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Editorial

Strengthening Mechanisms in Metallic Materials

Andrii G. Kostryzhev

School of Mechanical, Materials, Mechatronic and Biomedical Engineering, University of Wollongong, Wollongong, NSW 2522, Australia; kostryzhev@yahoo.com

1. Introduction and Scope

The mechanical properties of contemporary engineering alloys are approaching their natural limits. On the other hand, human civilisation faces further growing challenges: increased population, energy shortage, food and water supply instability, ecological problems, diversification of transportation and information transfer networks. Successful solutions to these challenges require stronger, tougher and lighter alloys, with extended application temperature range, corrosion and wear resistance.

Mechanical properties originate from alloy composition and processing history through microstructure development. Traditional processing technologies (casting, metal forming) were often designed to use a particular strengthening mechanism: grain refinement, phase balance, precipitation, solid solution or dislocation strengthening. This could be determined by the certain product requirements, available equipment, cost, or a company tradition. However, further property enhancement requires a revision of the strengthening mechanisms. Emerging alloy compositions (for instance, complex concentrated alloys) and processing technologies (additive manufacturing, laser treatment) open new opportunities in tailoring the microstructure-properties relationship. Therefore, in this special issue we tried to address the following questions: (i) Are the precipitates more effective than solute atoms? (ii) What is the most reasonable size of grains in a polycrystalline alloy? (iii) What state of dislocation structure is required? (iv) How many and what kind of phases are going to enhance the microstructure performance? (v) Will the complex concentrated alloys perform better than the traditional ones based on one-two principal elements?

We have managed to collect a diverse set of articles reporting the latest achievements in a wide range of Fe-, Al-, Cu-, Ti-, Ni-, and Mg-based alloys produced by casting, metal forming, powder metallurgy and additive manufacturing. The authors present detailed analyses of the processing–microstructure–properties relationships in their materials, and therefore, these data will be extremely valuable for a broad audience of metallurgical scientists and engineers. Below I briefly summarise the results to provide a quick introduction to the papers published and, hopefully, encourage you toward further reading of this special issue.

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2. Contributions

2.1. Lean Chemical Compositions

Formation of the second phases in pure metals and alloys with lean compositions is possible in rare cases (for example in iron, following a special heat treatment procedure). Therefore, the mechanical properties in these alloys are usually defined by three strengthening mechanisms: solid solution, grain refinement and dislocation strengthening of the matrix phase. The grain refinement and dislocation strengthening can be stimulated via a careful selection of processing parameters.

In [1], pure Cu was subjected to high-pressure surface rolling to obtain a surface layer with a gradient microstructure. The thickness of the refined surface layer was up to ~1.8 mm, and the grain size of the topmost surface was down to ~88 nm, depending on the rolling pressure, time, and temperature. A combination of grain refinement and dislocation strengthening provided a 2.4-fold increase in hardness, compared to the annealed condition of the base metal.

Pure Mg, studied in [2], was processed using two technologies: powder encapsulation, followed by cold pressing and either (A) hot extrusion or (B) hot sintering and hot extrusion. A 3.7 times larger grain size (11.6 μm compared to 3.1 μm) and higher density of mobile dislocations for route (B) resulted in an almost 2-fold increase in elongation, although the strength remained similar. A possible decrease in porosity following hot sintering may also have contributed to the increase in elongation.

The effect of the equal channel angular pressing (ECAP) technology on the formation of diverse dislocation structure (share bands, low angle boundaries) and grain refinement (following recrystallization during aging) in an AlMg5 alloy was studied in [3]. An appropriate selection of strain value during ECAP and ageing temperature after deformation resulted in a balanced combination of dislocation density and grain size after recrystallization leading to simultaneously high yield stress (270 MPa) and elongation (>20%). This alloy strength exhibited a 3-fold increase after ECAP compared to the solution-treated condition.

The effect of strengthening mechanisms on neutron irradiation damage in pure iron was studied in [4] using the cluster dynamics simulation. At high dose, the irradiation-induced voids were shown to dominate other factors in the irradiation hardening. Grain refinement, dislocation strengthening and phase balance exhibited little effect on the evolution of voids, while the solid solute atoms could effectively inhibit the nucleation and growth of voids. In addition, an increased number density of precipitates inhibited the irradiation hardening to some extent. The results obtained in this work can be used in the development of new nuclear materials based on bcc-iron.

2.2. Complex Chemical Compositions

In complex compositions, the phase formation and particle precipitation occur naturally; thus, very sophisticated processing schedules may not be required. However, the absolute contribution of second phases to strength and ductility depends on the phase characteristics: (i) a "soft" phase will increase elongation, and a "hard" phase will contribute to strengthening; (ii) "small"-sized particles with a high number density can provide precipitation strengthening, and "large"-sized particles may be beneficial for surface hardening and increased wear resistance.

In [5], a cast aluminium alloy 7075 was reinforced with 1.5 wt.% Al_2O_3 particles. This resulted in a 20% increase in hardness compared to the pure alloy. Two strengthening mechanisms were responsible for this: precipitation strengthening and grain refinement. In particular, the Al_2O_3 particles facilitated nucleation of new grains, leading to a decrease in grain size. Compared to the 7075-Al_2O_3 composite, the solution heat treatment provided an additional increase in hardness by 32%, following dissolution of $Mg(Zn,Cu,Al)_2$ and Al_7Cu_2Fe second phases and solid solution strengthening from Mg, Zn, and Cu. The age-hardening heat treatment added 52% to the hardness of the as-cast 7075-Al_2O_3 composite; this was associated with the precipitation of $MgZn_2$ particles. The dependence of hardness on aging temperature and time showed a maximum, which was explained by the coarsening of the particles, accompanied by a decrease in their number density.

Article [6] reports unique results of thin (3 mm) strip casting of non-modified Al-Li-Cu-Mg-Zr alloy and the same alloy modified with 0.17 wt.% Sc. The experiment was conducted using a specially designed and constructed laboratory twin-roll casting machine. Although no mechanical properties were reported in this initial study, Sc alloying resulted in grain refinement and precipitation of $AlSc_{1-x}Zr_x$ particles. These particles not only refined the as-cast microstructure, but prevented grain growth during heat treatment. Therefore, both grain refinement and precipitation strengthening mechanisms are expected to govern the mechanical properties in the Sc-rich alloy.

Pure Al powder was mixed with 1 vol.% WC particles, cold pressed at various loads, and sintered at different temperatures and times, to produce a metal matrix composite in [7]. Both WC and $Al_{12}W$ (precipitating during sintering) particles resulted in grain refinement (via grain boundary pinning during sintering) and precipitation strengthening. Thus, the yield stress increased by 75% and hardness by 40%, compared to pure Al. However, the wear resistance decreased by 40%, probably due to a lower toughness.

A forged, quenched and tempered tool steel with a martensitic microstructure was studied in [8]. Following complex alloying with Cr, Mo and V, several types of 55–355 nm particles were precipitated: MoMnCr-rich $M_{23}C_6$ (80% of all particles found), VMo-rich MC (9%), Fe_3C (9%), and Mo-rich M_2C (minor). Although complex microstructural changes took place during tempering, leading to strength decreasing and toughness increasing, the calculated precipitation strengthening effect was quite high, and accounted for up to 260 MPa (17% of total yield stress).

The literature review [9] of the microstructure–properties relationships in NiCu alloys highlighted a wide range of values in the exhibited mechanical properties: yield stress of up to 1100 MPa, tensile strength of up to 1300 MPa, and 15–60% elongation to failure. In addition, these alloys are highly corrosion resistant and may show good wear resistance. Such remarkable properties can be achieved if all four strengthening mechanisms are used, namely grain refinement, solid solution, precipitation strengthening and work hardening. Depending on alloy composition, deformation temperature and heat treatment, the relative contributions of strengthening mechanisms vary. Thus, in NiCu alloy parts produced using a wire arc additive manufacturing technology, microalloying with 3.0 Al, 0.5 Ti, and 0.088 C (all in wt.%) resulted in precipitation strengthening and the yield stress increased by 20% to 2 times (depending on heat treatment), with up to a 10% increase in wear resistance, and with only a 10% decrease in ductility [10]. Toughness was also higher in the NiCuAlTiC (precipitation hardenable) alloy compared to the NiCuMnTi (solution hardenable) alloy, due to a finer grain size and higher particle number density in the first one.

Laser alloying is a relatively novel technology for producing gradient microstructures and improving surface properties. In [11], ferritic 420 and austenitic 304 stainless steels were alloyed with three types of plasters containing (i) 85Nb + 15 graphite, (ii) 85Nb + 15 liquid glass, and 15Fe + 30Ni + 20B + 10Si + 25 liquid glass (all in wt.%). After this treatment, the surface microhardness increased by up to 8 times (to 16 GPa), and wear resistance increased by 1.6–2.6 times (depending on load during wear testing). This significant increase in strength was associated with the formation of martensite, some retained austenite (which allows to assume TRIP effect) and NbC, NbN, SiN_4, BN, Cr_7C_3 and $Cr_{23}C_6$ particles in the surface layer of steel 420, and high-dislocation-density austenite strengthened with TiC, TiN, NbC, Cr_7C_3, Cr_4C, CrB_2, SiN_4 particles in steel 304.

2.3. Multi-Phase Microstructures

Multi-phase microstructures are inherent in complex compositions. However, to fully access the benefits of multi-phase microstructures, a careful selection of processing parameters is required. Quite often, various strengthening mechanisms operate in different phases, this complicates the analysis of work-hardening behaviour. However, if characteristics of the phases (size, morphology, chemical composition, volume fraction) are properly tuned, a remarkable combination of properties may be achieved.

Review [12] presents a detailed analysis of plastic behaviours and the corresponding deformation physics for heterogeneous microstructures with bimodal or gradient grain/lamellar/phase distributions, nano-twins and nano-precipitates. Multiple examples for CrCoNi-, Ti-, Cu-, Mo-base alloys, high entropy alloys, and high-MnAlNi dual phase, interstitial free, TRIP, TWIP, and austenitic stainless steels are made to support the advantages of heterogeneous microstructures in contrast to homogeneous ones. Heterogeneous microstructures simultaneously show high strength and ductility, as well as better fatigue properties. However, strain localisations at the interfaces of microstructural constituents with extremely different plasticity may result in crack initiation. Therefore, future work is required to determine the optimal set of parameters for heterogeneous microstructures in order to maximise their positive effect.

Another example of complex stress–strain behaviour associated with microstructure heterogeneity is presented in work [13]. A duplex stainless steel containing 0.02C-21Cr-5Mn-1Ni (wt.%) exhibited a ferrite-austenite microstructure with a phase fraction ratio close to 50/50 and average grain sizes of 8.6 and 4.5 mm for ferrite and austenite, respectively. Despite the smaller grain size, the initial deformation (during tensile testing up to ~15% strain) mainly occurred in the austenite grains. This is supported by Kernel misorientation distributions plotted on the basis of EBSD analysis. A detailed TEM observation of austenite showed the formation of stacking faults at about 5% strain, which progressively transformed into twins in the 10–20% strain range. As the deformation increased above 15%, a larger portion of total strain was redistributed into ferrite grains; they deformed via the dislocation generation and glide. The complex nature of strengthening mechanisms in the studied steel resulted in continuous work hardening from ~600 MPa to ~900 MPa over a 20% strain range. Although no tensile testing to failure was conducted, this work supports the great potential of complex microstructures in ensuring superior mechanical properties.

2.4. Work-Softening

Traditional alloy design and selection of process parameters assume unidirectional testing of mechanical properties as the optimisation criterion. However, at the later stages of manufacturing technology (cold forming after hot deformation) or in service (high or low cycle fatigue) the metal alloys are frequently subjected to oscillating loading. In certain cases, reverse loading may initiate the dislocation motion at stresses lower than the yield point in the forward direction (this phenomenon is called the Bauschinger effect). Detailed analysis of this phenomenon is outside the scope of the present issue. However, the microstructural parameters (dislocation sub-structure, precipitates, phases) and strengthening mechanisms operating in a particular structure type significantly influence a potential yield stress decrease. Therefore, the composition-processing-microstructure design should take into account the future loading history.

In [14], a fully pearlitic bar steel with 0.8 wt.% C in hot rolled and cold drawn conditions was subjected to one cycle of forward–reverse loading with forward plastic pre-strain of up to 0.014. The hot rolled steel (with a lower initial strength) exhibited a reverse yield stress in the range of 60–30% (depending on forward pre-strain) of the forward yield stress. In contrast, the cold drawn steel (with a higher initial strength) showed a reverse yield stress in the range of 40–10% of the forward yield stress. This indicates that (i) a higher strength steel may lose more of its strength during reverse loading than a lower strength steel, and (ii) the yield stress in the reverse direction may be decreased by several fold; these results correspond to previous research. Thus, a question can be put forward for further consideration: is there a reason to indefinitely increase the alloy strength if it is going to lose more of its strength as a result of becoming stronger?

3. Conclusions and Outlook

This special issue attracted contributions on a wide range of metal alloys (Cu, Mg, Al, Ni, and several types of steel) processed with diverse technologies (casting, rolling, forging, powder metallurgy, additive manufacturing and heat treatment). Despite significant achievements in alloy chemistry and the development of processing technology, future challenges and growing demands for stronger and lighter materials will drive research into structural materials for years ahead. This will require deep understanding of fundamental aspects of strengthening mechanisms and principles of their practical application. Thus, as a guest editor, I hope that this issue will find a broad readership.

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