

ASYMMETRICAL FERRITE-AUSTENITE TRANSFORMATION DURING VACUUM SINTERING OF PLAIN IRON COMPACTS

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Abstract

The dimensional behaviour of plain iron compacts during sintering was studied by dilatometry in varying atmospheres. It showed that sintering in vacuum resulted in unsymmetrical ferrite-austenite phase transformation, the shrinkage during the α - γ transformation in the heating section being markedly less pronounced than the expansion during the γ - α transformation in the cooling section. This discrepancy was the more pronounced the higher the green density of the specimens was. This effect is linked to excessive grain growth in the specimens, and neither phenomenon is related e.g. to the heating and cooling rates. The asymmetrical transformation was also observed when sintering in Ar, though slightly less pronounced, while sintering in N₂ or low-pressure air resulted in the expected symmetrical transition; also addition of even small quantities of carbon to the starting powder caused the unsymmetrical transition to disappear and also resulted in a fine grained structure to be expected for porous sintered iron.

Keywords: Sintered iron, alpha-gamma transformation, dilatometry, atmosphere

INTRODUCTION

The ferrite-austenite phase transformation is a specific feature of plain iron and low alloy steels, and it is to a large extent the use of this phase transformation for heat treatment that has made steels the most universally used metallic materials [1, 2]. Dimensionally, the higher packing density of the austenitic fcc lattice compared to the bcc ferrite results in contraction during the α - γ transformation and a corresponding expansion during the γ - α transition. Also with sintered iron and steels this phase transformation takes place, and basically the behaviour of the materials is comparable to wrought steels (e.g. [3]) with the exception of microstructurally inhomogeneous sintered steels that exhibit rather uncommon transformation and resulting dimensional behaviour esp. during the cooling process, the different microstructural areas transforming at different temperatures [4, 5]. With sintered plain iron, however, quite regular transformation behaviour can be expected. Generally, the role of the ferrite-austenite phase transformation in the sintering process has been recognized quite early, mainly with respect to the slower sintering in the austenite range compared to ferrite [6-8] which results in the same mechanical strength being obtained after sintering e.g. at 900° and 1100°C, respectively. However, it has also been shown that cyclic treatment across the phase transformation can enhance sintering of iron, as shown on wires by Matsumura and Tuan [9].

Sintering of plain iron plays a major role e.g. for the manufacturing of soft magnetic precision components [10]. Usually this is done in a reducing atmosphere since

unlike in carbon containing sintered steels there is no reducing agent within the compact itself. The atmosphere is commonly H_2 or N_2-H_2 , carburizing or nitriding being unwelcome here [11]. Sintering of plain iron in vacuum is rather exotic since the oxide layers present also after sintering are commonly regarded as detrimental for the mechanical properties. Oxygen removal through dissociation of the oxides is rather improbable since it would necessitate extremely low oxygen partial pressures, typically in the range of $<10^{-10}$ bars [12].

In this work, plain iron compacts were studied in the dilatometer as a reference for sintering and degassing of plain carbon and low alloy steels [13-15]. The unexpected dimensional behaviour encountered in the ferrite-austenite phase transformation is described here.

EXPERIMENTAL PROCEDURES

Plain iron test specimens were prepared from standard water atomized iron powder grade ASC 100.29 (Höganäs) by compacting in a tool with floating die to form bars 55 x 10 x approx. 7 mm under die wall lubrication. The compacting pressure was varied accordingly. Some specimens were compacted with admixed lubricant (0.5 % HWC) and separately dewaxed. As a reference, wrought steel bars of corresponding dimensions were machined from Armco iron. Some specimens containing small amounts of carbon were produced by admixing natural graphite (UF4, Kropfmühl) to the iron powder.

The compacts were then inserted into a pushrod dilatometer Bähr 801 with alumina measuring system. The dilatometer was evacuated using mostly a two-stage rotary pump, the vacuum attained being in the range of about 6.10^{-3} mbar at beginning of the runs (cold). In part also a turbomolecular pump was used which resulted in an initial pressure in the system of about 5.10^{-5} mbar. In some runs, after several evacuation steps, a given gas pressure was set in the vacuum system, air and high purity N_2 and Ar grades, respectively being used. The dilatometric runs were then performed under static atmosphere in these cases.

Unless stated otherwise, heating and cooling rates were uniformly set at $10 K.min^{-1}$, and the isothermal sintering temperature was set to be $1300^\circ C$, the holding time being 60 min. The dimensional changes occurring during the phase transformations were determined from the dilatometric graphs; due to the very narrow temperature intervals within which the transformations occurred, no compensation for the expansion of the alumina measuring system was regarded necessary. The specimens were metallographically investigated using standard techniques; Nital etching being employed. For obtaining micrographs also from coarse-grained specimens, a microscope WILD M400 was used at uniformly 6.3x magnification.

RESULTS AND DISCUSSION

Dimensional behaviour of plain iron compacts in vacuum

Plain iron test bars were compacted at a pressure of 600 MPa, resulting in about $7.1 g.cm^{-3}$ green density, and sintered in the dilatometer in a rotary pump vacuum, following the standard cycle as given above. It showed that the general sintering behaviour was similar to that of e.g. carbon steels, with the exception of the higher phase transformation temperatures, as predicted by the Fe-C phase diagram. However, it was observed that the phase transformation tended to be decidedly asymmetrical, i.e. the shrinkage during the $\alpha-\gamma$ transformation in the heating section was markedly less pronounced than the expansion during the $\gamma-\alpha$ transformation in the cooling section, as

shown in Fig.1a for a standard plain iron compact. The difference is particularly visible in Fig.1b when plotting the dimensional change as a function of the temperature; while the contraction amounts to about 0.25 % relative to the initial length, the expansion is rather in the range of 0.6 %. This asymmetry also resulted in a virtual absence of overall shrinkage during the sintering process; the sintered bars were even a few μm longer than the green ones, despite the clearly visible shrinkage during the isothermal sintering period at 1300°C .

Since this phenomenon has not been reported before, despite the long tradition of sintering plain iron in PM, it was first suspected that the effect might somehow be linked to the die wall lubrication. Therefore, specimens were compacted with the common admixed lubricant and then dewaxed in H_2 and N_2 , respectively. The resulting dilatometric runs in the vacuum, however, showed virtually the same effect as given in Fig.1, i.e. a pronounced asymmetry in the phase transformation. This showed clearly that there is virtually no effect of the lubricating procedure, and also no effect of a pre-treatment in a reducing or inert atmosphere, at least if the treatment is carried out at temperatures below the α - γ transformation.

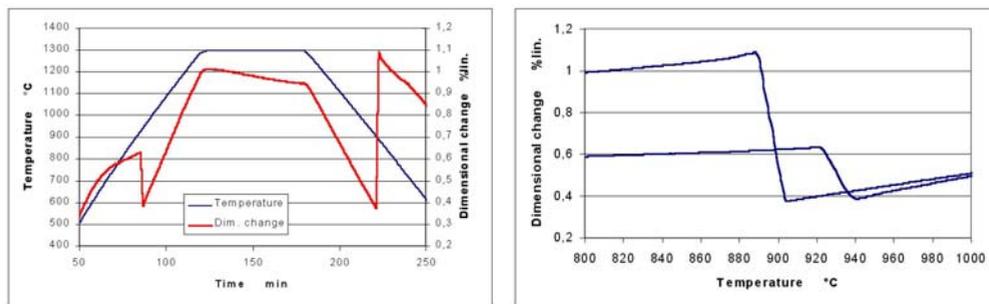
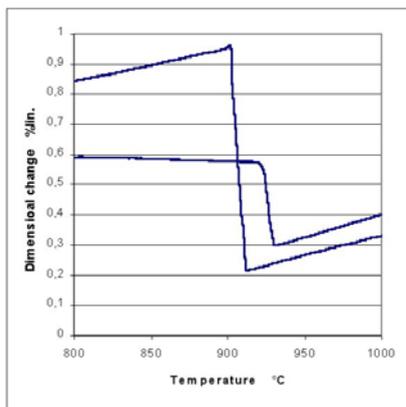


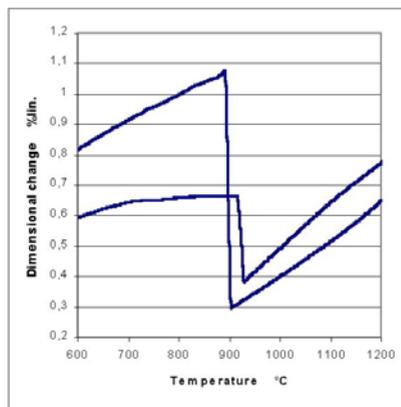
Fig.1. Dilatometric graphs of plain iron compact pressed at 600 MPa. Heating/cooling $10 \text{ K}\cdot\text{min}^{-1}$; $T_{\text{max}} = 1300^\circ\text{C}$, rotary pump vacuum.

One possible explanation for the asymmetry was the contribution of gas phase transport in or around the sintering contacts to the transformation. In this case, it was expected that a slower heating and esp. cooling rate would enhance the effect while more rapid temperature changes would rather suppress it. Therefore, the dimensional effect of the phase transformation was also investigated at heating/cooling rates varying between 1 and $25 \text{ K}\cdot\text{min}^{-1}$. Here it showed that regardless of the heating and cooling process, the pronounced higher expansion during cooling compared to the contraction during heating was measured reproducibly, as given in Fig.2.

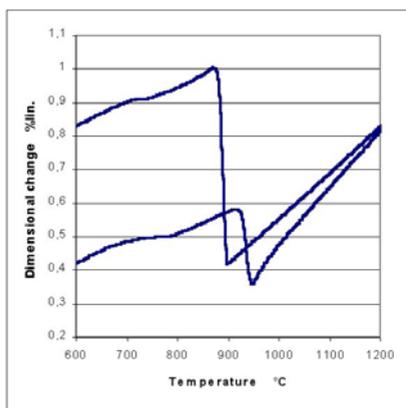
Metallographic investigation showed that the structure of the specimens had become extremely coarse during the sintering process, as clearly visible from Fig.3. Grains of up to several mm length had been generated; surprisingly this grain growth was apparently not linked to the cooling rate as might have been expected; cooling at 10 and $1 \text{ K}\cdot\text{min}^{-1}$ resulted in similarly coarse grain sizes. This phenomenon is rather surprising for porous sintered iron since it is generally established that the pores inhibit grain growth during sintering, and except at very high density levels, the grains usually cover the area of one original powder particle each, i.e. they exhibit about 60 to $100 \mu\text{m}$ diameter [16, 17]. Here, in contrast, the area of the grains is several orders of magnitude larger.



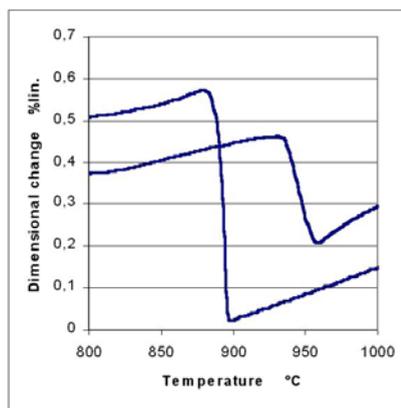
a) +/- 1 K.min⁻¹



b) +/- 3 K.min⁻¹

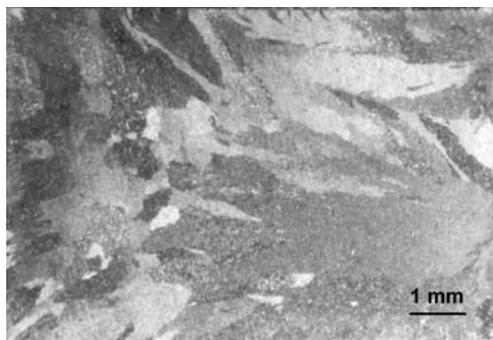


c) +/- 20 K.min⁻¹

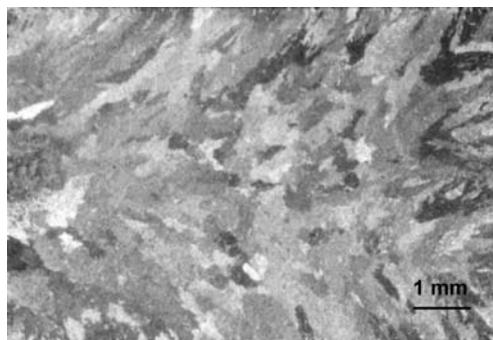


d) +/- 25 K.min⁻¹

Fig.2: Dilatometric graphs of plain iron compact pressed at 600 MPa. Varying heating / cooling rates; $T_{max} = 1300^{\circ}C$, 1 hr isothermal, rotary pump vacuum.



a) heating/cooling rate 10 K.min⁻¹



b) heating/cooling rate 1 K.min⁻¹

Fig.3. Macrostructure of iron compacts as in Fig.2; cross sections, polished and 60 s Nital etched.

Influence of the compacting pressure / green density

With respect to the grain growth phenomenon it was expected that the porosity, i.e. the green density, of the specimens would play a major role towards grain growth and unsymmetrical phase transformation. Therefore green compacts were prepared at pressures varying from 200 to 1000 MPa and sintered in the dilatometer as described above. The dimensional changes measured during the phase transformations are given in Table 1.

Tab.1 Dimensional change during ferrite-austenite phase transformation of plain iron powder compacts. Heating/cooling rate +/-10 K.min⁻¹, sintering 1 h 1300°C isothermal.

| Starting material | Comp. Pressure MPa | Green density g.cm ⁻³ | Initial vacuum (room temp.) mbar | Dim. change α - γ (heating) % linear | Dim. change γ - α (cooling) % linear |
|-------------------------------|--------------------|----------------------------------|----------------------------------|--|--|
| ASC 100.29 | 200 | 5.684 | 6.10 ⁻³ (rotary p.) | -0.26 | +0.23 |
| ASC 100.29 | 300 | 6.215 | 6.10 ⁻³ | -0.25 | +0.28 |
| ASC 100.29 | 400 | 6.613 | 6.10 ⁻³ | -0.25 | +0.35 |
| ASC 100.29 | 500 | 6.918 | 6.10 ⁻³ | -0.25 | +0.48 |
| ASC 100.29 | 600 | 7.127 | 6.10 ⁻³ | -0.27 | +0.63 |
| ASC 100.29 | 800 | 7.374 | 6.10 ⁻³ | -0.28 | +0.74 |
| ASC 100.29 | 1000 | 7.533 | 4.10 ⁻³ | -0.27 | +0.95 |
| ARMCO IRON | - | 7.87 | 6.10 ⁻³ (rotary p.) | -0.30 | +0.31 |
| ASC 100.29 | 600 | | 5.10 ⁻⁵ (turbo p.) | -0.26 | +0.63 |
| As above, 2 nd run | 600 | | 2.10 ⁻⁶ (turbo p.) | -0.26 | +0.61 |

When comparing the dilatometric graphs of these bars, the dimensional changes caused by the phase transformation were found to strongly depend on the compacting pressure (see Table 1): the higher the pressure, and thus the green density, was, the more asymmetrical the phase transformation showed to be, insofar as the expansion during the γ - α transformation in the cooling section of the cycle was significantly larger than the contraction caused by the α - γ transformation in the heating cycle.

This can be seen to an advantage in Figs.4a-c, depicting dilatometric graphs of specimens compacted at 200, 500, and 800 MPa. The entire graphs are shown, and the similarity of the curves is quite evident until the onset of the transformation in the cooling period, at which the total expansion was larger the higher the green density of the specimen was although the transformation takes place at virtually the same temperature. It is well visible that here the contraction during transformation is rather similar for all materials, being in the range of about 0.25...0.3 % linear, which is in reasonably good agreement with that found for Armco iron (0.31 %). If however the γ - α transformation is regarded, it stands out clearly that the expansion strongly depended on the compacting pressure. In the material compacted at 300 MPa the transformation resulted in an expansion similar to the contraction during heating. At 500 MPa compacting pressure, the expansion was about 0.5 %, i.e. double the amount found at lower density, and the specimen compacted at 800 MPa exhibited an expansion of about 0.75 %. i.e. three times that of the low density material.

If the absolute values of the dimensional change during the phase transformation – ignoring the direction of length change - are plotted as a function of the green density (Fig.5), a distinct trend can be observed: while the α - γ transformation during heating results in about 0.25 % shrinkage regardless of the green density, the γ - α transformation shows a pronounced increase of the expansion with higher green density that seems to grow

exponentially towards full density. In order to compare this behaviour to that of really fully dense materials, parallel tests were carried out with Armco iron bars of the same length; here it showed however that a virtually symmetrical phase transformation occurred, as given in Table 1. This indicates that the cause for the asymmetrical transformation seems to be linked to the particular microstructure for the powder compacts, i.e. the pores and/or the sintering contacts.

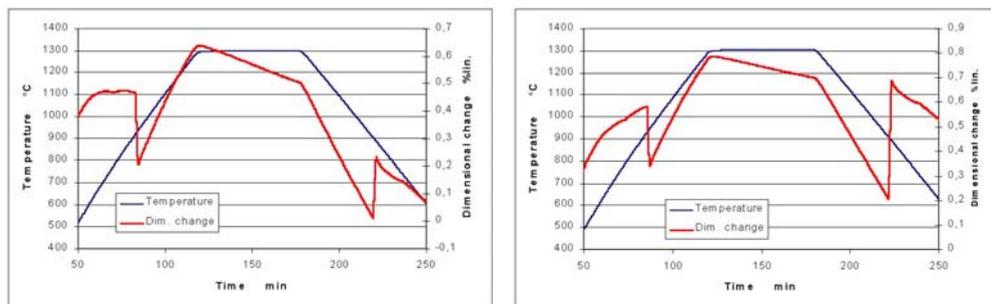


Fig.4. Dilatometric graphs of plain iron compacts with varying green density. $T_{max} = 1300^{\circ}C$, rotary pump vacuum

- ↻ a) Compacted at 200 MPa
- ⤴ b) Compacted at 500 MPa
- ⤵ c) Compacted at 800 MPa

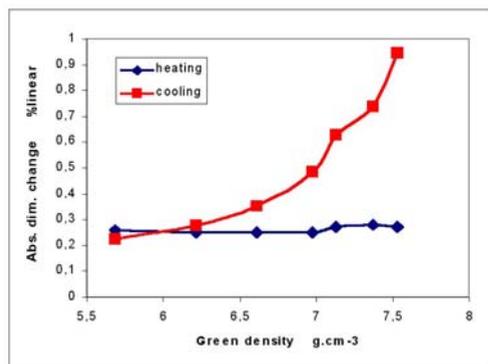
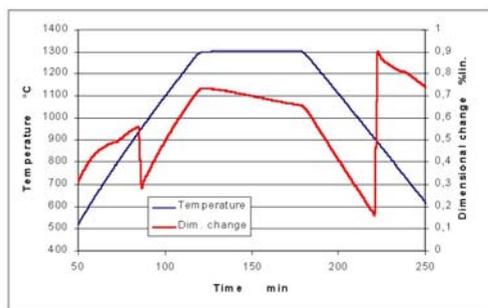


Fig.5. Absolute values of the dimensional change within α - γ / γ - α phase transformation during vacuum sintering of plain iron with varying green density.

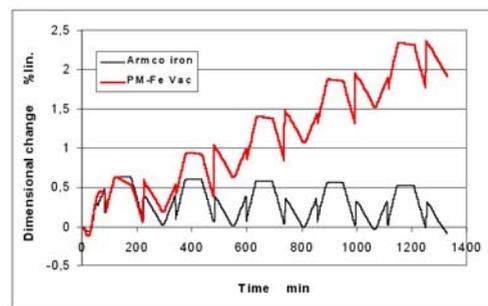


Fig.6. Dilatometric graphs for cyclic sintering of Fe powder compact ($p_c = 600$ MPa) and Armco iron. $T_{max} = 1300^{\circ}C$, rotary pump vacuum.

One possible reason might be supposed to be the slight oxygen pickup of the specimens in the rotary pump vacuum, which is not of very high quality; this oxygen might affect the transformation behaviour. In order to check this hypothesis, identical test

runs were also performed using a turbomolecular pump that resulted in a significantly better vacuum in the dilatometer (first run: about $5 \cdot 10^{-5}$ mbar, second run: $2 \cdot 10^{-6}$ mbar initial pressure as compared to $6 \cdot 10^{-3}$ mbar using the rotary pump). However, as shown in Table 1, the results were quite the same as those obtained in a standard rotary pump vacuum. This can be taken as an indicator that oxidation is probably not the reason for this behaviour since in this case a better vacuum should at least result in less pronounced asymmetry.

When comparing the results of the runs in high quality vacuum, it was rather surprising that there is virtually no difference in the transformation between the first and the second run, since some sort of "saturation" would have been expected, i.e. the second γ - α expansion would be lower than the first one. In order to check if there is such a "saturation effect", cyclic runs were carried out in the dilatometer. As a parallel, atomized iron powder compacted at 600 MPa and solid Armco iron were tested.

The resulting graphs for 5 cycles each are shown in Fig.6. The reference material Armco iron shows a slight shrinkage, possibly creep caused by the pressure of the dilatometer pushrod. The powder compact, in contrast, exhibits consistent expansion caused exclusively by the differences between α - γ and γ - α transitions, respectively (during isothermal sintering some shrinkage is observed even during the fifth cycle). The values for the expansion differ slightly between the cycles, but in any case there is no indication of a "saturation effect" of the asymmetrical transformation, and the length of the compact consistently increases. This swelling of the sintered bars could also be easily determined from the length after the dilatometric run and was even visible when putting the cyclically sintered and a green compact side by side, the former having grown about 1 mm.

When the microstructures of the sintered samples were investigated, it showed that the grain size in the cyclically sintered iron bar was virtually identical to that of the single sintered one, i.e. it was as coarse as shown e.g. in Fig.3a but not coarser. This indicates that the grain growth is a phenomenon that occurs rather parallel to the unsymmetrical expansion but does not cause it; otherwise cyclic sintering, which results in consistent expansion, would also result in further consistent grain growth.

Influence of the atmosphere and of carbon

The reason for this transformation effect and the grain growth phenomenon was not clear. Possible explanations could be an effect of chemistry – i.e. of impurities - in the sintering contacts, e.g. through interstitials such as C, N, or O, or of a gas phase transport mechanism through which iron atoms are introduced into the contacts, although in this case it is not clear why this occurs exclusively during the γ - α transformation and neither during the respective α - γ transformation nor during isothermal sintering at 1300°C under which conditions the vapour pressure of Fe or any Fe compound should be drastically higher than at 900°C. If the former explanation held true, sintering in atmospheres that contained interstitial atoms would enhance the effect; if the latter was correct, any atmosphere would suppress it.

In order to check these assumptions, dilatometric runs were performed with powder compacts pressed at 600 MPa, which material previously had shown distinctly asymmetrical transformation (see Fig.1). Sintering was carried out in static atmospheres of varying composition, both low pressures of air and varying pressures of N₂ and Ar being tested. The resulting values for the dimensional changes during both phase transformations are shown in Table 2.

Tab.2. Dimensional change during ferrite-austenite phase transformation of plain iron specimens sintered in different (stationary) atmospheres. Water atomized iron powder, compacted at 600 MPa. Heating/cooling rate ± 10 K.min⁻¹, sintering 1 h 1300°C isothermal.

| Atmosphere | Initial pressure (room temp.) mbar | Dim change α - γ (heating) % linear | Dim. change γ - α (cooling) % linear |
|------------------------|------------------------------------|---|--|
| Air | 0.1 | -0.28 | +0.48 |
| Air | 0.2 | -0.24 | +0.30 |
| Air | 50 | -0.24 | +0.28 |
| N ₂ 99.999% | 0.2 | -0.26 | +0.29 |
| N ₂ 99.999% | 50 | -0.22 | +0.25 |
| N ₂ 99.999% | 600 | -0.27 | +0.28 |
| Ar 99.999% | 600 | -0.23 | +0.57 |

As can be seen from the table, the transformation is more symmetrical the higher the partial pressure of air is. For sintering in N₂, the transformation is virtually symmetrical regardless of the pressure. A surprising behaviour has been encountered with Ar: here it showed that the transformation is not quite as asymmetrical as would be the case in vacuum (see Table 1); however, there is still a rather pronounced difference between the transformations in the heating and cooling sections, respectively.

In order to study these effects in more detail, cyclic sintering was done as described above, the atmospheres being 600 mbar N₂ and Ar each (of 99.999 % purity). The graphs are shown in Fig.7; here it showed that in the case of Ar, apparently some "saturation effect" takes place. In Fig.8 the γ - α expansion is shown as a function of the cycle no; for reference purposes, the cyclic runs in vacuum and with Armco iron given in Fig.6 should be compared. Here it can be seen that sintering in N₂ results in virtually the same stable behaviour as does cycling of Armco iron. Cyclic sintering in vacuum results in slightly varying but persistent expansion during each transformation, while in the case of sintering in Ar, the expansion decreases and at the 3rd cycle attains the level of Armco iron and of sintering in N₂, indicating a sort of "saturation" effect.

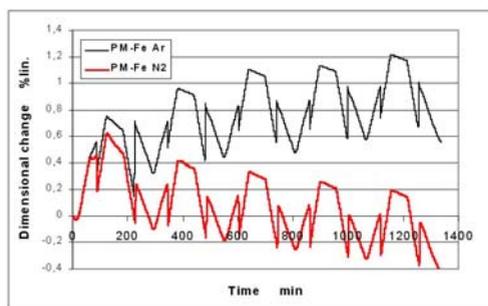


Fig. 7. Dilatometric graphs for cyclic sintering of Fe powder compacts ($p_c = 600$ MPa) in argon and nitrogen, respectively.
 $T_{max} = 1300^\circ\text{C}$.

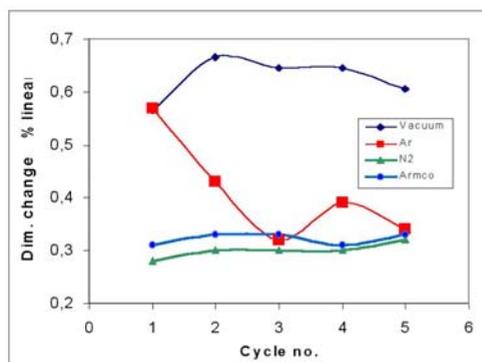


Fig. 8. γ - α expansion during cyclic sintering of powder compacts in different atmospheres as a function of the cycle no. Reference: Armco iron.

In order to assess the effect of carbon, which not only changes the transformation behaviour but also acts as a reducing agent, sintering runs were performed with compacts containing different amounts of carbon. Here it showed that the effect observed with plain iron disappears already at comparatively low carbon levels. While at 0.05 % C the cooling transformation is still significantly more pronounced than the heating one, at 0.1 % C the differences tend to level out, as can be seen from Fig.9. Although the exact value for the contraction/expansion is more difficult to assess for Fe-C than it is for Fe, since the transformation occurs within a wider temperature range – which phenomenon can to some extent be alleviated by taking values from a second dilatometric run, the disappearance of the asymmetry can be clearly seen from the net dimensional change of the specimens during sintering which for the Fe-C compacts is always negative, i.e. the specimens shrink, while for plain Fe the net expansion caused by the asymmetrical phase transformation is evident from the dimensions after sintering.

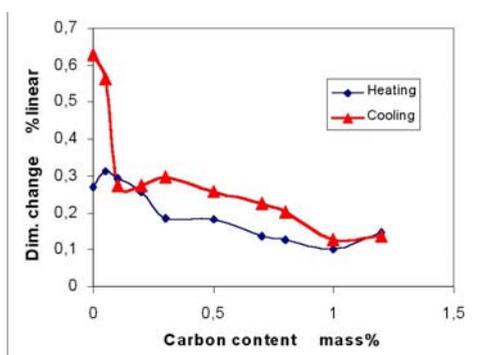
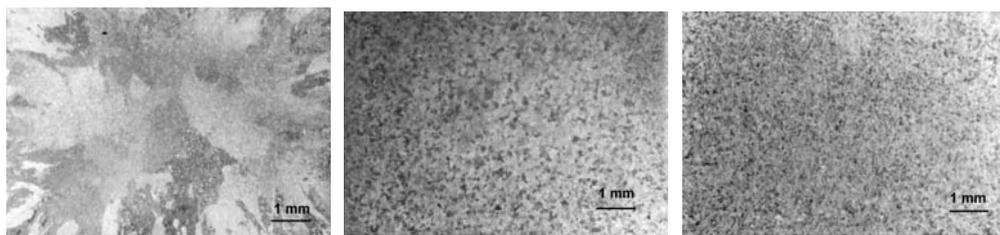


Fig.9. Contraction/expansion during phase transformation in Fe-x %C as a function of the carbon content. $T_{\max} = 1300^{\circ}\text{C}$, rotary pump vacuum.



a) plain Fe, vacuum, 5 cycles b) plain Fe; 600 mbar N_2 ; 5 cycles c) Fe-0.1%C, vacuum, 2 cycles

Fig.10. Macrostructure of sintered bars compacted at 600 MPa, cyclically sintered in the dilatometer. $\pm 10 \text{ K}\cdot\text{min}^{-1}$, $n \times 1 \text{ h } 1300^{\circ}\text{C}$. Nital etched.

The microstructures in this case are once more in good agreement with the transformation behaviour. While for the vacuum sintering runs, grain coarsening is excessive (Fig.8a), sintering in N_2 or in air results in a fine, equiaxed structure which would be expected for any sintered iron (Fig.8b). The same holds for the material Fe-0.1 % C; also here the microstructure is drastically finer than in the carbon-free compacts sintered under the same conditions, and is similar to that found after sintering in N_2 (Fig.8c).

The results indicate that there seems to be some influence of the residual oxygen in the sintered compacts. This is also corroborated by the effect that sintering of plain Fe in H₂ was never reported or observed to result in expansion [18]. In the materials with very low C content, reduction of the oxides is not completely attained due to an insufficient reducing agent being present, and therefore the behaviour after the isothermal sintering is still similar to that of plain iron. At higher C contents, a more effective deoxidation should result in cleaner sintering contacts. Fracture surface analysis e.g. by Auger electron spectroscopy might be more helpful; however, fractographic techniques have yet to be developed for the material that expose the former interparticle contacts during fracture with all the materials investigated in order to enable reliable comparison; AES investigations in materials with varying fracture modes tend to give misleading results [19].

However, this hypothetical effect of oxygen is apparently strongly dependent on the vacuum, indicating that some gas phase transport mechanism is effective here. Sintering at low pressures of air offers more oxygen; however, the asymmetrical phase transformation does not occur in this case. On the other hand, sintering in a high purity vacuum, in which case hardly any oxygen is introduced through the gas phase, results in pronounced asymmetry and in excessive grain growth. The results of the sintering runs in argon do not quite fit in here, since in this special case asymmetry was observed at least initially despite considerable gas pressure. In any case, these discrepancies indicate that further investigations are necessary to determine the mechanism of this surprising asymmetry of the phase transformation.

CONCLUSIONS

Vacuum sintering of plain iron compacts results in a pronounced asymmetry of the dimensional changes during the α - γ / γ - α transition, the expansion during cooling being significantly more pronounced than the preceding contraction during heating. During cyclic sintering this results in marked growth of the specimens. It is associated by excessive grain growth in the specimens, grains in the range of mm being observed.

The asymmetry strongly depends on the green density, being more pronounced at higher density levels. The contraction during heating is virtually unaffected by the density, while the expansion during cooling increases with higher density and e.g. at a density of 7.4 g.cm⁻³ attains about the threefold value as at 6.2 g.cm⁻³. Fully dense Armco iron, in contrast, results in symmetrical transformation

The asymmetry is observed when sintering in a reasonable vacuum (initial: $p_0 < 10^{-2}$ mbar) while sintering under low pressures of air tends to suppress the asymmetry. Sintering in N₂ results in symmetrical phase transformation regardless of the N₂ pressure; in both cases, the grain growth is also suppressed. In Argon, cyclic sintering reveals asymmetrical transformation in the first cycles but then the transformation approaches that found e.g. with N₂.

The reason for this surprising transformation behaviour is not yet clear; it can be suspected that the remaining oxygen plays a major role since the presence of carbon – acting as a reducing agent – eliminates this effect, also sintering in H₂ reportedly does not result in asymmetrical transformation. However, further investigations will be necessary to reveal the cause for the asymmetrical phase transformation in sintered iron.

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REFERENCES

- [1] Handbuch der Sonderstahlkunde. Ed. Houdremont. 3rd ed. Springer, 1956
- [2] Krauss, G.: Steels - Heat Treatment and Processing Principles. Materials Park OH : ASM, 1990
- [3] Dautzenberg, N., Dorweiler, HJ.: Powder Metall. Int., vol. 17, 1985, p. 279
- [4] Danninger, H.: P/M Science & Technol. Briefs, vol. 1, 1999, no.5, p. 192
- [5] Danninger, H., Gierl, C., Leitner, G. In: Proc. 2000 Powder Metall. World Congress, Kyoto. Part II. Eds. K.Kosuge, H.Nagai. The Japan Soc. of Powder and Powder Metall., 2001, p.943
- [6] Lenel, FV.: Powder Metallurgy – Principles & Applications. Princeton : MPIF, 1980
- [7] Hausner, HH., Mal, KH.: Handbook of Powder Metallurgy. 2nd ed. New York N.Y. : Chemical Publishing Inc., 1982
- [8] Höganäs Handbook for Sintered Components. Vol. 2. Höganäs : Höganäs AB, 1997
- [9] Matsumura, G., Tuan, WS.: Powder Metall. Int., vol. 15, 1983, no. 4, p. 188
- [10] Moyer, KH. In: ASM Handbook. Vol. 7. Materials Park OH : ASM, 1998, p. 1006
- [11] Tengzelius, J., Kvist, SA. In: Proc. P/M78 Europ. Symp. on PM, Stockholm. Vol.2. Stockholm : Jernkontoret, 1978, p. 46
- [12] Glassner, AR.: The thermochemical properties of the oxides, fluorides, and chlorides to 2500°K. U.S.Atomic Energy Comm. Rep. ANL-5750, 1957
- [13] Danninger, H., Leitner, G. In: Proc. Conf. Sintering '95. Eds. R.M.German, G.L.Messing, R.G.Cornwall. New York-Basel-Hongkong : Marcel Dekker, 1996, p.165
- [14] Danninger, H., Gierl, C., Leitner, G., Jaenicke-Rößler, K. In: Proc. PM'98 Powder Metall. World Congress & Exhib., Granada. Eds. V.Arnhold, A.Romero. Vol.2. Shrewsbury : EPMA, 1998, p. 342
- [15] Danninger, H., Gierl, C., Kremel, S., Leitner, G., Jaenicke-Roessler, K., Yu, Y.: Powder Metall. Progress, vol. 2, 2002, no.3, p. 125
- [16] Jangg, G., Drozda, M., Eder, G., Danninger, H.: Powder Metall. Int., vol. 16, 1984, no.2, p. 60
- [17] Stojmenov, A.: PhD thesis. Wien : TU, 1985
- [18] Pieczonka, T.: personal communication
- [19] Danninger, H., Atari, A., Lux, B., Kny, E., Tschulik, A.: Fresenius Z. Anal. Chemie, 1989, p. 333