Chapter 6
Sintering in the Constant Electric Field in the Noncontact Mode and in Magnetic Field

6.1 Sintering in the Constant Electric Field in the Noncontact Mode

A number of reports exist in the literature on the sintering enhancement by an applied field that is not associated with the passage of current through the compact. The specifics of the mechanisms of these types of sintering should apparently include the field-assisted acceleration of diffusion and, possibly, the double-layer effect influencing the specific surface energy [1–3].

Holland et al. [1] suggest that sintering schemes involving electric field in the noncontact mode hold great promise for the future of field-assisted sintering by dramatically reducing processing costs. Newman [2] investigated the effect of electric field strengths up to 7.7 kV cm^{-1} on the porosity of a steel compact using a set-up shown in Fig. 6.1. The following consideration was taken into account: the application of an electric field during sintering, which makes the compact a positive electrode of a capacitance circuit, produces a positive charge on the surface of the compact. Since the vacancies in a metal are negatively charged, the chemical potential of the vacancies at the surface may be lower than in the subsurface layer. As a result, diffusion of vacancies from the pores into the subsurface layer of the compact will occur improving the sintering process. A reduction in the porosity of the 0.2–0.4 mm layer below the surface of a Fe-based alloy compact by as much as 44% was observed. The reduced porosity was confirmed by nitro-carburizing experiments in which carbon diffusion was limited to a depth of only 0.2 mm below the surface. Specimens sintered without an electric field showed carbon diffusion depths over ten times the depth observed in specimens sintered in the applied electric field. The observed decrease in the surface porosity was attributed to a decrease in the chemical potential of vacancies at the charged external surface. The application of this effect in commercial processes is the surface porosity reduction crucial for the corrosion resistance control of metallic parts and metal hardening technologies based

E. A. Olevsky, D. V. Dudina, *Field-Assisted Sintering*,
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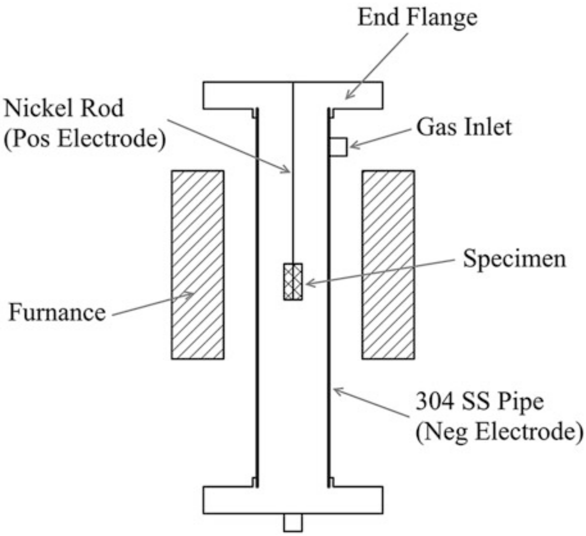

Fig. 6.1 Schematic of a set-up for sintering in the constant electric field (Reprinted from Newman [2], Copyright (2000) with permission from Elsevier)

on surface carburization. The surface modification has to involve a layer of a certain thickness only, leaving the material located deeper non-carburized and ductile.

Holland et al. [1] found that the electric field in the noncontact mode can benefit densification of dielectrics during slow heating, even if it is applied only up to temperatures much lower than those at which any significant diffusion in the sintered material can be expected (Fig. 6.2). A suggestion has been put forward that the electric field can facilitate the removal of surface contaminants from the nanosized powders, such as water and carbon dioxide, which evolve at 400–500 °C upon heating – at temperatures too low for any diffusion activity in the sintered powder material to start. It was pointed out that a great advantage of the noncontact mode is an opportunity of the application of electric fields together with different mechanical loading schemes, not just together with uniaxial pressing as in the commonly accepted scheme of combining pressing and passage of current.

6.2 Sintering in the Constant and Pulsed Magnetic Fields

The conditions of the growth and dissolution of pores in a solid placed in a magnetic field were analyzed by Kornyushin [3]. The magnetic lines around a pore are distorted. If a pore in a one-domain spherical magnetic solid elongates along the direction of the magnetic moment maintaining its volume, the distortion of the magnetic lines will be reduced and so will be the magnetic energy of the system. However, the energy of the system will increase due to an increase in the surface area of the elongated pore. For magnetic materials sintered in a magnetic field, particular pore-size distributions and pore orientations can be expected. These effects will be

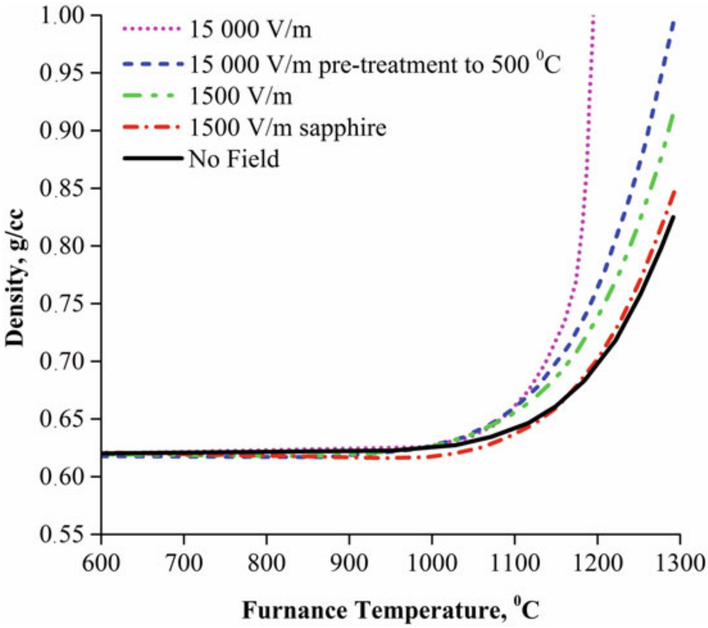

Fig. 6.2 Densification curves of 3YSZ sintered in air with and without electric field (Reprinted from Holland et al. [1], Copyright (2013) with permission from Elsevier)

achieved in materials, for which the Curie temperature and the sintering temperature are comparable. For materials with low Curie temperatures, there will be no influence of magnetic field on sintering. Litvinenko et al. [4] studied the effect of a constant magnetic field (~0.3 T) on the densification of cobalt powders due to the high Curie point of cobalt. The powder compacts were radiantly heated by the heating elements. Although the difference between the remaining porosities of the compact sintered in the magnetic field and the compact sintered without field was slight (65.5% and 68.2%), the resistivity of the compact sintered without magnetic field was almost twice the resistivity of the compact sintered in the presence of magnetic field. The authors explain this effect by a greater perfection of the interparticle contacts formed in the magnetic field.

The influence of a pulsed magnetic field on the density and quality of the sintered compacts has received a more detailed explanation. The contacting particles, when carrying an electric current, form conductors, which experience the action of Ampère's force in the external magnetic field. Such experiments were conducted by Li et al. [5], who combined the SPS processing of iron powders with the action of a pulsed magnetic field and obtained compacts of higher density and increased hardness than in the absence of the magnetic field. The effect of the pulsed magnetic field was concluded to be in the generation of eddy currents, enhancement of mass transport and particle rearrangement by breaking the previously formed bridges.

6.3 Summary

Sintering in the constant electric field in the noncontact mode and in magnetic field presents very rare types of processing and has been reported only in a limited number of publications. Apparently, it can be applicable to a limited number of material systems; however, when applicable, it can produce quite useful results. The specifics of the mechanisms of these types of sintering should include the field-assisted acceleration of diffusion and, possibly, the double-layer effect influencing the specific surface energy.

References

1. Holland TB, Anselmi-Tamburini U, Mukherjee AK (2013) Electric fields and the future of scalability in spark plasma sintering. Scr Mater 69(2):117–121
2. Newman DC (2000) Novel uses of electric fields and electric currents in powder metal (P/M) processing. Mater Sci Eng A 287:198–204
3. Kornyushin YV (1980) Influence of external magnetic and electric fields on sintering, structure and properties. J Mater Sci 15:799–801
4. Litvinenko YM, Solonin SM, Fridman GR (1982) Sintering of loose cobalt, nickel and iron powders in magnetic field. Soviet Powder Metall Metal Ceram 21(1):29–32
5. Li X, Ye Y, Tang Y, Qu S (2010) Effect of pulsed magnetic field on spark plasma sintering of iron-based powders. Mater Trans 51(7):1308–1312