An Overview of Advancement in the Application of Heat-Resistant Alloys

Sunday Albert Lawal and Oyewole Adedipe

Contents

Abstract

This chapter presents the advancement in industrial applications of heat-resistant alloys. The types and properties of various heat-resistant alloys and their common areas of applications are highlighted.

Keywords

Refractory · Alloy · Creep rate · Directionally solidified · Nitrogen · Microstructure

S.A. Lawal (✉) · O. Adedipe
Department of Mechanical Engineering, School of Engineering & Engineering Technology, Federal University of Technology, Minna, Niger State, Nigeria
e-mail: lawalbert2003@yahoo.com; adelordy2002@yahoo.com

L.M.T. Martínez et al. (eds.), *Handbook of Ecomaterials*,
https://doi.org/10.1007/978-3-319-48281-1_132-1

Introduction

Heat-resistant alloys are materials that have high creep resistance and strength at high temperature. Alloys strengthened by disperse particles of refractory oxides or by high-strength fibers which are composite materials are a variety of heat-resistant alloys. They are materials characterized by extreme high stability of their properties, which are not highly dependent on the residence time at high temperatures. However, this depends on the purpose for which it will be applied; heat-resistant alloys are made with increased resistance to fatigue, erosion, and low notch sensitivity, as well as with high thermal stability and short-term high-load resistance. For example, for space technology, heat-resistant alloys must have low evaporability. The alloy's structure and the strength of interatomic bonds in the alloys are responsible for the great heat resistance of the alloys. Because of these properties, these alloys are usually applied in the construction materials for internal combustion engines, steam and gas turbines, jet engines, and atomic power installations. Heat-resistant alloys are either classified according to their base or condition of usage. Classification according to the base gives a range of working temperatures, which is 0.4–0.8 of the melting point of the base, depending on the load applied and the duration of its application and the base classified according to their base. Heat-resistant alloys' base may be nickel, iron, titanium, beryllium, and other metals. According to the conditions of use, heat-resistant alloys may be divided into three groups: alloys subjected to significant but short-term mechanical stress (seconds or hours) at high temperatures, alloys subjected to loads at high temperatures for dozens and hundreds of hours, and alloys designed to perform under conditions of high loads and high temperatures for thousands of hours. It has been observed that the structural requirements of these alloys depend on these conditions of usage. For instance, any factors that cause instability of the structure of alloy under operational conditions can lead to acceleration of buckling and failure of processes. Heat treatment that leads to heterogenization of the microstructure – most often precipitation hardening – is usually necessary for high strength alloys, and in this case the strength is caused mainly by the appearance within the alloy of evenly distributed very small particles of chemical compounds (intermetallides, carbides, and other compounds) and by the microscopic distortions of the crystal lattice of the alloy base generated by the presence of the particles. Also, it has been observed that the corresponding structure of heat-resistant alloys retards the formation and movement of dislocations and also increases the number of bonds between atoms, which simultaneously participate in the resistance to deformation. Conversely, a large number of interatomic bonds make possible the retention of the required structure for long periods at high temperature [1–3].

Performance Characteristics of Heat-Resistant Alloys

It must be mentioned that the benefits of alloying elements in steels may be material dependent but this discussion is not within the scope of this chapter. However, to improve the performance of resistant alloys, what is done is the addition of other elements coupled with nitrogen, which in essence is beneficial to the performance under high operating temperature. The benefits of nitrogen on the creep resistance has also been discussed in the literature [4] where it has been established that the addition of nitrogen changes the dislocation structure in steels and hence causes an increase in creep performance. Further explanation of other alloying elements and how they enhance the creep resistance of steels can be found in Lei et al. [5]. In the following section, the processes that are associated with the performance of heat-resistant alloys are discussed.

Creep Performance of Heat-Resistant Alloys

The beneficial effects of various alloying elements on the performance of heat-resistant alloys have been discussed by various researchers. In Lei et al. [5], the effect of alloying element on the creep rupture of 21Cr-11Ni-N heat-resistant austenitic was investigated at different stresses. The specimens that were used for testing were extracted perpendicular to the rolling direction of the plates and the creep rupture tests were conducted at 650 °C using different stresses ranging from 100 to 300 MPa. It was found that the time for rupture in the materials increases with decrease in the stress levels. The results were explained by the addition of alloying elements which influenced the creep resistance of the material significantly. Analysis of the fracture surfaces of the specimens also revealed ductile striation mechanisms particularly at a stress of 250 MPa. The mechanisms were characterized by the sizes the dimples found on the fracture surfaces, and it was concluded that the bigger the dimples, the better the creep resistance of the material. However, from the above results, it may be inferred that creep resistance is not only influenced by material types but by the addition of alloying elements with each playing a peculiar role in the changes taking place within the material structure.

Mechanical Characterization of Heat-Resistant Alloys

One of the properties that are associated with heat-resistant alloys is their high specific strength which gives them the advantage for use in automotive and communication industries. Among the numbers of heat-resistant alloys, magnesium alloys have been identified as one of the most important structural material due to their high strength. In Huang et al. [6], the microstructures and mechanical coupled with flow properties of the as-cast and die-cast of three different magnesium alloys were investigated. The alloys were designated Mg–6.02Al–1.03Sm, Mg–6.05Al–0.98Sm–0.56Bi, and Mg–5.95Al–1.01Sm–0.57Zn. The microstructural examinations of the alloys were carried out using an optical microscope as well as scanning electron microscope, while tensile tests were carried at temperatures of 298 and 423 K using a tensile testing machine. There were no specific results showing similarities in the results as all the tested alloys exhibited excellent mechanical properties at both ambient and elevated temperatures respectively. The fracture surfaces of the tensile tested samples revealed both ductile and brittle fracture mechanisms characterized by the presence of dimples which dominated the surfaces. However, the characteristic features of the fracture surfaces and the results of microstructural investigations may be related to the differences in the alloying elements.

One of the important factors that should be considered when investigating the mechanical properties of heat-resistant alloys is the presence of residual stresses particularly in welded structures. These stresses are either compressive or tensile depending on their locations and the magnitude within the reference structure. Compressive residual stresses would increase the service lives of structures while tensile residual stresses are damaging to the structures. In Lobanov et al. [7], the effect of residual stresses was investigated using the electrodynamic treatment method (EDT) to reduce the level of the residual stresses in welded specimens fabricated from magnesium alloy ML10. Residual stresses were determined using the electronic speckle interferometry method which measures the displacement of the surface of the specimens, while the accompanied stresses were measured using the hole drilling method. The residual stress magnitudes in the specimen were reduced significantly by the application of the EDT. Several stress relieve techniques such as the post weld heat treatment (PWHT) have been discussed in the literature, but it must be mentioned that residual stresses in welded joints cannot be eliminated completely due to their complexities accompanied by specimen thickness, welding process used, specimen type, etc.

Regardless of the stress relieve method being employed after welding, welded joints are always prone to fatigue cracks especially when the cracks are propagated through the tensile segment of the residual stress profile. It is therefore important that failure analysis accompanied with mechanical characterization be conducted under the conditions that are similar to what the welded sections experience in service. A failure analysis conducted on the reformer furnace tube, made of HP-Nb microalloyed heat-resistant steel, revealed creep damage coupled with thermal stresses and crack-related failures [8]. Microstructural investigations and mechanical tests which includes tensile, stress rupture test, and Vickers hardness tests were conducted on specimens that were extracted from the microalloyed heat-resistant steel. Macrography analysis indicated that the heat-resistant material was produced by centrifugal casting process and the mechanical tests revealed that the failure occurred due to cracks developed at the heat-affected zones (HAZ).

Industrial Application of Heat-Resistant Alloys

Heat-resistant alloys have various areas of application which includes aerospace, maritime, and petrochemical industries due to their strength and corrosion resistance particularly at high temperature [4]. They are also used for power generation probably due to their performance at high temperature [9]. One of these steels is the 21Cr-11Ni-N steel which has been described as a cost-effective material considering the design concepts [5] and its cost benefits over alloys such as 309S (13% Ni), 310S (20% Ni) stainless steels and 330 (35% Ni) nickel alloy regardless of its lesser amount of nickel (11% Ni) [5].

Power Plant

HR3C is an austenitic heat-resistant steel of type 25Cr-20Ni developed by Sumitomo in the 1980s (ASME code: SA-213TP310HCbN; JIS code: SUS310JITB). It has been widely applied in USC power plants due to its excellent properties and performance at high temperature. As a result of its advanced properties at elevated temperature, this alloy has been considered as one of the most competitive super-heater and re-heater material in USC boiler [10]. It was researched and developed to improve 310 type stainless steels by adding niobium and nitrogen to increase creep strength at elevated temperatures [11, 12]. With the precipitation of M23C6 carbide mainly along grain boundaries and finely dispersed NbCrN nitride (Z phase) in the matrix [13, 14] the alloy obtains an excellent creeping strength at the designed service temperature of USC (600–650 °C) [15]. The high Cr content ensures a corrosion resistance superior to that of 18Cr-8Ni series alloys. It has been observed that by promoting the formation of continuous chromia layer, the alloy can withstand the steam oxidation environment during long-term service above 620 °C [16–18].

Similarly, 8–12% Cr ferritic/martensitic heating-resistant steels have been extensively used in many parts, such as in boilers, turbines, diaphragm, and in fossil fuel power plants as well as structural materials such as F82H and Eurofer97 in a fusion reactor because they are able to withstand high temperature. Since many parts in such plants are exposed to water vapor, oxidation resistance is highly important. Hence in order to improve the oxidation properties, accordingly it is better to increase the amount of Cr in steel. However, since δ ferrite is formed in the martensitic matrix with increasing amounts of Cr, the steels are composed of dual phases: martensite and ferrite. If the dual phase is formed in the heating-resistant steels, the high-temperature properties may deteriorate in light of the changes in the mechanical properties as well as the oxidation resistance due to variations in the microstructure. Furthermore, volume fraction of the ferrite is strictly restricted with less than 5% because it can be problematic from viewpoint of high temperature properties. Literatures have shown that many methods aimed to improve oxidation resistance without increasing the Cr amount have been adopted. The immersion treatment of Al into the steel matrix is generally known to improve the oxidation and corrosion resistance, heat resistance, and wear resistance properties of steel [19–22].

Another heat-resistant alloy is the type 21Cr-11Ni-N steel which is just a cost-effective lean alloy on the basis of the design concepts. This novel alloy contains just 11% Ni, which can offer the potential for heat-resistant properties competitive with some heat-resistant alloys, such as 309S (13% Ni), 310S (20% Ni) stainless steels and even 330 (35% Ni) nickel alloy [23], but at much lower cost. Substantial improvement on heat-resistant properties of this alloy is made by precise control of microalloy additions, especially the rare-earth elements (RE, such as Ce, Y) combined with N. Because it is a strong austenite stabilizer, N will change stacking fault energy and hence the dislocation structure will also be changed, leading to changes in creep resistance. Available literatures in recent time have examined the effects of N [24, 25, 103]. RE, as the active element, has also been found to improve creep cavitation resistance in austenitic steels, particularly by co-addition with B [24, 26, 104].

Ce is found highly effective in removing O and S in 347H austenitic steel, forming Ce2O2S, such that more B may segregate to cavities [105]. RE is also believed to tie up the S segregated at grain boundaries (GBs), preventing S-induced embrittlement [23]. High chromium ferritic heat-resistant steels have been widely employed as structural materials for high temperature components of fossil-fired power plants because of their superior high temperature strength, high thermal conductivity, and low thermal expansion coefficient. The present generation high chromium ferritic heat-resistant steels such as Gr.91, Gr.92, and Gr.122 are employed for components operating in the service temperature range of 550–620 °C [10, 27]. From the view point of fuel conservation, energy saving and reduction of CO_2 emission, there is a worldwide demand for enhancing thermal efficiency of fossil fired power plants that can be effectively achieved by increasing their steam temperature above 600 °C and pressure above 30 MPa [28, 29]. These elevated steam conditions impose stringent requirements on mechanical properties of structural materials, more importantly, on their creep strength. Significant efforts are being made worldwide to develop heat-resistant steels for such applications [29–32]. In Japan, research and development of next-generation ferritic heat-resistant steels using nitrogen as a potential alloying element is currently in progress for applications in future advanced thermal power plants whose operating temperature is above 700 °C [33]. The aim is to achieve 100,000 h target strength at 100 MPa at 700 °C in these heat-resistant steels. Creep properties of different grades of these newly developed high nitrogen ferritic steels are being evaluated using the conventional uniaxial creep test.

Austenitic heat-resistant steels (A-HRSs) are one of most frequently used structural materials in advanced coal-fired power plants. The conventional A-HRSs in power plants are generally heavy alloyed, especially expensive Cr, Ni elements. The recent skyrocketing raw material cost stimulates development of the A-HRSs with less alloying. As a result, some modifying elements, such as rare earths (REs), boron (B), nitrogen (N) [23, 24, 26, 34], are often added to the A-HRSs to improving properties whereby the alloys also can meet design requirement even if the Ni, Cr contents are reduced. Modified 21Cr-11Ni-N-RE lean austenitic heat-resistant steel is a new member in the family of A-HRSs by precise control of microalloy additions of RE and N. It can be used as dip tubes, reheater panels, and heat-exchanger tubes due to its high creep strength and excellent oxidation resistance. Hence it is an attractive alternative to typical A-HRSs, such as 309 (23Cr-13Ni), 310 (25Cr-20Ni) and/or even to nickel-based alloy of 800 H [23, 35, 36] in some high-temperature environments. Generally, the A-HRSs used for structural components in power plants undergo hot forming processes (such as rolling, forging, and extrusion). The microstructure of alloy is very sensitive to the hot working parameters, which also leads to a strong sensitivity of the properties. In order to achieve the desired properties of the product, the understandings of microstructural changes during hot working are essential. For instance, the grain microstructure of A-HRS with nominal compositions is as follows (mass%): C 0.089, Cr 20.88, Ni 11.07, Si 1.38, S 0.002, Mn 0.76, P 0.021, N 0.22, RE 0.056, and Fe in balance was observed using ZEISS K400 optical microscopy (OM). The average grain size was evaluated by the linear intercept method according to the ASTM standard. It was noticed that the initial

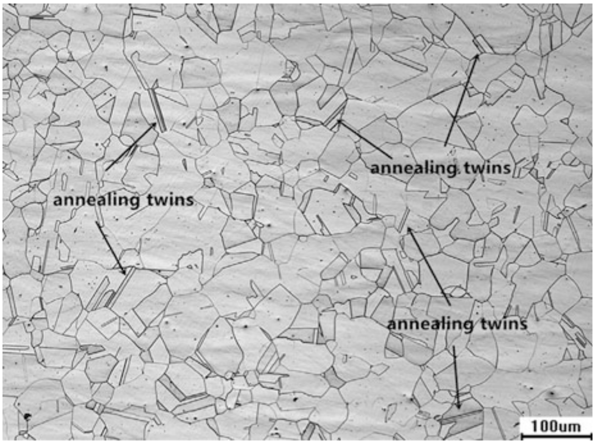

Fig. 1 Optical micrograph of the solution-treated test steel before hot deformation [37]

microstructure consists of equiaxed recrystallized grains with an average size of 82.7 mm and some lamella-like straight annealing twins, as shown in Fig. 1.

It is well known that work hardening (WH), dynamic recovery (DRV), and dynamic recrystallization (DRX) often occur in the alloys with low stacking fault energy during hot deformation [24, 38–40].

Petrochemical Industry

The HP-Nb heat-resistant austenitic stainless steels are designed to work in the extreme service conditions of high temperature and pressure. For example, the steels are widely used to manufacture the tubes for the reformer furnaces of petrochemical industry where the microstructural evolutions take place in the tubes [41]. The evolutions consist of coarsening the primary carbides, transformation of M_7C_3 to $M_{23}C_6$ carbide, dissolution of secondary $M_{23}C_6$ and NbC precipitates, and formation of the silicide and nitride phases. These microstructural changes usually lead to the degradation of creep resistance. Moreover, due to the multiple sources of thermal stresses in service, these tubes must resist against a wide range of applied forces inducing creep deformation in the tubes. It has been reported that a high creep resistance is achieved by optimizing the creep strength and ductility [42]. It should be noted that the both mentioned properties are highly affected by the amount and morphology of eutectic carbides, grain boundary film, and the intracellular precipitates [43, 44]. It has been shown that the grain boundaries are decorated with discrete precipitates and the increase in the intracellular precipitates prolongs the creep rupture life of the steels [45]. So, the creep resistance of the steels is expected to improve by adding the carbide-forming elements such as tungsten and nitrogen. Both elements have also been recognized as the effective solid solution strengtheners at high temperatures [46, 47]. However, referring to the published data [48, 49] the addition of tungsten does not improve the creep rupture life of the steel while adding nitrogen to wrought stainless steels [25, 50], and a new generation of austenitic steel casting (CF_8C-Plus) has improved the creep resistance of the steels due to distribution of fine nanoscale NbC precipitates [51]. Attarian and Taheri [52] investigated the effect of tungsten and nitrogen on the as-cast and the creep aged microstructures of heat-resistant HP-Nb steel. The steel was directionally solidified under two cooling rates of 31.2 and 7.6 K sec^{-1}. Creep rupture tests were conducted at temperatures of 1150–1255 K on the specimens prepared from the cast ingots in transverse and longitudinal directions. It was observed that the addition of nitrogen significantly increases the eutectic temperature and thus refines the dendrites and alters the morphology of M_7C_3 eutectic carbide. Also, it was found that due to short time aging, nitrogen addition decreases the M_7C_3 carbide fragmentation, increases the secondary $M_{23}C_6$ precipitation density, and impedes the formation of Cr-rich $M_{23}C_6$ carbide on the primary Nb(C, N) carbide/matrix interface. The bar shape morphology of M_7C_3 eutectic carbides of alloy HWN formed under the high cooling rate is shown in Fig. 2a and it has the highest eutectic temperature.

Hence, one can establish that the increase in eutectic temperature caused by the nitrogen addition has promoted the bar shape morphology. The M_7C_3 carbide morphology of alloys LW and LWN are compared in Fig. 2b, c. As it is seen from these figures, by adding nitrogen to the alloy the morphology of M_7C_3 carbide is altered from dendritic to cluster morphology.

The cast heat-resistant steels containing high amounts of chromium and nickel have been developed to supply the corrosion resistance, strength, and austenite phase stability required for the high temperature applications. Among these alloys, the HP-Nb heat-resistant steels are fundamentally the Fe–25Cr–35Ni austenitic heat-resistant steels modified with niobium to form the NbC carbides for precipitates stability at high temperature service conditions [53]. The HP-Nb steels of higher Ni content exhibit more resistance to creep deformation while the microalloyed HP-Nb as a generation of this group possesses higher stress rupture properties [54]. The tubes made of HP-Nb cast heat-resistant steels are the key components of the reformer furnaces used in chemical and petrochemical industries. The tubes are centrifugally cast in short segments and then welded together to achieve the full length required in service. Each tube in a reformer furnace contains a large amount of nickel catalysts and can be considered as a catalytic reactor. All reactions inside the reactor are strongly endothermic, and are encouraged by the increase in temperature, so the tubes wall must be fired to a temperature of about 1000 °C [55]. It has been reported that during such a high service temperature, the stability of the primary coarse precipitates in the cast tube material and the formation of other second phase particles determine the long-term creep resistance and the ultimate lifetime of these stressed components [53]. In general, the reformer furnace tubes are designed for a nominal lifetime of 100,000 h, but because the tubes are exposed to high temperature and high pressure due to the above service conditions and operation cycles, some damages frequently occurred within the tubes. Consequently, the real service lifetime is varied from 30,000 to 180,000 h depending on the quality of tube material and the service conditions [56]. The main damage mechanism limiting the tube life is the creep deformation driven by the internal pressure developed in the

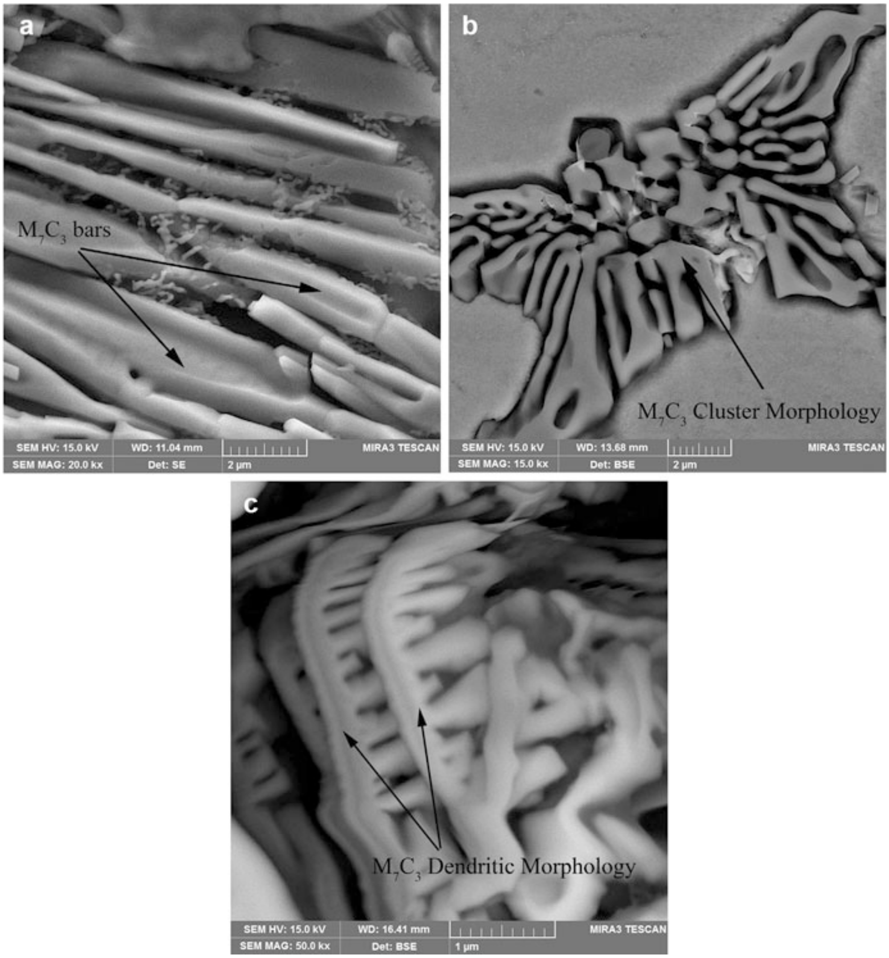

Fig. 2 The morphologies of M7C3 carbide: (**a**) alloy HWN, bar shape; (**b**) alloy LWN, cluster; (**c**) alloy LW, dendritic [52]

normal service condition and the thermal stresses developed during the start-up and shutdown cycles [57, 58]. It has been shown that the major load exerted on the tubes is through wall thermal stress that reduces their life with cyclic creep relaxation in a time scale controlled by the operational outline [58]. Thus, in order to extend the tube life the operational considerations for reducing the thermal stresses in the tube wall have been necessary [58]. This is because the thermal stresses are generated in every start-up and shutdown of the plant. On the other hand, thermal stresses are the problems occurring due to differential strains caused by the tube thermal expansion. For example, the protective chromium oxide scale in the tube wall has a different coefficient of thermal expansion than the base metal, thus, during the service it can produce a thermal stress in the tube. However, the thermal stress promotes the creep deformation in the tube material [59, 60]. Overheating is another most common failure cause of the reformer tubes, which occurs when the tube skin temperature increases above 1000 °C. Macroscopically, overheating is generally accompanied with longitudinal cracking and mechanical degradation of the tube and microscopically with excessive coarsening and dissolution of secondary precipitates [61, 62].

Heat-resistant steel is well known for its excellent strength, high oxidation resistance, and corrosion resistance under high temperature conditions, and it has been widely used in the fields such as aerospace, shipping industry, and petrochemical engineering [63, 64]. Rare earth has shown considerable effects on microalloying and improving performance of the steel. For example, cerium could decrease the content of oxygen and sulfur in spring steel. The Ce addition could also capture the residual elements and suppress their precipitation behaviors in the grain boundary [104]. The effect of rare earth on mechanical and microstructural behavior of a duplex stainless steel during hot working condition was investigated by Chen et al., and rare earths show evident microalloying properties in duplex stainless steel [65]. Xing et al. proved that the corrosion resistance of the 304 stainless steel could be modified and improved by CeO_2 [66]. With continuously developing technology, rare earth has been widely introduced in heat-resistant steel. Taking 253MA steel as an example, it is a new generation of austenitic heat-resistant steel mainly containing Fe, Cr, Ni and minor elements such as Ce, Mn, Si, and C. Cerium combined with silicon improves the oxidation resistance, erosion corrosion resistance, and oxide spallation resistance, and the target content of cerium is about 0.03–0.08 wt% in 253MA steel [67]. However, it should be added excessively in the refining process due to the low yield rate of cerium, which is much higher than that in the plain RE-treated steel. High contents of reactive cerium in the steel could induce serious slag-metal interface reactions in the mold when using conventional mold fluxes. The content of RE oxides in the mold fluxes increased, and the compositions of the mold fluxes changed, which could lead to deteriorated properties such as varying viscosity and surface tension during casting [68, 69]. What is worse, the surface defects and sticking breakout may be initiated in severe cases.

Automotive Industries

Magnesium alloys, one of the most important structural materials with high specific strength, are used widely in the automotive, communication, electronic, and aerial industries [70]. Mg–Al series alloys such as AZ91D and AM60B are the most widely used commercial heat-resistant magnesium alloys. However, the main strengthening phase β-Mg17Al12 exhibits low thermal stability owing to the low melting temperature of 710 K. When the temperature rises, the microstructure will become soft and coarse easily, and then the strength and creep resistance will decrease significantly. Thus, the alloys cannot usually be fabricated to the parts used under high temperature condition above 393 K for long time. Researchers often enhance the elevated temperature performance through precipitating the phases with high thermal stability such as Al_2Ca, Al_2Sr, Mg_2Si, and Al–RE by adding alkaline earth metal [71–73], Si [74, 75], and rare earth (RE) [76–80, 99]. RE with unique atomic electron and chemical property can purify the alloy melt, ameliorate the microstructure, and then enhance the mechanical property and corrosion resistance. Compared with other REs, the effects of cheaper Sm on the microstructure and mechanical properties of Mg–Al series alloys have been rarely studied yet [77, 100]. Meanwhile, the addition of Bi can also enhance the elevated temperature performance effectively through precipitating the Mg_3Bi_2 phase with high thermal stability.

3Cr20Ni10W2 is a representative austenitic heat-resisting alloy. This alloy is usually adopted as the material of exhaust valves on diesel engine in the large marine industry due to its high strength, superior creep strength, excellent oxidation resistance, excellent heat resistance, and high corrosion resistance. It is difficult to process such material due to its high strength and excellent heat resistance. Therefore, a special plastic processing technology involving high heating efficiency and isostatic loading, electric upsetting process is always used to form the exhaust valve component with 3Cr20Ni10W2 alloy. During hot forming process such as electric upsetting process, the deformed material is liable to undergo work hardening (WH), dynamic recovery (DRV), and dynamic recrystallization (DRX), three metallurgical phenomena for controlling microstructures and mechanical properties [38, 81, 82, 101]. In austenitic steels such as 3Cr20Ni10W2 alloy with higher deformation resistance, the kinetics of DRV is lower, and DRX can be initiated at a critical condition of stress accumulation [83]. The occurrence of DRX brings about grain refinement and deformation resistance reduction, due to which the evaluation of the rate and progress of DRX in terms of deformation conditions is important [102]. DRX kinetics describes the fact that the nucleation of DRX grains start at a critical strain which is a function of initial microstructure and deformation conditions. Then, the evolution of DRX microstructure can proceed further through the formation of a necklace structure with increasing deformation degree [84]. Quan et al. [85] performed a constitutive modeling for the dynamic recrystallization kinetics of as-extruded 3Cr20Ni10W2 heat-resistant alloy based on stress–strain data. It was observed that the initial microstructure of 3Cr20Ni10W2 heat-resisting alloy consists of rough equiaxed grains with a large quantity of twin boundaries as shown in Fig. 3a, while Fig. 3b–f shows the typical microstructures of the specimens deformed to a strain of – 0.91 at the strain rate of 0.01 s^{-1} and at the temperatures of 1203 K, 1253 K, 1303 K, 1353 K, and 1403 K, respectively.

2xxx series Al alloys, such as 2219 (Al-Cu-Mn) and 2618 (Al-Cu-Mg-Fe-Ni), are widely applied in aircraft industry because of their low density, high strength, and excellent heat resistance [86–88]. With the development of aviation technology, the aircraft flight velocity is further increased, and the strengthening and heat resistance of the aircraft Al alloy must be enhanced correspondingly. Thus, the development of new heat-resistant Al alloys is urgently needed. Al-Cu-Mg-Ag alloy, a new heat-resistant Al alloy prepared by adding trace amounts of Ag to Al-Cu-Mg alloys with high Cu:Mg ratios, has found to possess excellent mechanical properties at elevated temperatures, such as higher tensile strength and improved creep resistance [89, 90, 105]. Moreover, these alloys are potential aero metals, attracting many investigations

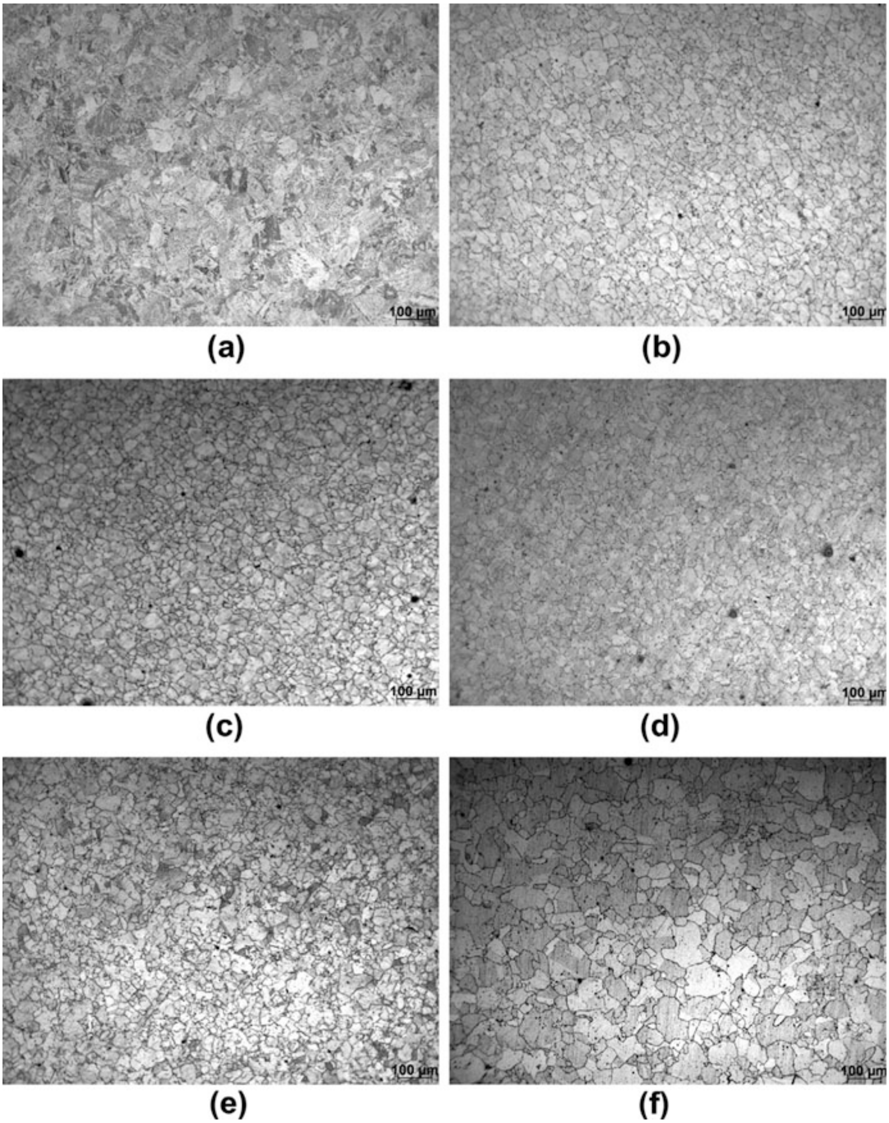

Fig. 3 Microstructures at a strain rate of 0.01 s_1 and temperatures of (**a**) as-received, (**b**) 1203 K, (**c**) 1253 K, (**d**) 1303 K, (**e**) 1353 K, and (**f**) 1403 K [85]

on their microstructures and properties. Al-Cu-Mg-Ag was first reported [91]. They demonstrated that trace addition of Ag (0.4 wt%) to traditional Al-Cu-Mg alloys with high Cu:Mg ration resulted in an increase of the aging hardening response. The Ag addition promoted the formation of a fine and uniform dispersion of plate-like precipitation on {111}a planes at the expense of the precipitation q0 (Al_2Cu) which is usually observed in Al-Cu-Mg alloys. The new phase was designated as U, showing excellent thermal stability at elevated temperatures compared with q0 [92–94]. Hutchinson et al. [95] suggested that the high resistance to plate coarsening exhibited by U plates was due to a prohibitively high barrier to ledge nucleation in the strong vacancy field normal to the broad face of the plate. On the other hand, Ag and Mg atoms are strongly segregated to the broad face monolayer interfaces of a/U [96]. The large misfit that exists normal to the broad face of the plate is unlikely to provide a driving force for the segregation of Ag and Mg [95]. Thus the growth of U phases is restrained by the limited supplement of these atoms. Ringer et al. [97] and Gable et al. [98] work demonstrated that the presence of the Al2CuMg (S) phase could destabilize the desirable U plate precipitates. Gable et al. [98] suggested that alloy design must account for this, and accurate representations of the aluminum-rich portion of the Al-Cu-Mg-(Ag) phase diagram are essential.

Conclusions and Further Work

The types and properties of various heat-resistant alloys and their common areas of applications were examined. Heat resistant alloys are materials characterized by extreme high stability of their properties, which are not highly dependent on the residence time at high temperatures, but depend on the purpose for which it will be applied. Heat-resistant alloys are made with increased resistance to fatigue, erosion, and low notch sensitivity, as well as with high thermal stability and short-term high-load resistance. Heat-resistant alloys are made with increased resistance to fatigue, erosion, and low notch sensitivity, as well as with high thermal stability and short-term highload resistance. The areas of industrial applications such as in turbine power plant, automobile industries and pressure vessels of heat resistant alloys depend on its creep and mechanical properties. Further work to improve on the creep and mechanical properties of heat resistant alloys will open up new applications.

References

1. Garofalo F (1968) Zakony polzuchesti i dliteVnoi prochnosti metallov i splavov. Moscow (Translated from English). https://encyclopedia2.thefreedictionary.com/Heatresistant+Alloys
2. Kurdiumov GV (1960) Priroda uprochnennogo sostoianiia metallov. Metallov'edenie i termicheskaia obrabotka metallov, 10
3. Rozenberg VM. Polzuchest' metallov. Moscow, 1967. Khimushin FF. Zharoprochnye stall i splavy, 2nd edn. Moscow, 1969. https://encyclopedia2.thefreedictionary.com/Heatresistant+Alloys
4. Jie QI et al (2016) Viscous properties of new mould flux based on aluminate system with CeO_2 for continuous casting of RE alloyed heat resistant steel. J Rare Earths 34(3):328–335
5. Lei C et al (2016) Effect of rare earth alloying on creep rupture of economical 21Cr-11Ni-N heat resistant austenitic steel at 60 °C. J Rare Earths 34(4):447–452
6. Huang Z et al (2015) Microstructures and mechanical properties of Mg-Al-Sm series heat-resistant magnesium alloys. Trans Nonferrous Metals Soc China 25:22–29

7. Lobanov LM et al (2016) Investigation of residual stresses in welded joints of heat–resistant magnesium alloy ML10 after electrodynamic treatment. J Magnes Alloys 4:77–82
8. Attarian M et al (2016) Microstructural and failure analysis of welded primary reformer furnace tube made of HP-Nb micro alloyed heat resistant steel. Eng Fail Anal 68:32–51
9. Sourmail T, Bhadeshia HKDH, MacKay CDJ (2002) Neural network model of creep strength of austenitic stainless steels. Mater Sci Technol 18:665
10. Viswanathan R, Bakker W (2001) Materials for ultra supercritical coal power plants-boiler materials: Part 1. J Mater Eng Perform 10(1):81–95
11. Igarashi M (2004) In: Yagi K et al (eds) Group VIII: advanced materials and technologies. Springer, Berlin
12. Park I, Masuyama F, Endo T (2000) Key Eng Mater 171–174:445–452
13. Swindeman RW, Maziasz PJ (1991) pp Medium: X; Size: Pages: (59 p)
14. Wang J-Z, Liu Z-D, Bao H-S, Cheng S-C (2013) J Iron Steel Res Int 20:113–121
15. Iseda A, Okada H, Semba H, Igarashi M (2007) Energy Mater 2:199–206
16. Hack H, Stanko G (2005) In: Proceedings of the 22nd annual international Pittsburgh coal conference, Pittsburgh
17. Natesan K, Park JH (2007) Int J Hydrog Energy 32:3689–3697
18. Viswanathan R, Sarver J, Tanzosh JM (2006) J Mater Eng Perform 15:255–274
19. Abe F, Araki H, Noda T (1991) Metall Mater Trans A 22:2225–2235
20. Asakura K, Yamashita Y, Yamada T, Shibata K (1990) J Iron Steel Inst 30:937–946
21. Dimmler G, Weinert P, Kozeschnik E, Cerjak H (2003) Mater Charact 51:341–352
22. Patriarca P, Jarkness SD, Duke JM, Cooper LR (1976) Nucl Technol 28:516–536
23. Chen L, Ma XC, Wang LM, Ye XN (2011) Effect of rare earth element yttrium addition on microstructures and properties of a 21Cr-11Ni austenitic heat-resistant stainless steel. Mater Des 32:2206–2212
24. Lo KH, Shek CH, Lai JKL (2009) Recent developments in stainless steels. Mater Sci Eng R 65:39–104
25. Mathew MD, Laha K, Ganesan V (2012) Improving creep strength of 316L stainless steel by alloying with nitrogen. Mater Sci Eng A 535:76–83
26. Lala K, Kyono J, Shinya N (2007) An advanced creep cavitation resistance Cu-containing 18Cr-12Ni-Nb austenitic stainless steel. Scr Mater 56:915–918
27. Masuyama F (2007) Creep rupture life and design factors for high-strength ferritic steels. Int J Press Vessel Pip 84:53–61
28. Fukuda M, Saito E, Semba H, Iwasaki J, Izumi S, Takano S, Takahashi T, Sumiyoshi Y (2013) Advanced USC technology development in Japan. In: Gandy D, Shingledecker J (eds) Advances in materials technology for fossil power plants-proceedings from the seventh international conference. ASM International, Materials Park, pp 24–40
29. Masuyama F (2001) History of power plants and progress in heat resistant steels. Iron Steel Inst Jpn Int 41:612–625
30. Gianfrancesco AD, Tizzanini A, Jedamzik M (2013) ENCIO project: an European approach to 700 °C power plant. In: Gandy D, Shingledecker J (eds) Advances in materials technology for fossil power plants-proceedings from the seventh international conference. ASM International, Materials Park, pp 9–23
31. Mathur A, Butani OP, Jayakumar T, Dubey DK, Chetal SC (2013) India's national A-USC mission-plan and progress. In: Gandy D, Shingledecker J (eds) Advances in materials technology for fossil power plants-proceedings from the seventh international conference. ASM International, Materials Park, pp 53–59
32. Shingledecker J, Purgert R, Rawls P (2013) Current status of the U.S DOE/OCDO A-USC materials technology research and development program. In: Gandy D, Shingledecker J (eds) Advances in materials technology for fossil power plants-proceedings from the seventh international conference. ASM International, Materials Park, pp 41–52

33. Nakashima H, Yamazaki S, Mitsuhara M (2015) Development of high nitrogen ferritic heat-resistant steel for boiler material in next generation power plant, CAMP-ISIJ meeting, vol 28, p 867
34. Nunes FC, Dille J, Delplancke JL, de Almmeida LH (2006) Scr Mater 54:1553–1556
35. Roy M, Pauschitz A, Wernisch J, Franek F (2004) Mater Corros 55:259–273
36. Wilson JD, Carney TJ, Kelly JC (2005) Micro-alloying improves resistance to high temperature environments. In: George R (ed) Corrosion 2005. NACE International, Houston, pp 422–432
37. Chen L, Zhang Y, Li F, Liu X, Guo B, Jin M (2016) Modeling of dynamic recrystallization behavior of 21Cr-11Ni-N-RE lean austenitic heat-resistant steel during hot deformation. Mater Sci Eng A 663:141–150
38. Lin YC, Chen XM (2011) A critical review of experimental results and constitutive descriptions for metals and alloys in hot working. Mater Des 32(4):1733–1759
39. Marandi A, Zarei-Hanzaki A, Haghdadi N, Eskandari M (2012) Mater Sci Eng A 554:72–78
40. McQueen HJ, Yue S, Ryan ND, Fry E (1995) J Mater Process Technol 53:293–310
41. Herda W, Rickard AJ (1979) A comprehensive collection of outstanding articles from the periodical and reference literature. In: Bradley EF (ed) Source book on materials for elevated-temperature applications. ASM, Materials Park, pp 55–63
42. Zhu SJ, Wang Y, Wang FG (1990a) J Mater Sci Lett 9:520–521
43. Andrade AR, Bolfarini C, Ferreira LAM, Vilar AAA, Souza Filho CD, Bonazzi LHC (2015) Mater Sci Eng A 628:176–180
44. Zhu SJ, Zhao J, Wang FG (1990b) Metall. Trans 21A:2237–2241
45. Wang F, Northwood DO (1993) Mater Charact 31:3–10
46. Kondo Y, Inazumi T, Takeyama M, Matsuo T, Tanaka R (1990) Tetsu to Hagane 76(2):246–253
47. Matsuo T, Nakajima K, Terada Y, Kikuchi M (1991) Mater Sci Eng A 146:261–272
48. ASM Specialty Handbook (1997) In: Davis JR (ed) Heat resistant, materials. ASM International, Materials Park, pp 207–210
49. Cox GJ (1980) In: Proceedings of the 47th international foundry congress, Jerusalem, Oct 1980, paper no. 12, pp 349–404
50. Kikuchi M, Sakakibara M, Otoguro Y, Mimura H, Araki S, Fujita T (1987) In: Marriott JB et al (eds) High temperature alloys their exploitable. Elsevier, London/New York, pp 267–276
51. Shingledecker JP, Maziasz PJ, Evans ND, Pollard MJ (2007) Int J Press Vessel Pip 84:21–28
52. Attarian M, Taheri AK (2016) Microstructural evolution in creep aged of directionally solidified heat resistant HP-Nb steel alloyed with tungsten and nitrogen. Mater Sci Eng A 659:104–118
53. Kenik EA, Maziasz PJ, Swindeman RW, Cervenka J, May D (2003) Structure and phase stability in a cast modified-HP austenite after long-term ageing. Scr Mater 49:117–122
54. Huber J, Jakobi D (2010) Centricast materials for high temperature service. Nitrogen + Syngas 307:36–39
55. Schillmoller CM (2000) HP-modified furnace tubes for steam reformers and steam crackers. NiDi technical series no 10 058(Canada), Nickel Institute Canada
56. Gong JM, Tu ST, Yoon KB (1999) Damage assessment and maintenance strategy of hydrogen reformer furnace tubes. Eng Fail Anal 6:143–153
57. Alvino A, Lega D, Giacobbe F, Mazzocchi V, Rinaldi A (2010) Damage characterization in two reformer heater tubes after nearly 10 years of service at different operative and maintenance conditions. Eng Fail Anal 17:1526–1541
58. Brear JM, Church JM, Humphrey DR, Zanjani MS (2001) Life assessment of steam reformer radiant catalyst tubes – the use of damage front propagation methods. Int J Press Vessel Pip 78:985–994
59. Jakobi D, Gommans R (2003) Typical failures in pyrolysis coils for ethylene cracking. Mater Corros 54:881–886

60. Konoki K, Shinohara T, Shibata K (1982) Creep rupture of steam reforming tube due to thermal stress. Plant/Oper Prog 1:122–127
61. Ray AK, Sinha SK, Tiwari YN, Swaminathan J, Das G, Chaudhuri S, Singh R (2003) Analysis of failed reformer tubes. Eng Fail Anal 10:351–362
62. Shariat MH, Faraji AH, Ashraf-Riahy A, Alipour MM (2003) In advanced creep failure of HP modified reformer tubes in an ammonia plant. J Corros Sci Eng 6 (Paper H012 preprint 69)
63. Hu BW (2006) The design idea of refractory steel. Equip Manuf Technol 4(4):50
64. Lin FS, Wang ZZ, Wang BZ, Cheng SC, Xie XS (2010) Research, application and development of domestic heat resistant steels and alloys for power plants. J Chin Soc Power Eng 30(4):235
65. Chen L, Ma XC, Wang MJ, Xue HY (2015) Effect of RE on molybdenum partitioning and resultant mechanical and microstructural behavior of a duplex stainless steel during hot working condition. J Rare Earths 33(1):107
66. Xing XG, Han ZJ, Wang HF, Lu PN (2015) Electrochemical corrosion resistance of CeO_2-Cr/Ti coatings on 304 stainless steel via pack cementation. J Rare Earths 33(10):1122
67. Zhu ZP (2008) Handbook for designation of stainless and heat resisting steel. Chemistry Industry Press, Beijing
68. Li XH, Li CL, Wang YS (2003) Influence of rare earth on the mould flux properties. Chin Rare Earths 24(5):18
69. Wang DY, Jiang MF, Liu CJ, Shi PY, Yao YK, Wang HH (2005) Effects of rare earth oxide on viscosity of mold fluxes for continuous casting. J Chin Soc Rare Earths 23(1):100
70. Polmear IJ (1994) Magnesium alloys and applications. Mater Sci Technol 10(1):1–16
71. Lou Y, Bai X, Li L-X (2011) Effect of Sr addition on microstructure of as-cast Mg–Al–Ca alloy. Trans Nonferrous Metals Soc China 21(6):1247–1252
72. Wang QD, Chen WZ, Zeng XQ, Lu YZ, Ding WJ, Zhu YP, Xu XP (2001) Effects of Ca addition on the microstructure and mechanical properties of AZ91 magnesium alloy. J Mater Sci 36(12):3035–3040
73. Xu CX, Ju H, Zhou Y (2011) Effect of Ca on microstructure and properties of Mg–Al–Si alloys. Adv Mater Res 194–196:1369–1373
74. Lu YZ, Wang QD, Zeng XQ, Zhu YP, Ding WJ (2001) Behavior of Mg–6Al–*x*Si alloys during solution heat treatment at 420 °C. Mater Sci Eng A 301:255–258
75. Yuan GY, Liu ZL, Wang QD, Ding WJ (2002) Microstructure refinement of Mg–Al–Zn–Si alloys. Mater Lett 56:53–58
76. Asl KM, Tari A, Khomamizadeh F (2009) The effect of different content of Al, RE and Si element on the microstructure, mechanical and creep properties of Mg–Al alloys. Mater Sci Eng A 523(1–2):1–6
77. Son HT, Lee JS, Kim DG, Yoshimi K, Maruyama K (2009) Effects of samarium (Sm) additions on the microstructure and mechanical properties of as-cast and hot-extruded Mg–5wt%Al– 3wt%Ca-based alloys. J Alloys Compd 473(1–2):446–452
78. Yokobayashi H, Kishida K, Inui H, Yamasaki M, Kawamura Y (2011) Enrichment of Gd and Al atoms in the quadruple close packed planes and their in-plane long-range ordering in the long period stacking-ordered phase in the Mg–Al–Gd system. Acta Mater 59(19):7287–7299
79. Zhang JH, Yu P, Liu K, Fang DQ, Tang DX, Meng J (2009) Effect of substituting cerium-rich mischmetal with lanthanum on microstructure and mechanical properties of die-cast Mg–Al–RE alloys. Mater Des 30(7):2372–2378
80. Zhang S-C, Wei B-K, Cai Q-Z, Wang L-s (2003) Effect of mischmetal and yttrium on microstructures and mechanical properties of Mg–Al alloy. Trans Nonferrous Metals Soc China 13(1):83–87
81. Kim SI, Lee Y, Byon SM (2003) Study on constitutive relation of AISI 4140 steel subject to large strain at elevated temperatures. J Mater Process Technol 140(1–3):84–89
82. Quan GZ, Tong Y, Zhou J (2010) Dynamic softening behaviour of AZ80 magnesium alloy during upsetting at different temperatures and strain rates. Proc Inst Mech Eng B J Eng Manuf 224(11):1707–1716

83. Momeni A, Dehghani K, Keshmiri H, Ebrahimi GR (2010) Hot deformation behaviour and microstructural evolution of a superaustenitic stainless steel. Mater Sci Eng A 527(6):1605–1611
84. Quan GZ, Li GS, Chen T, Wang YX, Zhang YW, Zhou J (2011) Dynamic recrystallization kinetics of 42CrMo steel during compression at different temperatures and strain rates. Mater Sci Eng A 528(13–14):4643–4651
85. Quan G-Z, Mao A, Luo G-C, Liang J-T, Wu D-S, Zhou J (2013) Constitutive modeling for the dynamic recrystallization kinetics of as-extruded 3Cr20Ni10W2 heat-resistant alloy based on stress–strain data. Mater Des 52:98–107
86. Li Q, Wu A, Li Y, Wang G, Yan D, Liu J (2015) Mater Sci Eng A 623:38–48
87. Nový F, Janeček M, Král R (2009) J Alloys Compd 487:146–151
88. Wang J, Yi D, Su X, Yin F (2008) Mater Charact 59:965–968
89. Bai S, Liu Z, Li Y, Hou Y, Chen X (2010) Mater Sci Eng A 527:1806–1814
90. Zhang JB, Zhang YA, Zhu BH, Liu RQ, Wang F, Liang QM (2013) Mater Des 49:311–317
91. Vietz JT, Polmear IJ (1966) J Inst Met 94:410–419
92. Bai S, Zhou X, Liu Z, Xia P, Liu M, Zeng S (2014) Mater Sci Eng A 611:69–76
93. Liu XY, Pan QL, Zheng LY, Fu QR, Gao F, Li MX, Bai YM (2013) Mater Des 46:360–365
94. Xia QK, Liu ZY, Li YT (2008) Trans Nonferrous Metals Soc China 18:789–794
95. Hutchinson CR, Fan X, Pennycook SJ, Shiflet GJ (2001) Acta Mater 49:2827–2841
96. Reich L, Murayama M, Hono K (1998) Acta Mater 46:6053–6062
97. Ringer SP, Yeung W, Muddle BC, Polmear IJ (1994) Acta Metall 42:1715–1725
98. Gable BM, Zhu AW, Shiflet GJ, Starke EA Jr (2008) Comput Coupling Phase Diagrams Thermochem 32:256–267
99. Li K-J, Li Q-A, Jing X-T, Chen J, Zhang X-Y (2009a) Effects of Sb, Sm and Sn additions on the microstructure and mechanical properties of Mg–6Al–1.2Y–0.9Nd alloy. Rare Metals 28(5):516–522
100. Li WY, Yu M, Li JL, Zhang GF, Wang SY (2009b) Characterizations of 21-4N to 4Cr9Si2 stainless steel dissimilar joint bonded by electric-resistance-heat-aided friction welding. Mater Des 30:4230–4235
101. Lin YC, Chen MS, Zhong J (2008a) Constitutive modeling for elevated temperature flow behavior of 42CrMo steel. Comput Mater Sci 42(3):470–477
102. Lin YC, Chen MS, Zhong J (2008b) Numerical simulation for stress/strain distribution and microstructural evolution in 42CrMo steel during hot upsetting process. Comput Mater Sci 43(4):1117–1122
103. Liu WB, Zhang C, Xia ZX, Yang ZG (2014a) Improving high temperature creep resistance of reduced activation steels by addition of nitrogen and intermediate heat treatment. J Nucl Mater 455:402
104. Liu YQ, Wang LJ, Chou K (2014b) Effect of cerium on the cleanliness of spring steel used in fastener of high-speed railway. J Rare Earths 32(8):759
105. Liu XY, Pan QL, Zhang XL, Liang SX, Gao F, Zheng LY, Li MX (2014c) Mater Sci Eng A 599:160–165