Chapter 1
Introduction

Abstract In this introductory chapter, attention is drawn to the rapid growth of information flow in the field of nanomaterials (NMs) and nanotechnologies. This growth has since the mid 90-ies almost exponential in nature, far ahead of the information accumulation in other areas of materials science and technology. Briefly, the NMs concept put forward in the works of Prof. H. Gleiter and his followers is described. There has recently been a heightened interest to the problem of the behavior of substances and materials in extreme conditions. The definition of extreme conditions with regard to NMs due to their peculiarity as unstable objects is specified. The main topics of monograph, such as the NMs behavior in extreme conditions of high temperatures, irradiation with ions and neutrons, as well as high mechanical and corrosion effects, are shortly described.

Several years ago, the MRS Bulletin Editor David Eaglesham published paper-question "The nano age?" and illustrated his mind by curves describing the publication activity in the different fields of the material science investigations. As shown in Fig. 1.1a (adapted from [1]), the advanced development of the NMs investigations is evident. Prolonging the curves of such nano-paper growth up to 2014 (according to estimations of Science Citation Index Expanded), we can see practically exponential growth of nano-information up to the present (Fig. 1.1b).

The NMs information growth (in that the nanotechnology one is also included) can be compared with tsunami! In general, the growth can be explained by both the widening of investigations/applications and the expansion of studied objects over, such as nanotubes, graphene, quantum dots, nanoglasses, etc. In addition, an interdisciplinary nature of nanoscience also promotes information widening. An essential role in the studies increase should be attributed to natural tendency of getting new results concerning the NMs behavior in different conditions. A thorough analysis of materials and substances evolution under extreme actions and conditions has recently become significant (e.g., [2–11]), at least because of two important circumstances. Firstly, the operating conditions of many modern devices and units are progressively changing towards increasing thermal, mechanical, radiation, corrosive, and other combined impacts of the operational environment, not to mention the time of service durations. Such a tendency requires

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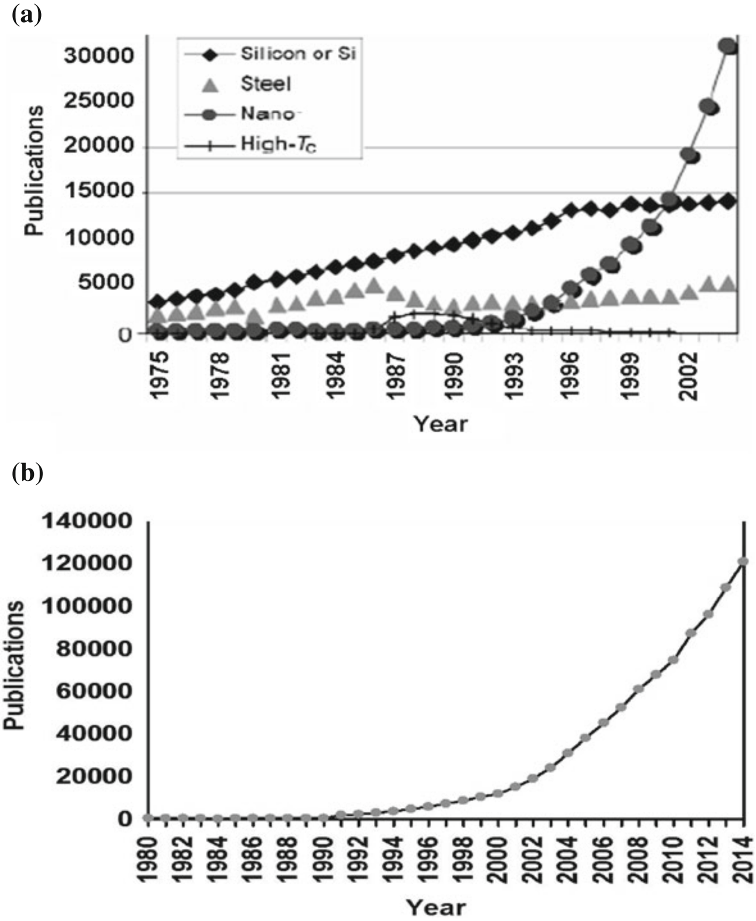

Fig. 1.1 Publications number over time for **a** different materials in the 1975–2005 period and **b** NMs in the 1980–2014 period

a special attention to the behavior and/or stability of NMs under listed extremes, since the search for new NMs must consider that they could withstand extreme environments. Secondly, a progress in astrophysics, cosmology, and geophysics leads to the new fundamental concepts and investigations connected with the substance extreme states as well as high energy and high mass densities creation [2–5]. In spite of the materials and substances tests at extremes are carried out at different pressure, temperature, and other parameters, test-modes sometimes overlap and undoubtedly complement each other.

Broadly speaking, the term “extreme conditions” in relation to NMs has features in comparison with conventional substances. It is well known that practically all NMs are far from the equilibrium, because many factors, such as the presence of numerous grain boundaries (GBs) as interfaces, triple junctions (TJs), residual stresses, segregations, and non-equilibrium phases, provide additional contributions to the Gibbs free energy (ΔG). In a greater or lesser extent, this commitment must always lead to the equilibrium violation, albeit simultaneously it creates the grounds for improvement of the NMs physical, mechanical, and operating characteristics. As will be shown below, the NMs (namely by virtue of their structure features) under extremes can be either more or less stable as compared with conventional coarse-grained (CG) counterparts. The situation is non-trivial due to numerous varying and discrepant results available in literature that demand analysis and generalization. The presentation given below assumes that the readers are acquainted with the basic data related to the NMs themselves and their manufacturing methods that were described in detail elsewhere [12–15].

It is useful to remind that historically the nano age in material science is associated with the NMs concept suggested by Gleiter and his followers [16–19]. Widely cited (citation index CI more than 2,900) review of Gleiter "Nanostructured materials" [20], published in 1989, played a major role in the expansion of research and publications (see Fig. 1.1) in this area. At present, Gleiter's concept lays the foundation of many modern theories in material science in general. The main issue of the approach concerns a principal role of numerous interfaces, which always are broadly presented in NMs. Theoretically, it was also proposed that solid body properties can be significantly changed by both modification of their crystal/electronic structure and new methods of doping by various elements regardless of their chemical nature or atomic size.

Apparently, the first estimation of the volume fractions of total interfaces, GBs, and TJs in NMs was published by Aust et al. [21]. The calculations were based in assumption that grains have the shape of 14-sided tetrakaidecahedras while the related intergrain spacing widths are about 1 nm. As can be seen from results [21] (see also later Fig. 5.1), in conventional CG crystalline materials the fraction of all interfaces (especially of TJs) is vanishingly small and can recorded when grain size (GS) is below of $\sim$100 nm. The TJs predominant volume content can be revealed at the nanograin sizes below of 5 nm only.

The consolidated (non-polymeric) NMs classification has been also suggested by Gleiter [22]. This classification involves of 12 types of nanostructures, i.e., 3 categories of shapes (layers, rods and equiaxed grains) and 4 families depending on the chemical composition of GBs and inclusions (Fig. 1.2) [22]. Therefore, there are many types of interfaces in NMs. Theoretical ideas introduced in publications [16–20, 22] were later extended and developed that allowed formulating new principles and methods. It must be noted that now there are principally new interesting ideas of processing nanocomposites from oppositely charged nanocrystallites [23] and nanoglasses with tunable structure [24–27]. These approaches open a wide prospect of creating different new NMs thus allowing "to synthesize materials with properties beyond the today limitations" [24].

However, a comprehensive description of the numerous nanostructures behavior and stability under highly variable conditions and actions remains practically impossible, first and foremost due to the lack of important data. In the current

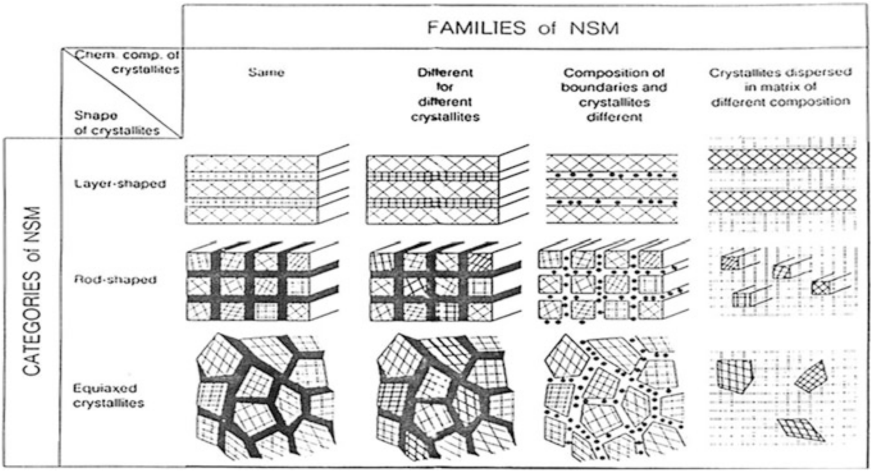

Fig. 1.2 Gleiter's classification of nanostructured materials (NSM): 3 categories of shapes (layers, rods and equiaxed grains) and 4 families depending on the chemical composition of GBs and inclusions (adapted from [22])

monograph, the main attention will be focused on the consolidated NMs-based metals, alloys and high-melting point compounds (HMPC), such as carbides, borides. nitrides, oxides, etc., for which the extremes influence has been extensively studied and even then only for two or three types of nanostructures (layer shaped objects, equiaxed crystallites and those with dispersed inclusions; see Fig. 1.2). The extreme conditions will involve thermal, irradiation, deformation, and corrosion impacts applied in the most realistic conditions, once characteristic for the present and future exploitation of NMs. From here on, we shall discuss not only NMs with the upper GS conditional limit of ~100 nm, but in many cases adjoining (related) materials with ultra-fine grained (UFG) structure (the GS value from about 100 to ~1000 nm) will be included for comparison as well.

References

1. Eaglesham DJ (2005) The nano age? MRS Bull 30:260
2. Fortov VE (2010) Ekstremal'nye Sostoyaniya Veshchestva (Extreme States of Matter). FIZMATLIT, Moscow (in Russian)
3. Hemley RJ, Crabtree GW, Buchanan MV (2009) Materials in extreme environments. Phys Today 62(11):32–37
4. Misra A, Thilly L (2010) Structural metals at extremes. MRS Bull 35:965–972
5. Boldyreva EV (2012) Supramolecular systems in extreme environments. Herald Russ Acad Sci 82:982–991
6. Fortov VE, Mintsev VB (2013) Extreme states of matter on the earth and in cosmos: is there any chemistry beyond the megabar? Russ Chem Rev 82:597–615

7. Bourne N (2013) Materials in mechanical extremes – fundamentals and applications. Cambridge University Press, New York
8. Low IM, Sakka Y, Hu CF (eds) (2013) MAX phases and ultra-high temperature ceramics for extreme environments. IGI Global, Hershey
9. Bini R, Schetto V (2014) Materials under extreme conditions. molecular crystals at high pressure. World Scientific Publishing, New Jersey
10. Fahrenholtz WG, Wuchina EJ, Lee WE et al (eds) (2014) Ultra-high temperature ceramics. Materials for extreme environment applications. The American Ceramic Society, Wiley, New Jersey
11. Andrievski RA (2014) Nanostructures under extremes. Phys-Usp 57:945–958
12. Poole ChP, Owens FJ (2003) Introduction to nanotechnology. Wiley, Weinheim
13. Koch CC, Ovid'ko IA, Seal S et al (2007) Structural nanocrystalline materials: fundamentals and applications. Cambridge University Press, Cambridge
14. Cavaleiro A, De Hosson JT (eds) (2006) Nanostructured coatings. Springer, Heidelberg
15. Valiev RZ, Zhilyaev AP, Langdon TG (2014) Bulk nanostructured materials: fundamentals and applications. Wiley, Weinheim
16. Marquardt P, Gleiter H (1981) Herstellung und eigenschaften von mikrokristallinen festkörpern. In: Heinicke W (ed) Proceedings of the Deutsche Physikalische Gesellschaft, Verhandlungen DPG (VI), vol 16. Physik Verlag GmbH, Weinheim, p 375
17. Gleiter H (1981) Materials with ultrafine grain size. In: Hansen N, Leffers T, Lilholt H (eds) Deformation of polycrystals. RISO Nat Lab, Roskilde, pp 15–21
18. Birringer R, Gleiter H, Klein H-P et al (1984) Nanocrystalline materials: an approach to a novel solid structure with gas-like disorder? Phys Lett 102:365–369
19. Birringer R, Herr U, Gleiter H (1986) Nanocrystalline materials—a first report. Trans Jap Inst Met Suppl 27:43–52
20. Gleiter H (1989) Nanostructured materials. Progr Mater Sci 33:223–315
21. Palumbo G, Erb U, Aust K (1990) Triple line disclination effect on the mechanical behavior of materials. Scr Met Mater 24:1347–1350
22. Gleiter H (1995) Nanostructured materials: state of the art and perspectives. Nanostr Mater 6:3–14
23. Gleiter H, Weissmüller J, Wollersheim O et al (2001) Nanocrystalline materials: a way to solids with tunable electron structure and properties? Acta Mater 48:737–745
24. Gleiter H (2008) Our thoughts are ours, their ends none of our own: are there ways to synthesize materials beyond the limitation today? Acta Mater 56:5875–5893
25. Gleiter H (2013) Nanoglasses: a new class of nanocrystalline materials. Beilst J Nanotech 4:517–533
26. Gleiter H, Schimmel Th, Han H (2014) Nanostructured solids – from nano-glasses to quantum transistors. Nano Today 9:17–66
27. Andrievski RA (2013) Metallic nano/microglasses: new approaches in nanostructured materials science. Phys-Usp 56:261–268