Influence of ageing on the texture development of tensile-deformed duplex steel

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Remanit dual-phase stainless steel in the annealed state was studied after 20% tensile deformation in 0, 45 and 90° with respect to the rolling direction and subsequent ageing at 475 and 850 °C for 3 h, and water quenched for texture development in ferrite and austenite phases by ODF analysis. It is concluded that 20% tensile deformation leads to deformation of both ferrite and austenite phases. The degree of deformation of the respective phases is dependent upon the deformation direction. Furthermore, the texture for the ferrite phase changes distinctly after ageing at 475 or 850 °C, but the texture for the austenite phase remains unaffected. Thus it may be concluded that ageing treatment leads to change predominantly of the ferrite phase.

1. Introduction

The duplex stainless steels containing ferrite and austenite phases are becoming more popular as they combine the best properties from both, i.e. pure ferritic and austenitic stainless steels. Duplex steels [1] have very good corrosion properties (including stress corrosion properties) in chloride-containing media, high tensile strength, good toughness and good weldability. Furthermore, these steels also show large anisotropy of strength in commercially produced sheets. Hutchinson *et al.* [2] concluded that this anisotropy of strength cannot be due to composite reinforcement in the duplex structure, but may be due to the texture hardening. In another study [3] the material was given surface treatment by grinding and shotpeening and as a result, a strong work hardening is observed in the austenite phase as compared to the ferrite phase. It has also been reported [4] that annealing leads to preferential recrystallization of the ferrite phase, and ageing at 475 °C produces changes mainly in the ferrite phase. Furthermore, upon ageing at 850 °C, a sigma phase is formed at the cost of the ferrite phase [5]. Tensile deformation of hot-rolled sheets leads to deformation of both phases, but the degree of deformation is dependent upon the deformation direction.

Studies were made of annealed hot rolled Remanit sheets after tensile deformation, to obtain information about the relative deformation of ferrite and austenite phases. The influence of ageing on the texture of tensile-deformed ferrite and austenite phases were also studied.

2. Experimental procedure

The chemical composition of $X_2CrNiMoN$ 225 (REMANIT, 1.4462) used in this investigation is given in Table I.

This material showed normal and planar anisotropy, and has been described in detail elsewhere [4]. The material was annealed and has further been referred to as "as-received sample". The tensile samples were prepared from as-received material in 0, 45 and 90° with respect to the rolling direction. The samples were deformed on a tensile machine by 20% at constant strain rate. Some of these samples were aged after tensile deformation. For each ageing experiment, a new sample was deformed. The annealing and ageing conditions are presented in Table II. Texture measurements [6, 7] were carried out on the etched surface of various samples after removing a surface layer of a few μm (assuming that annealing leads to a homogeneous texture). Using CoK_α radiation, three incomplete pole figures (2 0 0), (2 1 1), (2 2 0) for ferrite phase and (2 0 0), (2 2 0), (3 1 1) for austenite phase were

TABLE I Chemical composition of REMANIT (weight %)

C	Si	Mn	P	S	Cr	Mo
0.024	0.57	1.66	0.023	0.003	22.16	3.18
Ni	Al	B	Co	Cu		N
5.34	0.006	0.004	0.19	0.15		0.13

TABLE II Heat treatment conditions

Treatment	Conditions
Annealing	1030 °C/30 min/water quenched
Ageing	850 °C/3 h/water quenched
Ageing	475 °C/3 h/water quenched

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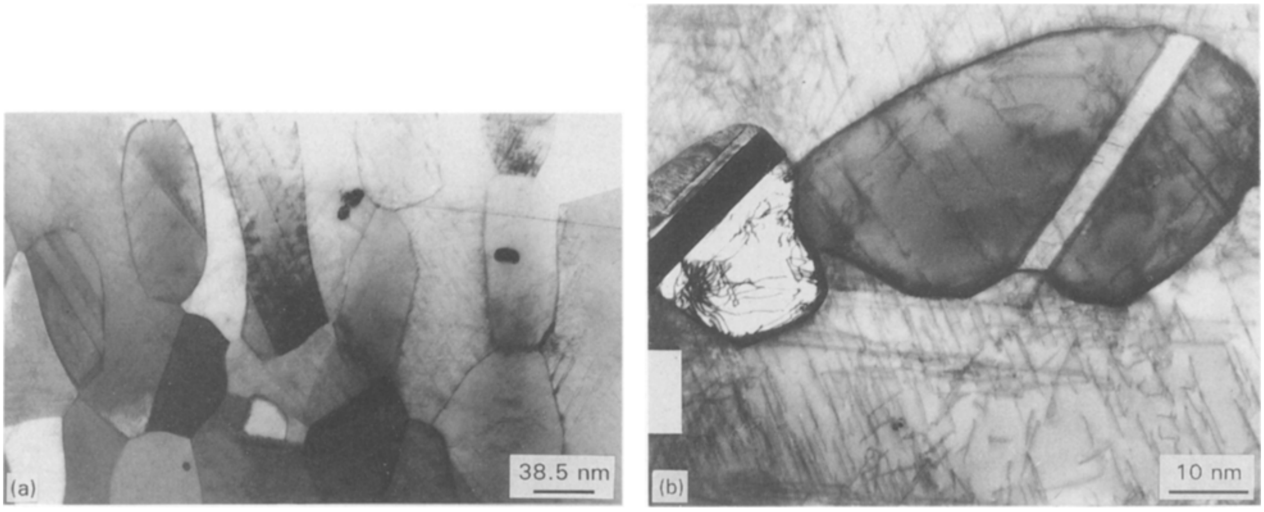


Figure 1 Microstructure of the as-received (annealed) sample in longitudinal plane.

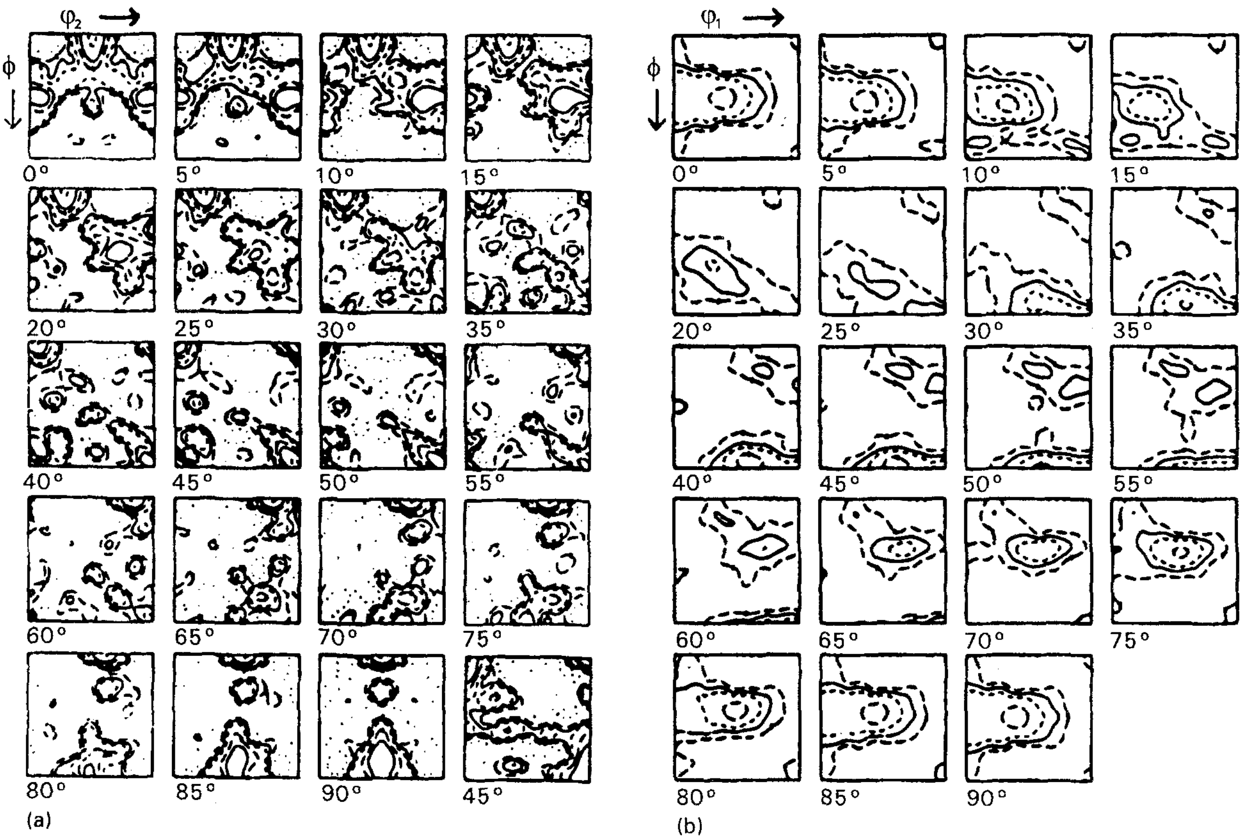


Figure 2 Presentation of even ODF by isolines corresponding to multiples of random orientation density for as-received sample. (a) Constant φ_1 section along with $\varphi_2 = 45°$ for the ferrite phase; (b) constant φ_2 section for the austenite phase.

measured (maximum tilt angle 70°). From these pole figures, the ODF was calculated using the series expansion method up to $L = 22$ for the even part, because there was no significant difference between complete and even ODF.

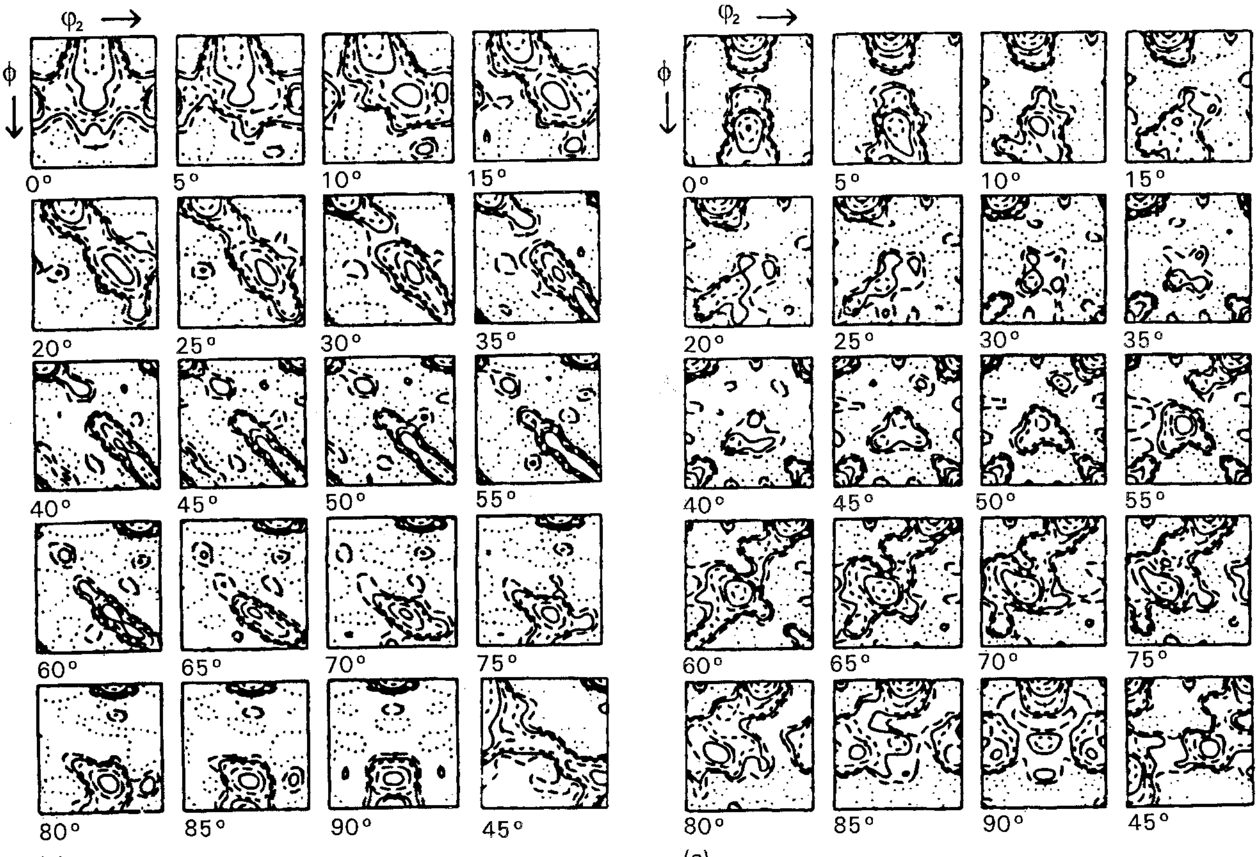
3. Results

The microstructure of the as-received (annealed) material is shown in Fig. 1. Here the austenite phase appears to be recrystallized, and small spherical precipitates are also observed. These precipitates, according to the morphology, were identified as Cr_2N [8].

Fig. 2a shows the even ODF for the ferrite phase of the as-received (annealed) sample. This shows an ideal texture component at $(0\,0\,1)\{1\,1\,0\}$ and possesses an orientation density of 6.4 times random. Fig. 2b shows the even ODF for the austenite phase of the as-received sample. This shows a weak ideal texture component at $(0\,0\,1)\{1\,0\,0\}$ with an orientation density of 1.5 times random.

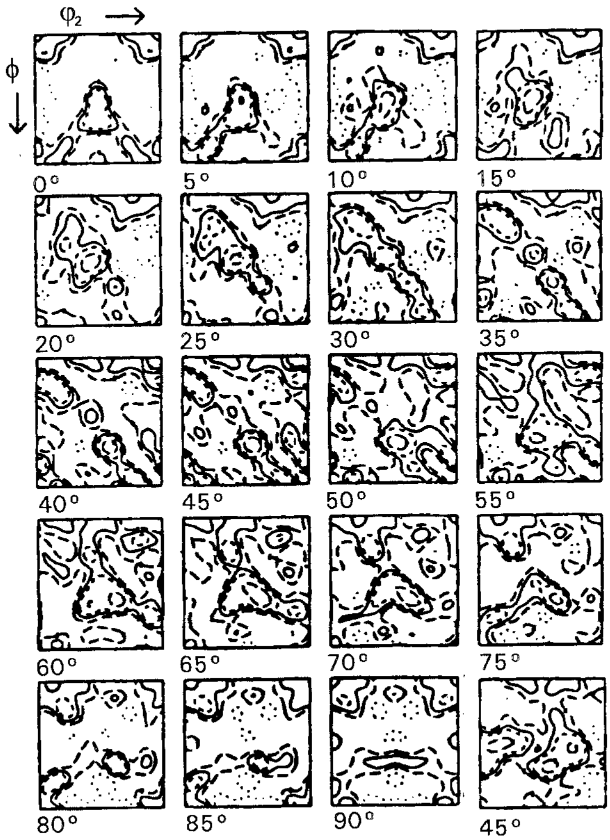
3.1. Ferrite phase

As mentioned above, the tensile samples were prepared in different directions from as-received material,



(a)

(c)



(b)

Figure 3 Even ODF for ferrite phase after tensile-deformation in (a) rolling, (b) 45° and (c) transverse directions.

and were subjected to 20% tensile deformation at a constant strain rate. These samples were used for texture investigations. Fig. 3 shows the constant φ_1 section along with $\varphi_2 = 45°$ for the ferrite phase of deformed samples. These ODFs indicate remarkable texture differences in three investigated directions. The ODF of 20% tensile deformation in the rolling direction (Fig. 3a) and in the transverse direction (Fig. 3b) indicates a somewhat strong ideal texture component at (0 0 1){1 1 0} with a constant orientation density of 7.5 and 9.4 times random, respectively. Thus the orientation density for the ideal texture component at cube-on-edge has been enhanced by 1.5 times in the rolling and transverse directions as compared to the as-received sample, but it has disappeared in the samples of 45° direction.

To gain an impression of quantitative texture development in the ferrite phase during tensile deformation, the orientation densities along the skeleton lines have been plotted for three directions, i.e. rolling, 45° and transverse, along with the value for the as-received sample. Fig. 4a shows the intensity variation along RD//{1 −1 0}. The as-received sample showed only one maximum for (0 0 1){1 −1 0} with an orientation density of 6.4 times random. Deformation in the rolling direction showed two maxima located at (0 0 1){1 −1 0} and (1 1 2){1 −1 0} + 10° with intensity values 7.5 and 5.5 times random, respectively. Deformation in 45° also showed one maximum located at (1 1 2){1 1 0} + 10° with intensity value 2.8 times random. Deformation in the transverse direction also indicated only one maximum which is located at (0 0 1){1 −1 0} and has an orientation density value of 9.4 times random. Fig. 4b shows the

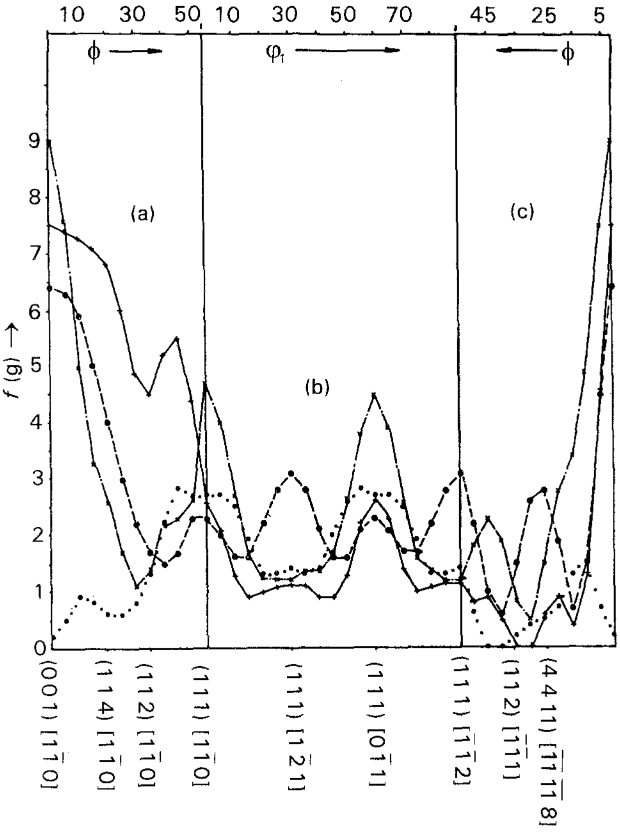


Figure 4 Orientation densities along the skeleton lines for the ferrite phase of tensile-deformed samples, along with ferrite phase of as-received sample. +, Rolling; ●, 45°; ×, transverse directions; ⊙, as-received.

intensity variations along the ND//(1 1 1). Here deformation in all the three directions showed only one maximum at (1 1 1){0 −1 1}, which was also observed in the as-received sample and had approximately the same orientation density. However, other maxima at (1 1 1){1 −2 1} present for the as-received material has disappeared in deformed samples. In Fig. 4c, the intensity variations along φ at $\varphi_1 = 90°$ and $\varphi_2 = 45°$ are plotted. Here the maximum for the as-received sample is located at (4 4 11){−11 −11 8}. It has been shifted to (1 1 1){−1 −1 2} + 10° and has an intensity value of 2.3 times the random for the transverse direction, whereas it is absent in the rolling and in the 45° direction. Thus, tensile deformation in the transverse direction develops a new texture component which is 10° away from (1 1 2){1 1 −0}, whereas the texture component at (0 0 1){1 1 0} has disappeared after tensile deformation in the 45° direction. It may also be noted that the texture component at (1 1 1) {1 −2 1} has disappeared after deformation in all the three deformation directions.

Fig. 5 shows the even ODF for the ferrite phase of tensile-deformed and subsequently aged samples at 475 °C. It is reported [9] that ageing at 475 °C leads to the embrittlement of the ferrite phase. The tensile deformation in the rolling and transverse directions, and subsequent ageing at 475 °C, leads to the development of a cube-on-edge texture component which has approximately equal orientation density in the order of 10 times random in both samples. It is interesting to note that the density of this texture component has been enhanced by 1.5 times, as compared to the as-received sample. However, after 45° deformation and ageing at 475 °C, this texture component has disappeared and a new texture component at cube–cube is registered, with a density of 4.1 times random. This

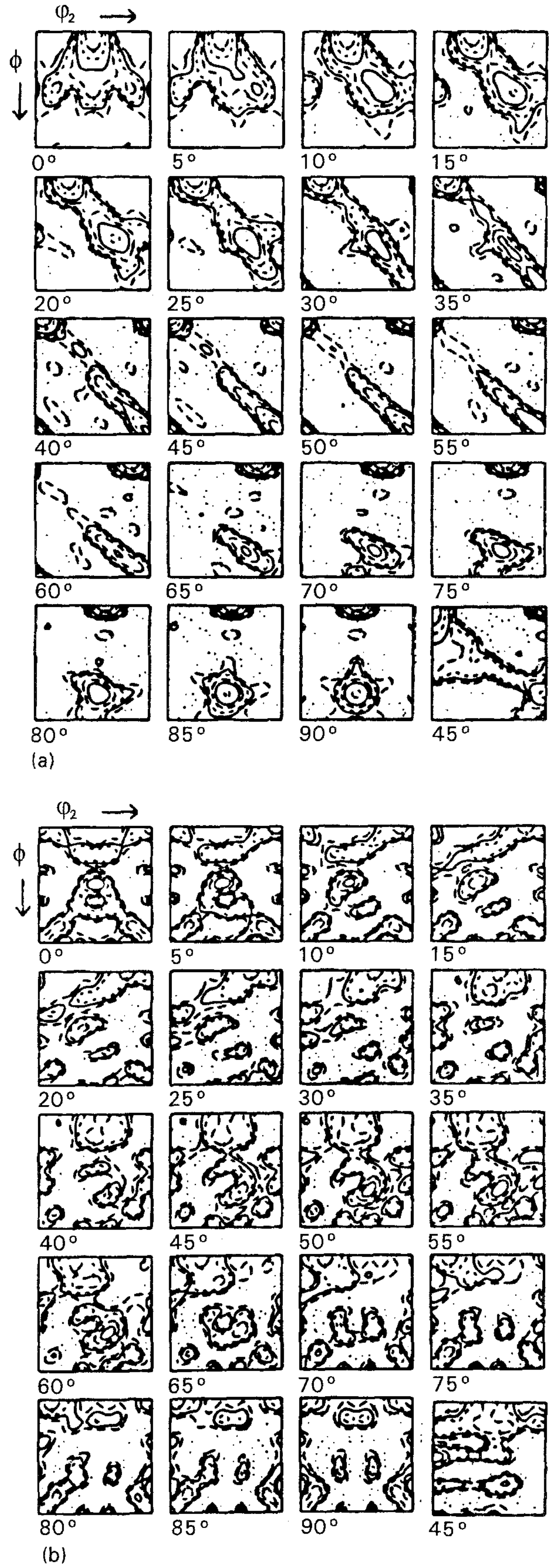


Figure 5 Even ODF for austenite phase after tensile deformation in (a) rolling, (b) 45° and (c) transverse directions.

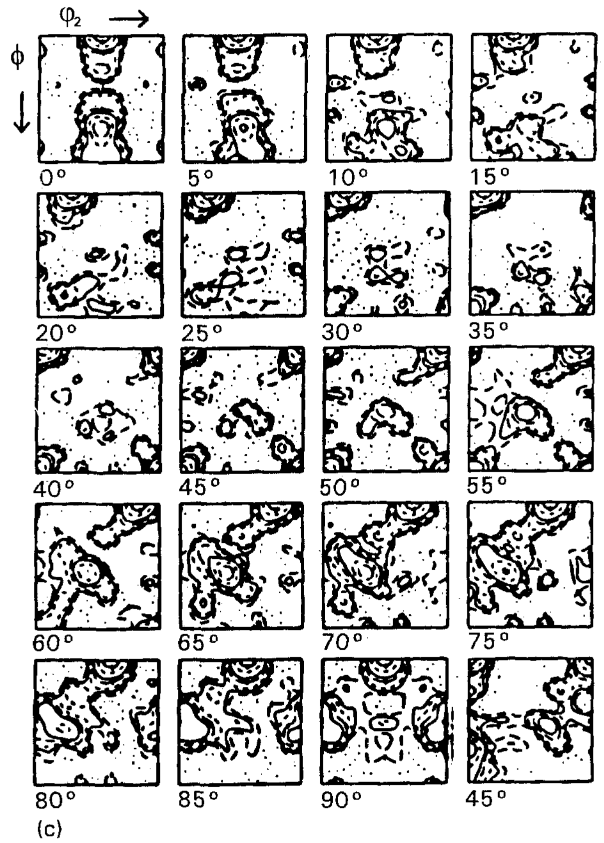


Figure 5 (Continued)

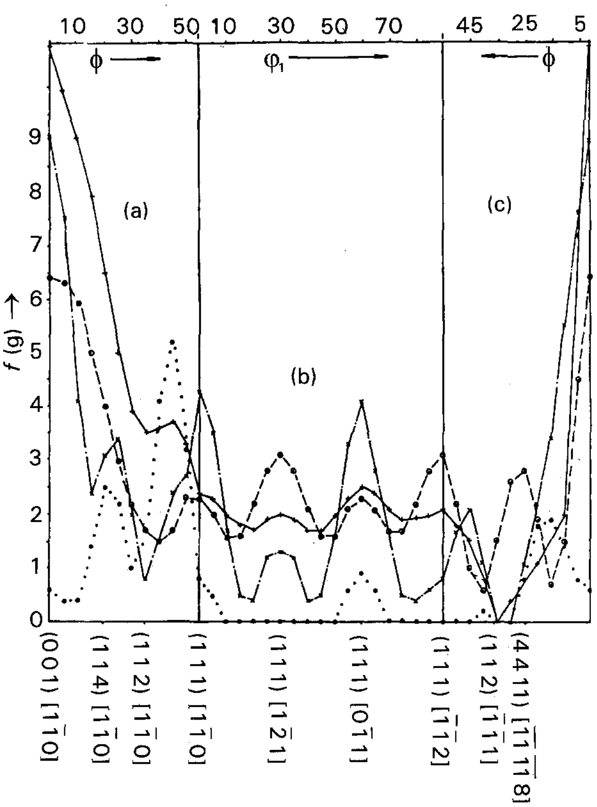


Figure 6 Orientation densities along skeleton lines for austenite phase after tensile deformation along with austenite phase of as-received sample. +, Rolling; ●, 45°; ×, transverse directions; ⊙, as-received.

ideal texture component was not present in tensile-deformed samples in the 45° direction. Thus ageing at 475 °C leads to the development of this new texture component.

The variation of orientation density along skeleton lines is presented in Fig. 6. Fig. 6a shows density variation along RD//{1 1 0}. A new texture component 10° away from (1 1 2){1 −1 0} is registered after 475 °C ageing of all the three deformation directions. It is very prominent in the rolling direction and has an orientation density of 5.2 times random. In the 45° direction, there is a slight hump with a density value of 3.7 times random, and for the transverse direction it appears as a shoulder. Another new texture component is observed 4° away from (1 1 4){1 −1 0} for 45° and transverse directions, and has an approximately equal orientation density value of the order of 3 times random. Thus it may be concluded that ageing at 475 °C leads to the development of two new texture components at (1 1 2){1 −1 0} and (1 1 4){1 −1 0} as compared to the as-received sample. However, as compared to deformed samples, only one new texture component is noted at (1 1 4){1 −1 0} for the 45° and transverse directions. The orientation density variation along ND//(1 1 1) is presented in Fig. 6b. Comparison with the as-received samples shows that the orientation density for the texture component (1 1 1){0 −1 1} has enhanced in the transverse direction and remains unchanged in the rolling direction. A very weak but new texture component at (1 1 1){1 −2 1} has been observed. However, it may be noted that the 45° direction showed no remarkable texture component in this region. The orientation density variation along φ at $\varphi_1 = 90°$ and $\varphi_2 = 45°$

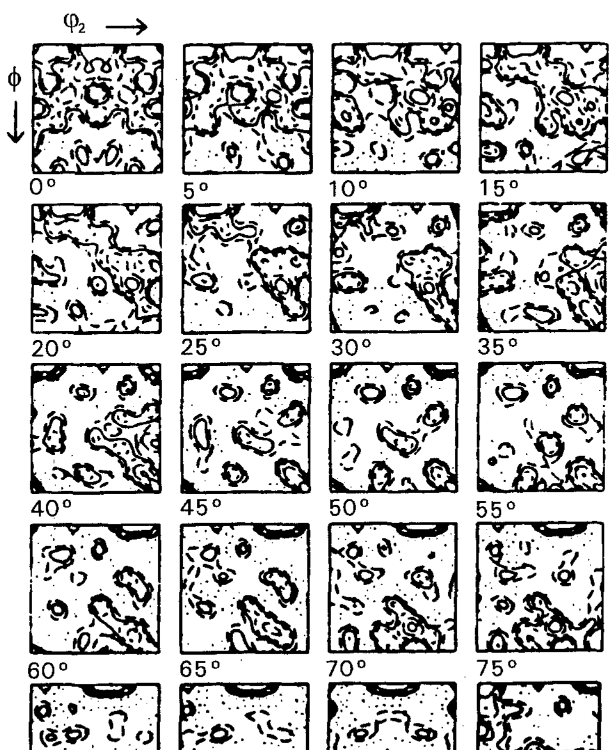


Figure 7 Even ODF for the ferrite phase of samples tensile-deformed and aged at 475 °C in (a) rolling, (b) 45° and (c) transverse directions.

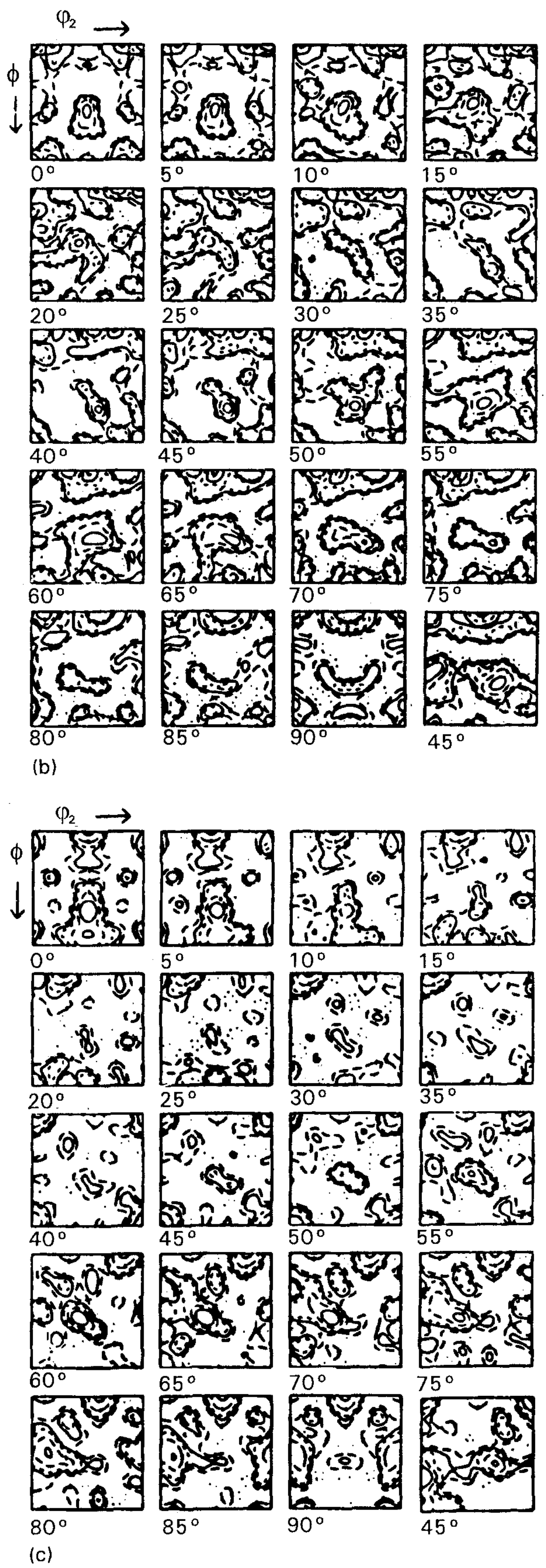


Figure 7 (Continued)

(Fig. 6c) indicated that the texture component (4 4 11) {−11 −11 8} is shifted by 10° for the 45° direction and has not been observed for the other two samples. Furthermore, a weak but new texture component is observed at (1 1 2){1 −1 −1} + 10° for the transverse direction.

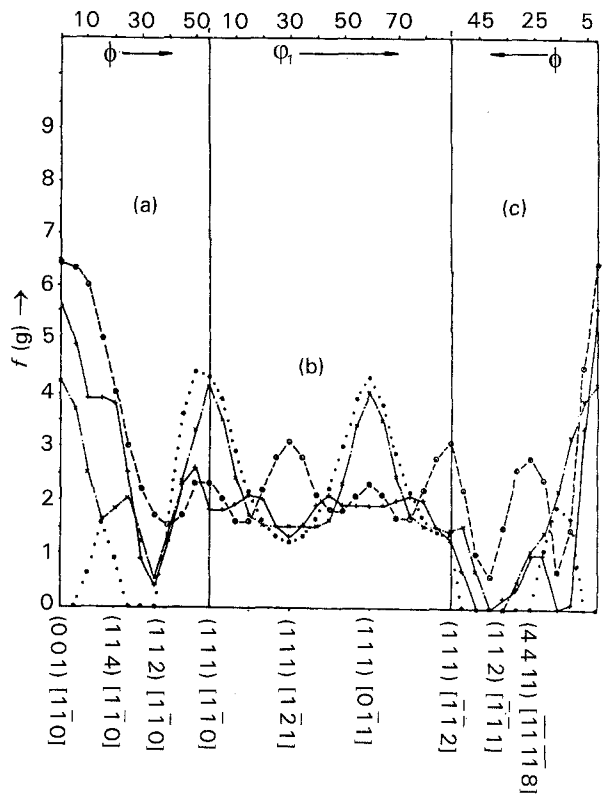
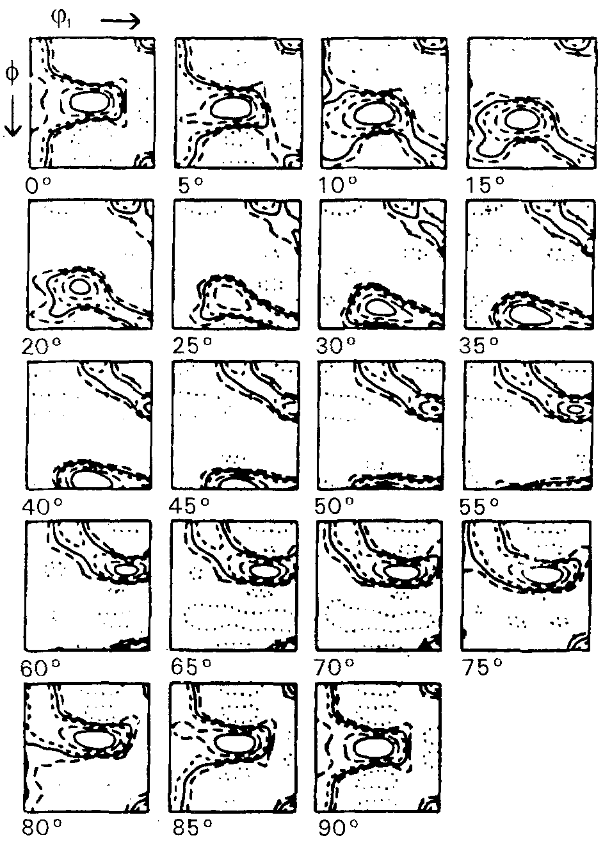


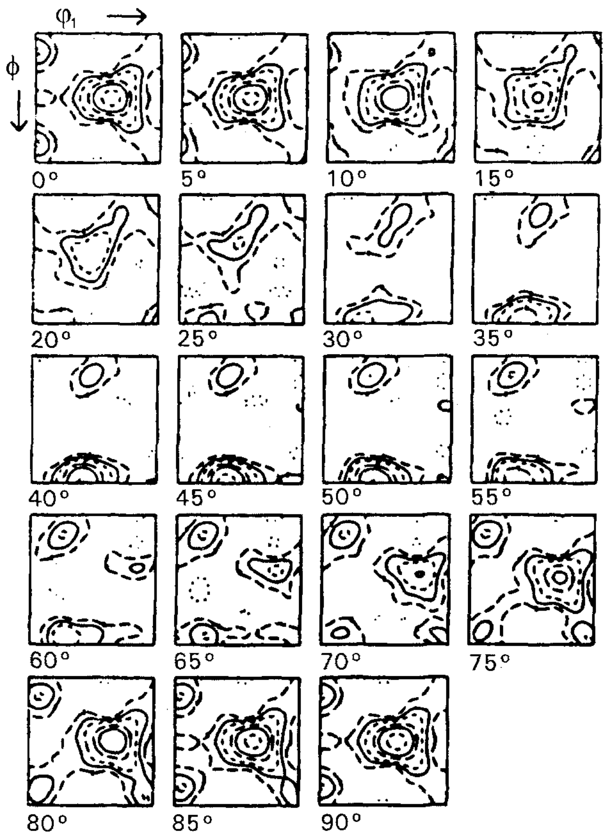
Figure 8 Variation of the orientation density along skeleton lines for the ferrite phase after tensile deformation and ageing at 475 °C in (a) rolling, (b) 45° and (c) transverse directions. +, Rolling; ●, 45°; ×, transverse directions; ⊙, as-received.

Fig. 7 presents the even ODFs for the ferrite phase deformed and subsequently aged at 850 °C. It is known that ageing at 850 °C leads to the formation of sigma phase at the grain boundaries, which in turn is responsible for the embrittlement of the material [4, 8]. Fig. 7a shows the constant φ_1 section along with $\varphi_2 = 45°$ for the ferrite phase of tensile-deformed sample in the rolling direction, and aged at 850 °C. Here the ideal texture component cube-on-edge is visible, but it is shifted by 4° and has a constant orientation density of 5.6 times random. The position and density for this texture component are unchanged as compared to the as-received sample and to deformation in the rolling direction. The tensile deformation in the 45° direction and ageing leads to the development of an ideal texture component cube–cube, and its orientation density is 4.1 times random. This is a new texture component as compared to the as-received sample, and is the same as in the 45° direction. However, tensile deformation in the transverse direction and ageing develops an ideal texture component at cube-on-edge, and its orientation density is 4.2 times random.

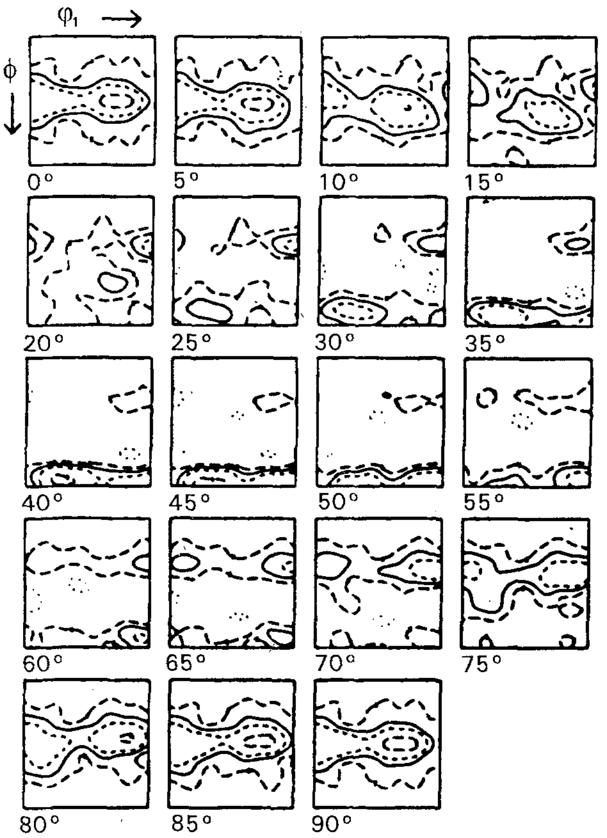
The variations in orientation density along the skeleton lines for the tensile deformed and aged ferrite phase are presented in Fig. 8. The orientation intensity variations along RD//{1 −1 0} show a maximum at (1 1 4){1 −1 0} which is shifted by 4° for all three samples and has a maximum orientation density of 3.8 times random for samples deformed in the rolling direction and aged, whereas the other two samples



(a)



(c)



(b)

Figure 9 Even ODF for the ferrite phase after tensile deformation and ageing at 850 °C in (a) rolling, (b) 45° and (c) transverse directions.

have approximately equal density and a value of 2 times random (Fig. 8a). It would be of interest to note that this texture component was absent in samples as-received, deformed and aged at 475 °C. The orientation density variation along ND//(1 1 1) has been plotted in Fig. 8b, which shows a maximum for samples deformed in the 45° and transverse directions and aged at (1 1 1){0 −1 1}; the orientation density for both samples is ~ 4.2 times random. Comparison with the as-received sample indicates that this texture component has been enhanced by two times, and the texture component at (1 1 1){1 −2 1} has disappeared after ageing. However, an almost constant orientation density in this region has been observed for samples deformed in the rolling direction and aged. Furthermore, compared with the as-received sample, the texture component at (4 4 11){ −11 −11 8} has disappeared after ageing at 850 °C.

3.2. Austenite phase

Fig. 9 shows the constant φ_2 section for the austenite phase of the tensile-deformed samples in rolling, 45° and transverse directions. The ODFs showed a weak ideal texture component at (0 0 1){1 0 0} for deformation in the rolling and transverse directions, whereas it is absent in the 45° direction.

Fig. 10 shows variations in the orientation density along the skeleton lines for the austenite phase of tensile-deformed samples, along with the as-received sample. The orientation density variations along φ at $\varphi_1 = 90°$ and $\varphi_2 = 45°$ has been plotted in Fig. 10a. Here, the as-received sample has a density maximum for (4 4 11){ −11 −11 8} with an orientation density

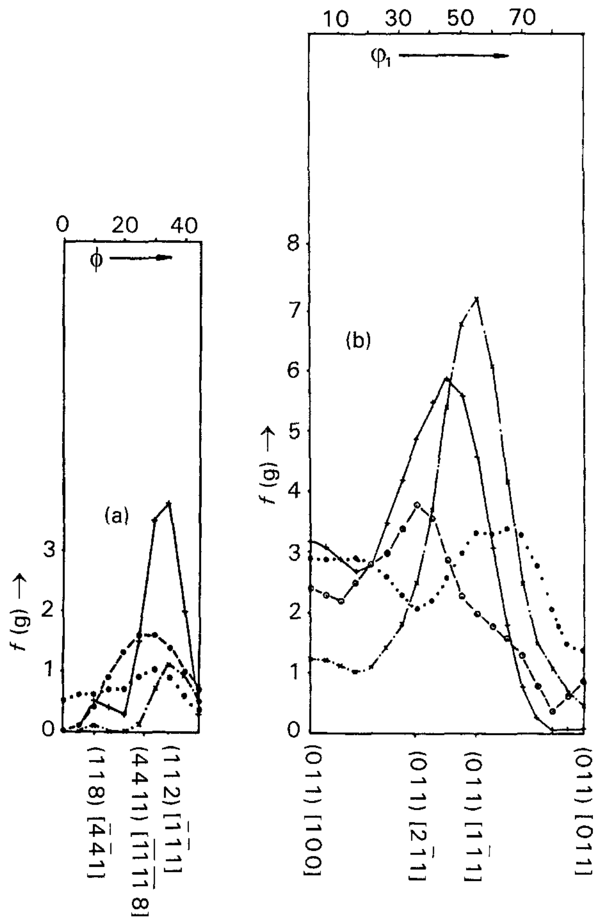


Figure 10 Orientation densities along skeleton lines for the ferrite phase of samples tensile-deformed and aged at 850 °C. Values for as-received sample are also plotted for comparison. +, Rolling; ●, 45°; ×, transverse directions; ⊙, as-received.

of 2.4 times random. After 20% tensile deformation in all three samples, this maximum has shifted to (1 1 2) {−1 −1 1} + 2° and has an orientation density of 3.8 times random for deformation in the rolling direction. The orientation density for the other two samples is approaching the random value. Fig. 10b shows variation in orientation density along φ at $\varphi_1 = 45°$ and $\varphi_2 = 0$. Here the maxima for all three deformed samples have been shifted with respect to the as-received sample, and are located at different positions. Deformation in the rolling direction showed two texture components lying at (0 1 1){1 −1 1} and (0 1 1) {2 −1 1} with orientation density of the order of 3.2 and 5.8 times random, respectively. However, deformation in the 45° and transverse directions showed only one maximum located near (0 1 1){1 −1 1} and has an orientation density of 3.4 and 7.2 times random, respectively. It is interesting to note that the maximum for deformation in the 45° direction has a diffuse peak. In comparison to this, the as-received sample has only one maximum at (0 1 1){2 −1 1} and its density is 3.8 times random. Thus 20% tensile deformation of the annealed sample (as-received) leads to a deformed austenite phase in all three deformation directions.

The even ODF for the austenite phase of tensile-deformed samples and subsequent ageing at 475 or 850 °C indicated no significant difference from the tensile-deformed samples, and is not discussed further here.

4. Discussion

The ferrite phase of the as-received sheets showed a strong cube-on-edge texture component (orientation density of 6.4 times random) along with three other texture components located at (1 1 1){1 −1 0}, (1 1 1){1 −2 1} and (4 4 11){−11 −11 8}, which had approximately the same orientation density of the order of 3 times random.

Comparison of the ferrite phase of samples 20% tensile-deformed in the rolling direction and as-received showed a new texture component which was 10° away from (1 1 2){1 −1 0} with an orientation density of 5.5 times random, whereas the texture components at (0 0 1){1 −1 0} and (1 1 1) {−1 −1 0} remained unchanged. However, the texture components at (1 1 1){1 −2 1} and (4 4 11) {−11 −11 8} disappeared. As compared to this, the 45° direction showed that the ideal texture component at (0 0 1){1 −1 0} had disappeared, and orientation density for (1 1 2){1 −1 0} had decreased. However deformation in the rolling direction showed that the texture component at (1 1 2){1 −1 0} had disappeared and the orientation density for (1 1 1){1 −1 0} was enhanced.

The comparison of the as-received samples and those aged at 475 °C showed that the density for ideal texture component cube-on-edge increased in the rolling and transverse directions by 1.5 times. However, it disappeared and a new ideal texture component at cube–cube had developed for the 45° direction with an orientation density 4.1 times random. Furthermore, a texture component 10° away from (1 1 2){1 −1 0} and (1 1 4){1 −1 0} developed in the rolling and transverse directions. Comparison of the texture for the ferrite phase of tensile deformed (Fig. 4) and aged (Fig. 6) samples indicated that a new texture component appeared 4° away from (1 1 4) {1 −1 0}. Furthermore, as compared to deformation in the 45° direction, a new texture component at cube–cube developed after ageing in this direction. Thus ageing at 475 °C as compared to deformed samples developed a new texture component at (114) {1 − 10}.

Comparison of the texture for the samples aged at 850 and 475 °C showed that the orientation density for the (0 0 1){1 −1 0} component was enhanced by a factor of 2 after ageing at 475 °C, as compared to ageing at 850 °C for the samples of deformation in transverse direction. The texture component at (1 1 2){1 −1 0} which was present after tensile deformation and subsequent ageing at 475 °C disappeared after ageing at 850 °C.

The austenite phase of the as-received sample showed only two texture components located at (4 4 11){−11 −11 8} and (0 1 1){2 1 1}. However, first component was very weak and had an orientation density of 1.5 times random, whereas other components had a density value of 3.8 times random.

The orientation density for the component (0 0 1){1 1 0} appeared to decrease for the austenite phase as the tensile-deformation direction changed from 0 to 90° with respect to rolling direction. The orientation density for deformation in the transverse direction was highest for the texture component (0 1 1) {1 −1 0} as compared to the deformation in the 45° and rolling directions. Thus it may be concluded that tensile deformation in different directions leads to a change in the texture of both ferrite and austenite phases. Furthermore, the texture of the austenite phase obtained after tensile deformation is retained even after ageing at 475 or 850 °C.

5. Conclusions

Tensile deformation in rolling and transverse directions leads to the development of some new texture components in both ferrite and austenite phases. This may in turn lead to the directional magnetic properties; this requires confirmation. Thus studies of the magnetic properties as a function of tensile deformation will indicate whether Remanit could be used as a rotor material in hysteresis motors. Furthermore, it is of interest that the various heat treatments, i.e. ageing for 3 h and water quenching at 850 and 475 °C after 20% tensile deformation, lead to changes in the texture of the ferrite phase, but the texture of the austenite phase is not changed. This confirms previous work [4] and requires a thorough study of the phase transformation mechanism to establish why the texture of the austenite phase has not changed.

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