealed on deformation curves in the form of repeating inhomogeneities, i.e. steps or teeth of different types, and has a number of common factors for different materials and temperatures. In the majority of works in this area, SY is connected to macro- and mesolocalization of deformation, which is revealed in the form of shear bands for mono- and polycrystalline metals and alloys. Traces of shear bands on surfaces of ready-made products significantly increase roughness of surfaces, decrease fatigue strength and corrosion resistance. Therefore, it is important to solve the problem of specifying ranges of actions, within which serrated yielding is implemented, in order to eliminate them in technological modes of metal processing (at least during finishing operations).

Competitive nonequilibrium processes related to hardening and softening are active during deformation of materials at high temperatures. The increase of dislocations density in a metal, their interaction with each other and with other defects of the crystalline lattice make the greatest contribution to hardening. Without phase transitions, alloy softening occurs due to dynamic recovery, polygonization and recrystallization (however, these processes can be considered as types of phase transitions, from the point of mechanics).

Loss of monotonicity of temperature dependence and sensitivity to rate of mechanical properties (flow stress, in particular) during inelastic deformation under simple and complex loadings is found in ferrum-based alloys, i.e. alloy steels, intermetalic metals and other alloys. Experimental methods of studying the considered phenomenon are extremely resource-intensive (especially for complex loading tests) and applicable only for existing materials. It is preferable to use methods and approaches based on mathematical modelling for the analysis of serrated yielding, determination of optimal processing modes and design of new materials. It is not possible to construct mathematical models of the studied processes with a required degree of sufficiency without a thorough study of available empirical data and specifying leading physical mechanisms; and the main part of this review is devoted to it.

According to the available experimental data, it is well known that temperatures and strain rates significantly influence deformation processes. For most polycrystals, in the absence of phase transitions, the increase of temperature and decrease of strain rate lead to a reduction of stresses of inelastic deformation resistance. The influence of strain rate and temperature on materials behavior are presented in the following works [47, 71, 72, 73 etc.] The influence of temperature and strain rate on material response depends largely on a mode of their changing, type of a crystalline lattice, and defect structure.

Holding polycrystals after preliminary plastic deformation at high temperatures (0.1-0.2 $T_r$, $T_r$ is the homological temperature equal to the ratio of the process temperature to the material melting temperature in Kelvin degrees) leads to a significant increase of flow stress during subsequent plastic deformation; this phenomenon is called aging and caused by “fixing” dislocations with atoms of “solutes” diffusing to them.

Among the effects related to static strain aging (SSA) and dynamic strain aging (DSA) we will mention the following ones: occurrence of a “yielding tooth” on a deformation curve, its repeated occurrence, a qualitative dependence of a “tooth” from the rigidity of the loading system and serrated yielding, which is associated with the Portevin–Le Chatelier effect (sensitivity) in the majority of works.

Physical processes causing SSA and DSA in alloys lead to microstructure changes, which affects macroproperties of products. That is why it is necessary to know thermomechanical conditions initiating SSA and DSA, relations between physical mechanisms of aging with other mechanisms of hardening and softening in order to understand and model processes taking place in the course of material deformation.

## 2. Aging and Diffusion Defects

A significant difference of alloys behaviour from the reaction of pure metals on different interactions are well known, they are already used by the mankind for centuries. Most alloys used in industry are formed based on some main metal (for example, in ferrum steels), other components may amount from tenth (and hundredth) up to tens of percent of atomic weight; later the atoms of the latter will be called “solute” ones. A great variety of alloy properties is generated not only due to a variety of physical and chemical interactions and microstructure at the stage of a material formation (e.g., crystallization from alloys), but also due to processes occurring at stages of a subsequent thermomechanical processing of workpieces. Diffusion processes are most important for the considered serrated yielding; they are studied and described in a great number of works, including classical monographs in solid mechanics [14, 16]. A significant part of works in this area is devoted to different aspects and results of experimental studies.

The paper in [75] is about methods and results of experimental studies of static strain aging of specimens made from eutectoid steel drawn with high degrees of reduction (more than 3) [75]. Differential scanning calorimetry and thermoelectric methods are used for the experimental analysis. Based on the experimental results it is stated that the aging process can be divided into two stages. At first, in the neighbourhood of dislocations in the ferrite phase carbon atoms located in the interstices of the iron lattice are moving, but because of a small concentration of carbon in the ferrite this process quickly exhausts itself. It is noted here that the local equilibrium concentration depends on the dislocation density which increases with an increase of dislocations density. At the second stage dissociation of martensite and diffusion of carbon atoms in the neighbourhood of dislocation cores until they reach a locally equilibrium concentration.

Results of thermomechanical tests of the specimens from titanium-base alloy (Ti-Al) can be found in [56]. The specimens were pre-reduced by 0.6-3.4 % with strain rates of $10^{-5}$-$10^{-4}$ $s^{-1}$, after it, they were unloaded until they reached different values of stresses (from 2/3 to 1/10 of flow stress) and were exposed at temperatures ranging from 200 to 500 °C. During further loading there was a considerable increase of flow stress with a subsequent sharp fall of the latter, which can be explained with static strain aging effects. It is shown that the holding temperature and time highly affect the value of stress increase, while the level of stresses maintained in the process of aging has practically no influence on the value of the flow stress increase.

[67] discusses mechanical testing results of uniaxial symmetric cyclic deformation of cylindrical specimens made from stainless steel 316L(N), which give an idea of how dynamic strain aging influences fatigue strength. The experiments are given for wide ranges of strain amplitudes (0.25-1.0 %), strain rates $3\cdot10^{-5}$-$3\cdot10^{-2}$ $s^{-1}$ and temperatures (298-873 K). The results of the experiments prove that dynamic strain aging taking place at temperatures ranging within 673-873 K significantly decreases fatigue strength. The results of similar studies with regard to austenitic stainless steel (15Cr-15Ni-2.5 Mo) modified with titanium are presented in [64].

[68] provides data of experimental mechanical and microstructural (using electron microscopy) studies on how temperature, holding time and cooling rate influence the process of static strain aging. The experiments were carried out using four grades of ultra low-carbon (with 0.0032-0.0052 % of carbon) steels at annealing temperatures of 750-920 °C. The influence of aging on mechanical properties was estimated by an increase of yield stress (a "yielding tooth"). Results of similar studies performed with specimens from Al-Mg are given in [28]. Special attention is paid to an influence of alloy additives of boron on viscosity and plasticity of alloys.

Results of detailed experimental studies of Luders bands in tubular specimens from steel 1045 (C - 0.487, Si - 0.28, Mn - 0.74 %) under stretching, torsion and combined loading (ray trajectories and trajectories with a break/rupture by $90^{o}$) at room temperature are outlined in [81]. The formation of Luders bands is explained with a release of dislocations from Cottrell atmospheres and a sharp increase of their density. Distribution characteristics of bands are described depending on types of deformation trajectories.

The work in [36] suggests using experiments of simple cyclic loading at different temperatures (–20, 20 and 60 °C) and different methods of preliminary heat treatment of specimens to study the effects of strain aging on behaviour of aluminium alloys. Some part of specimens has been prepared to have a maximum preliminary aging at high temperatures, when solute atoms create discretely distributed particles of the secondary phase. Another series of specimens was subject to the so called natural aging at room temperature. Later specimens of both groups were subject to cyclic loading at fixed strain amplitude (±0.6 %). It is shown that the specimens of the first group show a fast initial increase of amplitude values of stresses with their subsequent steady decrease. The authors explain softening as cutting of particles of a rigid phase with moving dislocations and formation of shear bands. Specimens of the second group showed a monotonic increase in the amplitude stresses (up to the formation of cracks), the higher the test temperature, the greater the amplitude stresses. This hardening is explained by the effect of dynamic strain aging due to diffusion of solute atoms uniformly distributed in the material (solid solution).

The results of the experimental study of the effect of dynamic strain aging on features of texture formation of various layers of a rolled sheet of low-alloyed chromium (the content of alloying elements of La, Ti, Nb, Ta is in the range of 0.2-0.5 %, and 0.008-0.01 % of solute atoms C, O, N) [59]. A significant change in the texture distribution along the thickness of the sheet is shown, depending on reduction modes, which the authors explain by the influence of the latter on the diffusion flows of solute atoms, which, in turn, lead to a difference in the realization of the conservative and nonconservative modes of motion of dislocations.

Work [3] provides an experimental study of the influence of dynamic strain aging alloy AMg6 on resistance of plastic deformation in the range of temperatures 300-500 °C and strain rates 0.1-4 $s^{-1}$. Metallographic studies of AMg6 alloy have been carried out with the purpose of revealing the main mechanisms of hardening and softening in the investigated temperature and strain rate range. Metallographic methods of studies showed that in AMg6 alloy, dynamic strain aging takes place during deformation, which leads to extraction of intermetallides from the solid solution matrix at a test temperature of 400 °C. It is established that in AMg6 alloy, a partial dissolution of the intermetallide precipitates occurs at a temperature of 400 °C.

The results of mechanical tests for monotonic and cyclic uniaxial loading of stainless steel specimens at constant and cyclically varying temperatures are given in [78]. Testing temperature varied within the range of 293-823 K, strain rates varied within $10^{-5}$-$10^{-3}$ $s^{-1}$. It follows from the analysis of the experimental results that at low temperatures the material exhibits a high sensitivity to strain rate, which decreases with an increase of temperature when temperatures of serrated yielding in a certain temperature range occur. If temperature increases, an increase in cyclic hardening is also observed. It is noted that the specified effects express (among other mechanisms) the influence of dynamic strain aging. A macrophenomenological thermoviscoplastic model with a combined hardening law is used for the description; here isotropic hardening takes into account strain aging, and two components of residual microstresses ("back stresses") are available in the law of kinematic hardening responsible for close and far acting stress fields.

The methods and results of investigating the influence of formations (the second phase) on mechanical characteristics and the anisotropy of plastic properties in the uniaxial stretching of the aged Al-Mg-Si alloy are presented in [19]. During the model construction, previously obtained results of other researchers are widely used, in particular, the analytical solutions to problems of nucleation and growth of inclusions. To describe deformation, the elastoviscoplastic model with the power law of flow is used. The influence of inclusions and solute atoms of alloying elements (Mg and Si for the considered alloy) is taken into account in the ratio for critical shear stresses along sliding systems (SS); hardening is determined by the density of dislocations, the evolution equation also includes the dependence of the equation parameters on the concentration of the atoms of alloying of solutions and inclusions. A direct model (of the 2nd type) [13], is built into the ABAQUS package was used for implementation. The theoretical results show a satisfactory compliance with the data of the experiments performed by the authors.

## 3. The Portevin-Le Chatelier Effect

Based on models of solid mechanics and available experimental data, it can be stated that all deformation processes, in which diffusion processes (diffusion of point defects, nonconservative motion ("creeping") of dislocations, etc.) play a great role, are sensitive to strain rate and temperature [13]. The Portevin-Le Chatelier (Savart-Masson) effect is one of the best known manifestations of the influence of diffusion processes on the behaviour of deformable materials.

It is worth reminding that, depending on the applied loading method, there are two types of mechanical tests, i.e. "rigid" (kinematic) and "soft" force loading. In the first case, the traverse speed is set, and the force response of the system is measured. In the second case, external force factors are set (for example, the stress value necessary for the implementation of the prescribed deformation) and the kinematic response of the material is measured.

From the point of view of macroexperiments on uniaxial loading, the Portevin-Le Chatelier effect occurs in certain cases, such as at low strain rates and elevated temperature, diagram σ-ε acquires a sawlike shape ("teeth") under "rigid" loading; under "soft" loading the diagram becomes steplike (Fig. 1) [1, 2].

Initially the discovery of this effect belongs to F. Savart (1837) and A. Masson (1841) [1, 2], but the work of these researchers was not given due attention and later (1923) the effect was "rediscovered" by A. Portevin and F. Le Chatelier [61], whose names denote this effect in most modern works. For the sake of justice, it is important to note that, unlike Savar and Masson, Portevin and Le Chatelier originally intended to study just serrated yielding. To solve this problem, they used specimens from alloys (aluminum + 4.5 % of copper) and (aluminum + 4.5 % of copper + 0.5 % of magnesium); the tests were carried out in a kinematic type machine (rigid loading) at deformation rates of 0.08 min$^{-1}$.

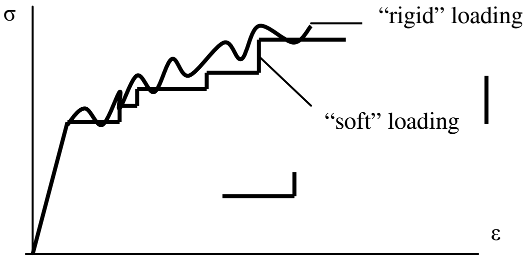

Fig.1. Diagrams of uniaxial "rigid" and "soft" loadings

This effect has been studied by many researchers (K. Elam, T. Sutoki, E.A. MacReynolds, O.V. Dillon, U.N. Sharp and others). The experimental studies showed a dependence of the amplitude of the teeth on temperature and temperature prehistory (Sutoki), the effect of the metals purity on the Portevin-Le Chatelier effect, and the wave-like character of the movement along the specimen of the deformation step (McReinolds). At the moment there are several explanations of the Portevin-Le Chatelier effect. One of the first ones was given by A.G. Cottrell [30] and explained the effect with a diffusion of solute atoms to dislocations and their "pinning" due to the interaction with the solute atoms [14, 16]. It is worth mentioning that this point of view is shared by many researchers of the Portevin-Le Chatelier effect today (for example, [22, 33, 39, 45, 50, 53, 57, 58, 62, 70] and longs lists of their references. B.M. Lempriere (1962) denoted the effect as instability of strain rate for some materials and fluctuations of the test machine; the need in taking account of the experimental set-up is also noted in [53]. At present, none of these hypotheses is prevailing and proven experimentally, so there are no models that adequately describe this effect for various materials and loading conditions.

Materials showing serrated creep can be divided into two groups by the scale of this phenomenon. The first group includes materials exhibiting macroscopic serrated creep. The most well-known example of localization of deformation at a macroscopic level is the appearance of a neck at the final stage of stretching the specimen [10, 12, 15], the Luders-Chernov bands. Macroscopic serrated creep is found in metals and alloys prone to the Portevin-Le Chatelier effect [61], i.e. polycrystalline alloys of systems Al-Cu, Al-Mg [1, 2, 52], Ni-Cr, Ni-Fe-Cr [40-42].

The second group includes materials demonstrating mesoscopic serrated creep associated with the dynamics of dislocation clusters at the mesoscopic structural level (lines and slip bands, twins, etc.). In this case serrated creep occurs in the form of a sequence of jumps of deformation on creep curves. This group of materials includes single crystals of zinc, ice, alkali-halide single crystals, polycrystalline brass, copper, lead, and a number of polymers.

Usually the effect of the Portevin-Le Chatelier effect is observed in a number of dilute solutions of introduction and substitution (aluminum, copper, soft steel alloys), some metallic composites [11, 31], and for each material the effect manifests itself in a certain temperature-rate region [6, 7]. These temperature-rate regions of the Portevin-Le Chatelier effect correspond to the inverse high-speed and anomalous temperature of the flow stress dependency, i.e. if the strain rate increases, the flow stress does not increase but decreases, and as the temperature increases, the flow stresses remain either independent of its increase or increase.

## 4. Experimental Studies

Experimental data indicating a nonmonotonic response in the case of monotonic inelastic deformation or loading of specimens were discovered long time ago. Earlier we have already mentioned the works of Savart [65], Masson [49], Portevin-Le Chatelier [61], peculiar curves of deformation are shown in the experiments of Montel [55].

For small and large deformations, this effect has been studied for the last two centuries by many experimenters and theoreticians (K. Elam, T. Sutoki, E.A. MacReynolds, O.V. Dillon, U.N. Sharp and others), but a satisfactory explanation and description to date has not been received.

Irregularities of the stress-strain diagram for tensile metallic specimens were first described by Dulot in 1813 [2]. Stepwise relations in case of “soft” loading are known since 1837 as the Savar-Masson effect.

Masson described a steep, almost vertical (in the σ-ε diagram) stress increase, accompanied by very small deformation, up to the value at which a sudden sharp increase in deformation at constant stress occurred (ladder effect).

In 1923 Portevin and Le Chatelier tested specimens from alloys (aluminum + 4.5 % of copper) and (aluminum + + 4.5 % of copper + 0.5 % of magnesium) in a kinematic type machine (“rigid” loading) at strain rates of 0.08 $\text{min}^{-1}$. They found serrated yielding and occasionally clear sounds associated with the appearance of each step of yielding [2].

In 1949 McRainolds found [52] that the formation of each horizontal domain of the graph is due to the passage of a slow “wave” pattern along the specimen.

A.G. Cottrell considered the effect of sensitivity in solid substitutional solutions (by the example of V-C) in [77]. Estimates are obtained for the intervals of strain rates and temperatures, in which the effect of sensitivity appears on the basis of a qualitative analysis of the interaction of solute atoms with dislocations.

An interest to experimental studies of the Portevin-Le Chatelier effect is still great among present time researchers. It should be noted that most of the experiments are implemented for the case of uniaxial loading of flat or cylindrical (with circular cross section) specimens. Three main types of the Portevin-Le Chatelier effects have been allocated based on the experimental data of uniaxial loading: 1) Type A. The appearance and movement of a single (solitary) wave along the axis of the specimen, which can occur many times; 2) Type B. Deformation bands appear and disappear in an oscillating or intermittent mode, propagating along the sample (stop-and-go); 3) Type C. Bands arise (and disappear) randomly along the length of the specimen. Like every classification, the above is somewhat conditional; in real experiments there can be a different combination of these three types.

Results of the experimental studies of inelastic deformation of titanium alloys (Ti – 15 % Mo and Ti – 25 % Mo) in a wide range of temperatures and strain rates are presented in [20]. Serrated yielding was observed in the experiments on uniaxial tension at temperatures of 575-775 K and strain rate $1.31 \cdot 10^{-4}$ $\text{s}^{-1}$ for the Ti alloy of 15 % Mo; the structure was studied at different stages of deformation of the specimens with the use of electron microscopy. At different scale levels (from tens of nm to mm) deformation processes are described in detail, which are responsible for serrated yielding. For the alloys under consideration, the main mechanism of serrated yielding is the alternating occurrence and destruction (by shifting bands) of the ω-phase particles in the environment of a stable β-phase. It is noted that in the alloy Ti - 25 % Mo, not prone to the formation of ω-phase, deformation is realized monotonically throughout the temperature-strain rate range under consideration.

By analyzing the results of numerous experiments aimed at investigating serrated yielding, it can be concluded that the source of discontinuous, irregular response of the material under monotonous influences is the presence of inhomogeneities in the properties of the material and the features of the motion of large dislocation arrays (i.e. their coordinated motions) at various scale levels, from nanosizes to values commensurate with the dimensions of macrospecimens. In this case, these inhomogeneities themselves can arise and disappear due to the processes of motion and interaction of defects of various nature and dimensions occurring in a material.

Methods and analysis of results related to the experimental studies of serrated yielding in specimens from titanium aluminides are presented in [60]. Uniaxial compression tests are carried in vacuum at temperatures of 20-500 °C and strain rate $2 \cdot 10^{-3}$ $\text{s}^{-1}$ for alloy TiAlNb, 20-900 °C and $5 \cdot 10^{-4}$ $\text{s}^{-1}$ for alloys TiAlMo and TiAlMoNb. On the basis of studying various quantitative compositions of alloys, it is established that the sensitivity effect is observed in alloys in which the stoichiometric ratio for Ti atoms is violated, in which (or with a smaller number of titanium atoms) titanium atoms occupy quite definite places in the crystal lattice. Excess titanium atoms form solute clouds around dislocations, interaction with which determines the irregular nature of deformation.

Results of the experimental studies of how specimens made from Al –2.03%Mg–1.13%Cu–0.95%Zn alloy behave are given in [80]. The experiments were carried using flat specimens of 20 and 50 millimetre long under uniaxial stretching, at room temperature, in a wide range of loading rate alterations ($7.6 \cdot 10^{-4} \div 10.5$ MPa $s^{-1}$). The authors connect the Portevin-Le Chatelier effect with formation and distribution of shear bands. There is a significant effect on the kinetics of the shear bands of the presence of stress concentrators, loading rate, and the length of the specimen.

The results of systematic studies of specimens behaviour from Cu+Al and Cu+Mn alloys under uniaxial loading over a wide range of temperatures and strain rates are given in [57, 58]. Based on the analysis of uniaxial stretching diagrams (curves $\sigma$–$\varepsilon$), the diagrams of regions of stable and unstable (serrated) inelastic deformation are constructed; the presence of three characteristic regions of the process parameters is noted, where the Portevin-Le Chatelier effect occurs. According to the authors, the difference in the processes of dynamic strain aging in the three indicated regions is due to the difference in diffusion mechanisms (“lattice” (normal) and “tunnel” diffusion).

Results of the experimental studies related to the influence on serrated yielding of the nitrogen content in austenitic stainless steel 316L are given in [39]. The tests were made using cylindrical specimens under uniaxial tension with constant strain rates within the range ($2 \cdot 10^{-4} \div 10^{-2}$) $s^{-1}$ at 293, 373, 573, 673, 773, 883 and 973 K. The contents of nitrogen was changing within the range of 0.01-0.15 %. It is shown that the region of serrated yielding shifts toward higher temperatures with an increasing content of nitrogen. An increase in the nitrogen concentration up to 773 K also leads to an increase in the critical accumulated deformation of the start of serrated yielding; at higher temperatures the increase in the nitrogen content does not affect the critical deformation. It is also observed that the energy of dynamic strain aging starts to activate as the nitrogen concentration starts to increase.

The anisotropy of sensitivity for aluminum sheet alloys was demonstrated by results of the experimental studies given in [29]. The tests were carried out on samples of Al-Mg, of AA5182 alloy, obtained by continuous casting (CC) and casting into moulds (CIM), followed by hot and cold rolling and various types of heat treatment. The specimens obtained for testing differed significantly in microstructure, i.e. samples from a CC alloy had an approximately equiaxed grain without a clear texture, whereas CC samples had an elongated grain shape in the direction of rolling and texture. The experiments were carried out on specimens cut in the rolling direction, in the transverse direction and at an angle of 45° to the rolling direction under kinematic stretching (rigid loading). The distribution law of amplitude of the stresses jumps (the share of jumps having a certain amplitude value) was used as the main characteristic of the discontinuous flow. It is shown that for CC samples, the distribution laws of amplitude of the stress jumps are almost the same for different specimens, whereas for CC specimens, these laws are significantly different. The authors explain the anisotropy effect by the concentration of solute atoms predominantly along the grain boundaries, which creates easier conditions for dislocations’ slip along the direction of grains elongation.

The results of experimental tension studies of the specimens from polycrystals of Al-Mg alloy and single-crystal Cu-Al alloy are presented and analyzed in [24]. The experiments were carried out at room temperature in a wide range of strain rates ($5.56 \cdot 10^{-6} \div 1.39 \cdot 10^{-2}$) $s^{-1}$. Polycrystalline samples had a different structure, i.e. in the state of delivery (after rolling), obtained after annealing and deep annealing. In the whole range of the studied strain rates, modes of discontinuous plasticity were implemented. In order to process the measurement results, the methods of chaotic dynamics and fractal analysis were used. It was found that at medium speeds, the deformation has a chaotic character (shear bands of type C), and at high speeds a transition to self-organized criticality (slip bands of type B and A) is observed.

[43] shows the results of tests on indentation and stretching of samples from aluminum alloy (3.6 Mg, 0.39 Mn, 0.30 Fe, 0.16, Si, 0.076 Cu, 0.072 Cr, 0.031 Zn, 0.018 Ti, 0.014 Zr in mass percent) at room temperature. Indenters of conical, pyramidal and cylindrical shapes are used. A satisfactory agreement of the results in all the experiments was shown. The transition to a “stationary” mode of discontinuous plasticity (that is, approximately same stress jumps with a continued monotonic loading) with large deformations is noted.

The work in [69] is of a considerable interest (especially from the point of view of identification and verification of models of the sensitivity effect), where the results of the experimental study of behaviour of Al-Cu alloy specimens subjected to uniaxial stretching at low speeds ($10^{-4}$, $10^{-3}$, $5 \cdot 10^{-3}$ $s^{-1}$) are presented. The specimens were heat-treated until a solid solution (heating and aging for 3 hours at a temperature of 500 °C, cooling in an oven and holding at temperatures of 500 °C, 400 °C, 300 °C, 200 °C and 100 °C followed by aging). As a comparison, one of the series of specimens was annealed (holding for 2 hours at a temperature of 500 °C and slow cooling in a furnace). An increase in the treatment temperature leads to an increase in the Cu concentration in the solid solution, a decrease in temperature contributes to the formation of local zones of Cu precipitates and the formation of $CuAl_2$ inclusions, which affects the behaviour of macrospecimens. It is shown that with an increase in the treatment temperature, a transition is observed from type C shear bands to type B bands with a simultaneous increase in the amplitude of stresses of serrated yielding.

The tension experimental results shown in [74] of cylindrical specimens from magnesium alloy (94.7 % Mg, 4.32% Li, 0.97 % Al) at strain rates $3.33\cdot10^{-4}$, $6.66\cdot10^{-4}$, $3.33\cdot10^{-3}$, $6.66\cdot10^{-3}\ \text{s}^{-1}$, and room temperature have a negative rate sensitivity and serrated yielding for the specified parameters of deformation. The authors explained the alloy behaviour peculiarities with a diffusion of Li and Al atoms to dislocation clusters at various dislocation barriers.

The technique and results of the experimental study of samples from alloy 3033 (Al – Mn) under uniaxial compression to true (logarithmic) deformation values of 80 % are presented in [33]. The tests were conducted in wide ranges of strain rates (from $10^{-3}$ up to $10^{4}\ \text{s}^{-1}$) and temperatures (from 77 K to 800 K). A significant influence on the material microstructure and behaviour, the history of temperature effects, accumulated plastic deformation and strain rate are noted. It is shown that serrated yielding, the manifestation of which is associated with strain aging, can occur even at high strain rates at elevated temperatures. Based on the physical analysis and review of the experimental data, a modification of the relation aimed at determining the flow stress was proposed, in which, however, the effect of strain aging was not explicitly reflected.

In [8, 9, 17, 18], it was established that the jump-like deformation of AMg6 alloy is a structural-sensitive effect. In [8, 9], the dependence of the initial deformation of jumps on the grain size after severe plastic deformation was revealed. The characteristics of jump-like deformation, especially the number of jumps, the mobility and morphology of the first deformation strips, change dramatically after annealing in the vicinity of the temperature of the limited solubility of magnesium in aluminum TSV ≈ 275 °C [17, 18].

A detailed presentation of the methodology and results of carefully performed experiments (including electron microscopy studies) on uniaxial stretching of magnesium alloy specimens containing an additive of rare-earth (0.2 % Nd) material at room temperature with $3.3\cdot10^{-5}$, $1.1\cdot10^{-4}$, $1.1\cdot10^{-3}$, $3.3\cdot10^{-3}$ and $1.1\cdot10^{-2}\ \text{s}^{-1}$ strain rates are given in [54]. The paper notes the distinction of serrated yielding associated with the Luders bands and the Portevin-Le Chatelier effect, both in kinematic characteristics (geometrical dimensions, motion rate) and in mechanisms. In materials with a hexagonal lattice, a significant contribution (about 50 %) to deformation caused by Luders bands is made by twins, the latter, when approaching the grain boundaries, can generate twins in neighbouring grains. The Portevin-Le Chatelier effect is connected to the dislocation mechanism of deformation and the inhibition of dislocations by impurities diffusing to them.

In [13], it was suggested that the sensitivity effect may be a macroscopic manifestation of the instability of inelastic deformation by various mechanisms at micro- and mesolevels arising in different ranges of impact values. These can include dislocation depinning from the Cottrell atmospheres, grain-boundary shifts, the emergence of mesobands and cooperative shear bands, and destruction, - the restoration of particles of rigid inclusions, and sharp rearrangements of dislocation substructures. Each of these phenomena has been confirmed in experimental studies at the meso- and microlevels, and in modelling using models of different scale levels.

## Models for the Portevin-Le Chatelier Effect Description

Plastic (inelastic) deformation of any materials and in any ranges of effects can be interpreted as a combination of a huge number of abrupt changes of parameters of various nature and dimension, from point defects to conglomerates of grains. In other words, inelastic deformation can be considered as a series of multiscale instabilities. When these unstable processes are implemented on microscales ("hopping" of dislocations in the energy relief of Peierls, breakthroughs of dislocation clusters through barriers of different nature, etc.), then on macro, and even on mesoscales, they are observed as monotonic, smooth changes in body configuration, since these unstable processes are realized by large sets of physical carriers of inelastic deformation, they are disordered, inconsistent neither in time nor in space. However, if the movement of various carriers or their groups begins to be carried out in a coordinated, self-organized manner, the unstable nature of the deformation becomes observable at the meso- and macrolevel. This is manifested in the "response-effect diagrams" in the form of non-monotonic response curves for monotonically varying effects, and in such cases they are referred to as "noncontinuous", "sawtooth" or "serrated" plastic deformation.

At the moment the processes of plastic deformation development is considered at all scale levels, such as micro-, meso- and macroscopic structural levels. The study of the "subtleties" of the evolution of dislocation substructures and point defects, especially in the internal regions of the specimens, with the help of the experimental methods, is associated with enormous difficulties and high costs. Therefore in the recent 20 years mathematical models of different scale levels have been intensively developing.

Mathematical models allow studying the phenomenon of plasticity of crystals, including the conditions of deformation defect occurrence, their movement, interaction, annihilation, which are difficult or impossible to observe in a real physical experiment.

## 6. Macrophenomenological Models

One of the well-known phenomenological models focused on the description of the sensitivity effect under uniaxial loading was proposed in [44]. The rate sensitivity of the material is determined by the sum of two components which of them is independent and dependent on strain aging; the latter is established using a dislocation submodel that includes two evolution equations (ordinary first-order differential equations) for scalar densities of mobile and forest (immobile) dislocations. The implementation region of the regime of serrated yielding corresponds to a negative rate sensitivity, the boundaries of this region are determined by the zero rate sensitivity. It is noted that the model makes it possible to determine the critical values of the accumulated deformations (the beginning and the end of serrated yielding), which are actually observed in the experiments.

In work [53], two types of plastic flow instability are associated with diffusion aging: the propagation of Luders bands and the Portevin-Le Chatelier effect (PLC), focusing on the description of the sensitivity effect. The movement of dislocations is considered as a process of a very fast free movement and a long-term stop on obstacles of various natures. During stops on obstacles to the nuclei and in the vicinity of dislocations, solute atoms flow together, thus forming “clouds” (atmospheres) of atoms, interacting with dislocations and hindering their movement. With a further increase in stresses, the dislocations are split and they move to the next obstacle; it is assumed that the dislocations do not “pull” the atmosphere after them. The latter assumption does not seem to be sufficiently substantiated the hypothesis about dragging a part of the atoms of the atmosphere by moving dislocations after them seems to be more plausible, as a result of which the viscous resistance to the movement of dislocations surrounded by solute atoms should increase. A brief review of works devoted to experimental and theoretical studies of the sensitivity effect is given.

The model modification proposed by McCormick in 1988 was used as a basic equation:

$$\dot{\varepsilon} = \dot{\varepsilon}_0 e^{\frac{-\Delta G}{\kappa\theta}},$$

where $\dot{\varepsilon}$ is deformation speed, $\Delta G$ is Gibbs free energy, $\kappa$ is the Boltzmann constant, $\theta$ is the absolute temperature, $\dot{\varepsilon}_0$ is the so called deformation speed (equal to the shear rate at zero Gibbs free energy). It is assumed that $\Delta G$ is a function of the effective stress (the difference between the effective stresses and the yield stress at 0 K) and the solute concentration. The solute concentration is determined by the function of the delay of dislocations on obstacles, referred to the characteristic diffusion time; shows the phenomenological relationship to determine the delay proposed earlier by other researchers. Ultimately, a determining relation was obtained (the dependence of stress on strain rate and temperature) for uniaxial loading. It is noted that during the quasistatic deformation mode, the rate sensitivity of the material, according to the model, turns out to be negative, and therefore, the deformation is unstable. For a number of authors, the occurrence of a mode of alternating rate sensitivity is associated with dynamic processes, with a possible change of the sign of rate sensitivity and a transition to the“sawtooth” nature of the response. For a multiaxial stress-strain state (SST), the defining relation is generalized by a commonly used technique, i.e. replacing uniaxial measures of stress and strain rate with corresponding deviators.

Most of the articles aredevoted to studying the system deformation stability including the deformable specimen and a loading system, considered as an elastic rod. For analysis, the apparatus of linear perturbation theory is used. Stability conditions for spatial and temporal perturbations are obtained; a significant effect on the deformation stability and the nature of the unstable behaviour of the rigidity of the loading system and the characteristics of hardening of the material were shown. It is noted that the proposed material model allows us to describe both the “sharp yield point” and the effect of the sensitivity.

Another mechanism of serrated yielding which was called by the authors of the pseudo sensitivity effect, observed in ordered solid solutions, is considered in [26]. During thermomechanical effects under inelastic deformation, a decrease in ordering takes place, which can be restored due to diffusion mechanisms. A constitutive model is considered for the case of uniaxial loading. A kinetic equation is proposed for the order parameter, varying from 0 (completely unordered) to 1 (fully ordered solid solution). As a defining relation, we used the equation of a nonlinear viscous fluid with a power dependence of stresses on strain rate, in which the flow stress depends on the order parameter. An analytical solution of the system of constitutive model equations is obtained, the analysis of which made it possible to determine the presence of limits of temperature and strain rate in which serrated yielding mode can be implemented.

The statistical analysis results of stress-strain curves for uniaxial loading of single-crystal specimens from Al-4.5 % Mg alloy are given in [46]. The experiments were carried out for two orientations of the crystallite with respect to the axis of tension (<111> and <100>) at temperatures of 300, 350, and 400 K and strain rates in the range of $\left(3.2\cdot10^{-6} \div 1.3\cdot10^{-3}\right)\mathrm{s}^{-1}$. In order to describe the sensitivity effect, a uniaxial deformation model was used, in which the flow stress is determined by the sum of terms depending on the accumulated deformation and on the current strain rate (both terms depend on temperature), with the dependence of stress on the strain rate (2nd term in the additive representation) has a N-shaped view. To consider the spatial inhomogeneity of deformations, which reflects the formation and propagation of shear bands observed in the experiments, a simple rod model is proposed, according to which a one-dimensional specimen is represented as a set of a finite number of layers. In each elementary rod (layer), the flow stress, in addition to the two components mentioned above, contains an additional additive term, which depends on the difference of stresses in the layer under consideration and two adjacent ones. It is shown that the model under consideration allows to qualitatively describe the space-time distribution of strain localization and the sensitivity effect.

A stochastic model for describing the sensitivity effect at meso- and macrolevels was proposed in [35]. This effect is explained by the collective interaction of dislocations by long-range stress fields. A stochastic differential equation (of the Fokker-Planck-Kolmogorov type) is obtained, which describes the evolution of the distribution function of the probability of deviation of local deformation from the mean one by a given value. The model is used to describe the behaviour of a single-crystal specimen deformed by a single shear; a comparison of theoretical and experimental results demonstrates a satisfactory conformity.

A brief review of papers that propose various mechanisms responsible for the sensitivity effect and the models for their description can be found in [34]. The author proposes a constitutive model which is considered for the case of uniaxial loading which allows to properly reproduce the mode of serrated yielding. For this, an additional term with an internal variable responsible for the dynamic aging process is introduced into the evolution equation for the flow stress. A careful analysis of the linear stability of the constitutive material model was carried out, estimates of the limits of the stable (monotonic) response and the region of serrated yielding in material state values (temperature, strain rate and strain) were obtained.

In [82], a macrofenomenological viscoelastic model was used in combination with the finite element method (FEM) in a 3-dimensional formulation to describe the PLC effect. The ratio for the rate of inelastic deformations includes the dependence on the concentration of solutions. A phenomenological equation for the concentration of impurities, depending on the accumulated inelastic deformation and aging time, was also proposed. Numerical experiments were performed for specimens with rectangular and circular cross sections (Al-Mg-Si alloy) subjected to stretching with a constant strain rate. As an initial perturbation, a deviation was introduced either in one finite element, or with the help of deviations randomly distributed over the entire volume within (0 ÷ 10) MPa. It is shown that the model makes it possible to qualitatively describe the sensitivity effect implemented due to the formation and movement of the neck along the sample axis.

A similar model was used in [32] to analyze the deformation of Al-Li and Al-Cu alloys. For the numerical study, samples with rectangular cross-sections with flat edges, with V-shaped cuts (with angles of 60 and 90°) and with flat cuts simulating cracks were applied. The generation and propagation of shear bands, the effect on the kinetics of changing the shape of the notch and taking into account strain aging are analyzed in detail.

[27] describes the application of the cellular automation method in a two-dimensional formulation for the analysis of the sensitivity effect. The motion of dislocations in a field of randomly distributed barriers on which dislocations can temporarily linger is considered. During the delay, solute atoms flow to the hindered dislocations, which increases the necessary activation energy for further movement. The activation of delayed dislocations occurs under the action of applied stresses, long-range interaction forces, and random temperature fluctuations. It is shown that the sensitivity effect is observed only with a simultaneous consideration of long-range forces between dislocations and dynamic strain aging.

An extensive list of works devoted to experimental studies and theoretical models of the sensitivity effect is given in [62]. Just like in most other works, the main mechanism is considered to be dislocations pinning with solute atoms by solute atoms during delays in the movement of dislocations by barriers of a different nature. It is noted that the sensitivity effect should be distinguished from other types of plastic deformation instability (for example, Luders bands), first of all with repetitiveness, in a certain sense with “renewability” of mechanisms and driving forces of the sensitivity effect. The analysis of existing models reveals a number of their significant disadvantages, in particular, the inability to determine main parameters of unstable deformation (width, propagation velocity and deformation value in localization bands), and the difficulty of using them within continual models.

According to the authors, a distinctive feature of the proposed model is considered to be the introduction of two characteristic time scales, one of which is associated with dynamic strain aging, and the second one is associated with the mobility of dislocations. The McCormick model is used as a base one, according to which the rate of plastic deformation is determined by an Arrhenius-type law, i.e. by the exponential law on the activation energy of the dislocation motion, the process temperature, the current rate sensitivity of the material and effective stress equal to the difference between the applied and internal stresses. Internal stresses are associated with strain hardening and are considered to be linearly dependent on plastic deformations. An additional additive term, proportional to the concentration of solute atoms, deposited on dislocations, is introduced into the activation energy. An evolutionary equation is proposed to describe the change in this “addition” to the activation energy, which is an ordinary differential equation (ODE). A detailed qualitative analysis of the evolution equation was carried out (stationary mode, bifurcations, critical points, etc.). In the future, this evolutionary equation is supplemented by a diffusion term. The defining equation itself is expanded by the inclusion of a term describing the behaviour of the loading system. The qualitative analysis of the resulting system of two differential equations (ODE and partial differential equation (PAE)) was carried out using the numerical procedure. It is shown that the proposed one-dimensional and essentially macrophenomenological model qualitatively and satisfactorily describes the sensitivity effect.

To analyze the motion of dislocations and their interactions with solute atoms in [37], the phase field model was used, into which the diffusion of solute equations were introduced. The resolving equations of the model are obtained on the basis of the thermodynamic approach, relations for the elastic, chemical, and dislocation components of the free energy are proposed. The interaction of solute atoms with a Frank-Reed source, fixed and moving dislocations is considered. It is shown that the model qualitatively and correctly describes both long-range interactions (stress fields of dislocations) and short-range order interactions (with solute atoms).

A detailed review of the methods and results of the study of the instability of plastic deformation (including sharp yield point and serrated yielding) is given in [4, 5]. Low-temperature (at temperatures of liquid hydrogen, helium, or nitrogen) and high-temperature (at 0.3-0.7 homologous temperature) serrated yielding are distinguished. Low-temperature serrated yielding is associated with twinning processes and phase transformations. There is a significant impact of size and surface condition of the specimens on the process. High-temperature serrated yielding is caused with the deformation localization with the formation of shear bands. Based on the results analysis of uniaxial stretching of specimens from different materials, various natures of formation and evolution of shear bands at a constant rate of stress or strain changing are noted. Based on the analysis of known experimental data, conclusions are drawn about the general patterns of serrated yielding. It is emphasized that this effect is determined by the processes of the mesolevel, and not the microlevel [4]. The second part of the [5] review contains a detailed analysis of the theoretical principles and models proposed to describe serrated yielding. The author believes that the main disadvantage of the reviewed papers is the lack of analysis of the processes occurring at higher than the microlevels in most of them.

The results of experimental studies of serrated yielding of smooth and notched cylindrical, prismatic and flat aluminum alloy specimens subjected to single-axis loadinguniaxial loading at room temperature in the range of strain rates from $10^{-5}$ up to $10^{3}$ $s^{-1}$ are presented in [21, 22]. The macrofenomenological elastic-viscoplastic model based on experimental data under single-axis loading was considered in [21]. According to the model, the flow stress is determined by the sum of the yield strength, the value of the resistance increased due to plastic hardening and the term depending on the rate of inelastic deformation ("viscous resistance"). It is assumed that the last term in a certain range of strain rates may have a negative derivative ("negative rate sensitivity"). A qualitative analysis of the model for the case of uniaxial loading was performed. A considerable attention is paid to the analysis of the stability of inelastic deformation, for which the method of small perturbations is used. The model under consideration is generalized to the case of a three-dimensional stress-strain state (SSS) and is used in the LS-DYNA finite element package to study the deformation of cylindrical specimens (smooth and with an annular undercut with different rounding radii) of aluminum alloy 5083-H116. The characteristics of the evolution of the SSS are given and analyzed for specimens of various configurations and at different strain rates. The results indicate the implementation of serrated yielding in a wide range of strain rates. The influence on the results of computations of the finite-element lattice and the integration step over time is investigated. The paper [22], which contains the results of carefully performed and processed experimental studies on "single-axis" loading of specimens of circular and rectangular cross-sections, is closely related to the above-considered paper.

A macrophenomenological model for the analysis of serrated yielding was proposed in [76]. The uniaxial loading of a polycrystalline specimen under plane stress and plane deformed state is considered. It is assumed that inelastic deformation is implemented by a shear along one and/or two slip systems. The shear rate on each slip system is determined by a viscous-plastic law of power type, which also includes the dependence on the concentration of solutes in this system. To determine the concentration of solutes in the slip system, an evolutionary relationship has been proposed, according to which the concentration increases when the accumulated shear increases and the shear rate decreases along this system. To determine the position of shear bands, the linear bifurcation approach is used. A satisfactory agreement of the computation results with the experimental data is noted.

In [23], a geometrically nonlinear macrofenomenological viscoelastic model was used in combination with the finite element method (FEM) in a 3-dimensional formulation to describe the sensitivity effect. The constitutive model is based on the the Neo-Hookean law, and the Almancy strain tensor, determined from the elastic component of the placement gradient, is taken as a measure of elastic deformation. The rate of inelastic deformations is determined by the relations of the theory of plastic flow, in which the flow stress depends on the concentration of solute atoms; the latter is determined by the phenomenological evolutionary equation (a function of accumulated plastic deformation and aging time). The values of material parameters were experimentally determined on the basis of tensile tests. Polycrystalline flat specimens with ((5.1 · 1.5 · 21) mm dimensions were made of Al-Mg alloy (AA5754). All specimens were cut from sheet materials with a stretching axis in the direction of rolling. After grinding and polishing, the specimens were subjected to annealing (exposure for 2 hours at a temperature of 400 °C) and quenched in water. Tension tests were carried out at room temperature at constant strain rates from $2 \cdot 10^{-3}$ to $6 \cdot 10^{-3}$ $s^{-1}$. The comparison of the theoretical results with the data from the experiments conducted by the authors reveals a satisfactory conformity.

The results of the experimental and theoretical studies of a single-axis loading of specimens (aluminum alloy Al-4 % Cu (A2017)) are presented in [38]. The main goal of the work is to study the space-time features of three types (bands A, B, and C) of the manifestation of the sensitivity effect. A brief description of the experimental procedure is given. In order to reduce residual stresses, the specimens were annealed (for 4 hours at a temperature of 723 K with a slow cooling in the furnace). The average grain size of the specimen was determined using an optical microscope and was 30 μm. All the tests were carried out on uniaxial tension at constant strain rates in the range of $10^{-5} \div 5 \cdot 10^{-3}$ s$^{-1}$. It is shown that as the strain rate decreases, a change in the type of the A → B → C shift bands is observed.

For the theoretical description of the sensitivity effect, a macrofenomenological one-dimensional viscoplastic model is used, taking into account the effect on the strain rate of the concentration of solutes. An evolution equation to determine the change in the latter is proposed. A description of the difference scheme for the analysis of the rod deformation, which takes into account the rigidity of the loading system, is given. A comparison of theoretical and experimental results for the three types of curves demonstrates a satisfactory agreement.

The results of experimental and theoretical studies of single-axis loading of samples (aluminum alloy 2024) cut from rolled sheet billets at angles of 0°, 45° и 90° to the direction of rolling are presented in [25]. All tests were carried out at room temperature, the strain rate was from $1 \cdot 10^{-5}$ to $7 \cdot 10^{-1}$ s$^{-1}$. In the range of low strain rates $(1 \cdot 10^{-4} \div 1 \cdot 10^{-3})$ s$^{-1}$, there is a “reverse” high-speed hardening (decrease in the flow stress with the increasing strain rate), accompanied by a serrated flow pattern. At strain rates exceeding $1 \cdot 10^{-2}$ s$^{-1}$, the flow stress increases with an increase in the strain rate and the strain is monotonically implemented. For the theoretical description of the deformation process, the macrofenomenological theory of elastic-viscous plasticity is used, in which the additive decomposition of the strain rate into elastic, plastic, and viscous components is adopted. The flow stress is represented by the sum of the components depending on the accumulated plastic deformation, the strain rate and the process of strain aging. A generalization of geometrically linear defining relations for the case of large gradients of displacements is proposed. A considerable attention is paid to the statistical analysis of theoretical and experimental data, on the basis of which the conditions for the transition from the nonlinear chaotic mode (type C bands) to the “self-organized criticality” mode (type A bands) are established.

Modifications of the macrophenomenological model proposed earlier (2001) by the first author of the paper below (together with J.R.Klepazcko), allowing to describe the effects of dynamic strain aging (negative velocity sensitivity of the material), are given in [63]. Modifications of the model are focused on the description of behaviour of aluminum alloys (with magnesium, manganese, silicon, zinc and other components) in wide ranges of strain rates $(10^{-4}$-$10^{4})$ s$^{-1}$ and temperatures (223-500 K). Determining relations are formulated for the case of uniaxial loading; flow stresses in the proposed ratios are assumed to be equal to the sum of the components responsible for strain hardening, viscous resistance, and decrease in strain resistance in a certain range of strain rates; each component is temperature dependent. The evolution equations for the material parameters included in the relations are given. A satisfactory agreement between the simulation results and the experimental data was shown both in the area of the negative rate sensitivity (strain rate $(10^{-4} \div 10^{2})$ s$^{-1}$) and the transition to positive rate sensitivity at higher strain rates). The paper does not consider the application of the proposed ratios to describe the sensitivity effect, however, they are suitable for such an analysis.

The numerical analysis results of flat and cylindrical, smooth and notched samples of the nickel super alloy subjected to uniaxial tension at temperature of 500 °C and strain rates $(10^{-6} \div 10^{-2})$ s$^{-1}$ are given in [50]. The MacCormic model was used to describe strain aging. The model was implemented using the finite element method in two-dimensional and three-dimensional settings. It is shown that at low strain rates ($10^{-6}$ s$^{-1}$ order), the instability of plastic flow corresponds to the formation of type C bands, in the intermediate region ($10^{-4}$ s$^{-1}$ order) corresponds to the formation of type B, and at relatively high strain rates ($10^{-2}$ s$^{-1}$ order) corresponds to the formation of type A. A considerable attention is paid to the integration procedure (in time) of constitutive equations, an algorithm is proposed that significantly reduces the cost of computing time while maintaining stability and accuracy. The influence of the used lattices on the calculation results has been thoroughly studied.

In [48], based on the physical analysis of strain hardening, it is assumed that the dependence of the flow stress on the strain rate can be represented as two components: the contribution from the viscous resistance to dislocation motion and through the dependence of strain hardening due to clusters of immobile dislocations. At low strain rates and an elevated temperature, solute atoms “flock” to dislocation clusters, fixing these dislocation barriers; an increase in the strain rate contributes to the activation of a part of immobile dislocations and reduces the influx of solute atoms to dislocation clusters. These mechanisms make strain hardening sensitive to strain rate and temperature, leading to the appearance of ranges of these parameters in which negative rate sensitivity and serrated deformation occur. It is noted that taking into account these mechanisms allows us to explain the experimentally observed fact of the occurrence of intermittent plasticity only after reaching some critical accumulated plastic deformation. Using the proposed model based on the linear analysis of stability, a criterion is proposed that establishes the time when the Portevin-Le Chatelier effect appears for uniaxial loading depending on the accumulated plastic deformation, temperature and strain rate.

The macrophenomenological model, which is a modification of the MacCormick model and focused on the description of the behaviour of metastable stainless steel of the austenitic class, was considered in [45]. In the equation of the yield surface, the flow stress depends on the terms responsible for dynamic and static strain aging, martensitic transformation of a part of the material and speed hardening, i.e. softening. A considerable attention is paid to the identification procedure, for which the results of the authors' own experiments are used. A brief description of the experimental procedure and the results obtained are given. Tests were carried out at constant and stepwise varying strain rates, with unloading and holding (from 3 to 56 days) between two stages of monotonic deformation. The qualitative agreement of the theoretical results with the experimental data is noted.

As already noted above, in a number of studies on the sensitivity effect, the manifestation of the latter is associated with the appearance of shear bands. Since the shear band is a region of localized deformations, attempts to use gradient plasticity theories to describe them are reasonable. In [79], a simplified rigid-plastic gradient model is considered, in which an additional term proportional to the second gradient of the intensity of the accumulated plastic deformation is introduced into the hardening law. The variants with plasticity independent and dependent on the strain rate are investigated. For the test problem of a simple shear, the features of the origin and evolution of the shear bands are considered. The physical reasons of possible fluctuations of the yield stress and their connection with the diffusion of solute atoms are not analyzed in the work.

The gradient elastoplastic model, in which the second gradients of the displacement vector are introduced and the moment stresses associated with them, are presented in [66]. The results of applying the model to studying the localization of plastic deformations (formation of shear bands) are considered; as an example, the pure shear problem is used. The flow stress is assumed to depend on the invariants of the small strain tensor and the 3rd rank tensor, a measure of the strain generated by the second gradients of the displacement vector. The deformation resistance is approximated by a piecewise linear function of a strain measure containing a softening region. Although this model is not directly oriented on the description of the sensitivity effect, it seems possible to use it for this purpose, for which it is necessary to introduce the dependence on the strain rate and temperature in the stress-strain diagram, which can be done using the parametric dependence of the coefficients in the fitting yield curve as a function of process parameters.

In [51], to study the Luders bands and serrated yielding, it is proposed to use a simple version of the macrophenomenological gradient theory, in which the intensity gradient of accumulated plastic deformation is introduced as an additional internal variable. Using the example of the numerical solution of plane problems of stretching a band (with different thicknesses), it is shown that the results obtained using the classical theory of plastic flow substantially depend on the approximation of a region by finite elements. The proposed model allows to exclude a similar dependence.

## 7. Conclusion

A brief overview is proposed concerning the work aimed at describing physical mechanisms and results of the experimental studies of alloys deformation in the temperature-speed ranges, in which diffusion processes have a significant influence on the behaviour of materials. Special attention is paid to the consideration of serrated yielding, the occurrence of which most authors associate with the formation of shear bands and the interaction of dislocations with the atmospheres of solute atoms. The experimental data given in the cited papers confirm the validity of this point of view. The study of the “subtleties” of the evolution of dislocation substructures and point defects, especially in the internal regions of the specimens, with the help of the experimental methods, is associated with enormous difficulties and high costs. Therefore in the recent 20 years mathematical models of different scale levels have been intensively developing. It should be noted that mathematical models cannot completely replace experimental studies, the latter need to be developed and improved, since without new empirical data it is hardly possible to create new in-depth models with a high predictive potential. In this paper the authors consider only well-known macrophenomenological models, therefore, this review does not pretend to be overwhelming. It should be noted that this class of models is based on experimental studies, that is why macrophenomenological models do not have universality, nor can they be used to predict the properties of designed materials. To a large extent, in the considered models, the correctly understood physics of the processes is “directly” introduced into the defining relations, without using parameters describing the indicated mechanisms and their carriers. The paper did not consider approaches based on physical theories of plasticity and multilevel models, which will be considered in the next publication. According to the authors, multilevel models do not have many of the disadvantages noted above.

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