THE EVALUATION OF TOUGHNESS IN AA6005(A) ALLOYS USING DOUBLE EDGE NOTCHED TENSILE (D.E.N.T.) TESTING

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Abstract

The toughness of AA6005(A) (Al-Mg-Si) alloys in extruded form has been evaluated using the Double Edge Notched Tensile (D.E.N.T.) test, and the results obtained have been compared with data obtained using the Kahn tear test. It is shown that the D.E.N.T. test may be used to investigate the specific work of fracture and the plastic deformation energy components of the toughness of the material. Specifically, the change in toughness and fracture behaviour of AA6005A thin section extrusions has been studied as a function of the manganese content (0 - 0.31 wt.%) of the alloys. This has enabled the critical deformation behaviour of the different alloys to be identified and related to the microstructural features governing the fracture process.

Introduction

The use of aluminium alloys in structural (transport) applications is increasing currently as a result of the increasing requirements for weight saving. At present, the Al-Mg-Si (6XXX) alloys AA6061 and AA6082 are widely used for structural extruded sections. However, the relatively high solute content of these alloys results in higher flow stresses at extrusion temperatures and, therefore, low extrusion speeds and productivities. Also, these alloys are highly quench sensitive and need fast quench rates to satisfy tensile strength requirements. Thus, although the required strength may be obtained by forced air quenching of thin sections, the water quenching required for thicker sections can lead to severe distortion problems. Ideally, an alloy is required that can be extruded rapidly, air quenched at the press and is able to achieve sufficient strength and toughness for use in structure critical applications. In an attempt to achieve these requirements, more dilute 6XXX alloys with slightly lower strength levels have been considered. Alloys with excess Si contents and reduced Mg levels can be used to achieve the same strength levels as balanced alloys, but with a reduced high temperature flow stress and, therefore, increased extrudability. One such alloy is AA6005 which has high extrudability, is relatively quench insensitive and can, therefore, be quenched off the press without distortion problems. Historically, however, excess Si alloys such as AA6005 have been considered to be more brittle than alloys containing balanced amounts of Mg and Si [1,2] and this has led to some concern regarding the use of these alloys for structural applications [2,3]. Manganese additions to AA6005 form dispersoids within the microstructure which not only act to inhibit recrystallisation and grain growth but also increase the toughness of the materials [3] and thereby increase their potential use for structural or semi-structural applications. Such alloys have been given the Aluminum Association (AA) designation AA6005A. In the present work, the term AA6005(A) is used to signify those alloys which contain low levels of Mn (AA6005, in which Mn $\leq$ 0.10 wt.%) or additions of Mn of up to 0.5 wt.% (AA6005A, in which Mn + Cr = 0.12-0.50 wt.%).

Currently, assessments of the effect of Mn additions on AA6005(A) toughness have been restricted to measurements using Kahn tear tests [see, for example, ref.2] and thick, compact tension specimens [see, for example, ref.4]. However, an assessment of the toughness, or "fitness-for-purpose", of thin section materials for such applications is difficult using conventional toughness testing techniques. Thick sections are required for "standard" fracture toughness tests (e.g., J-integral), and the results of the Kahn tear test have been shown to be dependent upon specimen geometry and dimensions [5,6], and can only be used to provide a relative ranking of behaviour. Hence the approaches that have been used to date are restricted in their ability to provide a more fundamental understanding of the role of alloying elements on toughness in typical extrudate section thicknesses.

There are, however, alternative approaches to defining quantitatively the toughness of a material under: (a) the elastic-plastic conditions of deformation that exist in these low yield strength, high ductility materials, and (b) the plane stress conditions imposed by the use of thin sections (typically less than ~2.5mm). Conventionally, the toughness of a material may be considered to be directly related to the amount of energy stored in a body prior to final fracture. This quantity may in turn be subdivided into a measure of the energy required to initiate a crack and the energy associated with the plastic deformation which normally accompanies crack formation. Cotterell and Reddel [7] proposed an analysis of the fracture response of Double Edge Notched Tensile (D.E.N.T.) specimens which separates the energy to cause fracture and the plastic deformation which occurs prior to fracture. Therefore, it is possible to define a constant fracture energy for the material which is representative of the material's ability to resist crack initiation. These analyses have been developed by a number of workers [8-11] and have been successfully applied to material with extensive ductility. The D.E.N.T. test considers that the total work required to fracture a specimen (W_t) is composed of two terms. The first term (W_f) is that associated with the fracture "process zone" and gives rise to both localised necking and fracture. The second is the work arising from the plastic flow (W_p) in an area remote from the fracture process which is assumed to be represented by a circular patch. Therefore:

$$\text{Total work} = \text{Work Done in Process Zone} + \text{Remote Plastic Work} \quad (1)$$

$$W_t = W_f + W_p \quad (2)$$

If L is the length of the specimen ligament, B the thickness and R the specific, essential work of fracture, this relationship can be defined further as:

$$W_t = R.L.B + \alpha.L^2.B.E_p \quad (3)$$

where α is a geometric term (= $\pi/4$ for a circle) and E_p is the plastic work per unit volume. By division throughout by the product (L.B), equation (3) is reduced to that of a straight line having slope equal to ($\alpha.E_p$) and intercept equal to R. Thus, the energy related with the process of fracture (R) (which is essentially a "surface" term) can be separated from the energy associated with plastic deformation (which is a volume term), which is assumed to take place before fracture initiates, by plotting the value of ($W_t/(L.B)$) as a function of the ligament length, L. For a conventional linear elastic material the plastic work per unit volume associated with failure would be zero and consequently the specific essential work of fracture, R, can be related to Linear Elastic Fracture Mechanics (L.E.F.M.) toughness parameters. In the present work, this approach to toughness evaluation has been applied to a range of 6XXX alloys and the results compared to those currently obtained from Kahn tear testing of thin section extrusions. This framework has then been used to develop a more significant understanding of the role of alloying elements and material properties to the toughness of medium strength 6XXX extrusion alloys.

Experimental

A range of AA6005(A) extruded sections, 2mm in thickness, were tested using both Kahn tear testing and D.E.N.T. approaches, the compositions of which are given in Table 1. Tensile (L orientation), Kahn tear and D.E.N.T. testing was carried out on material which had been peak aged (7 hours at 175°C), following press air quenching (P.A.Q.). The Kahn tear testing was conducted on a standard specimen geometry in which the notch is perpendicular to the extrusion direction (L-T orientation). Evaluations of unit initiation energy (U.I.E.) and unit propagation energy (U.P.E.) were calculated according to standard procedures.

It should be noted that the specimens developed in the initial D.E.N.T. work of Cotterell and Reddel [7] were 300mm in length and 75mm wide, with ligament lengths of 12mm to 48mm between the two 60° notches. In the present work, testing has been conducted on smaller specimens (100mm x 25mm, with ligament lengths ranging from 4mm to 16mm) shown in Figure 1, having an identical dimensional ratio to that of the specimens used by Cottrell and Reddel, and capable of being obtained from typical experimental extruded sections. Again testing was carried out in the L-T orientation. This "modified" specimen geometry was shown to give results in good agreement with those obtained using the larger specimens. By measuring the total work to fracture, W_t, from the area under the load-elongation curve for a series of ligament lengths, a plot of $W_t/(L.B)$ versus L can be generated from which the slope and intercept data can be readily obtained by appropriate curve (line) fitting routines.

Alloy	Si	Mg	Mn	Fe	Cu
AA6005 - 0 Mn	0.69	0.51	0.006	0.19	0.11
AA6005 - 0.10 Mn	0.69	0.48	0.10	0.25	0.005
AA6005A - 0.16 Mn	0.69	0.52	0.16	0.24	0.005
AA6005A - 0.31 Mn	0.70	0.49	0.31	0.25	0.006

Table 1 - Compositions, in wt.%, of the alloys used in this investigation.

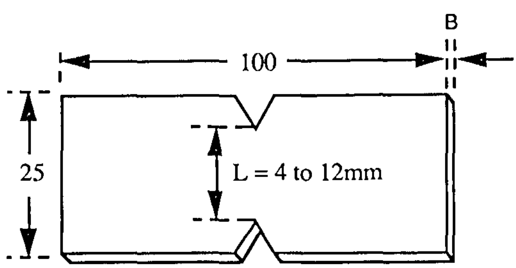

Figure 1 - Diagram showing the dimensions (in mm) of the small D.E.N.T. specimen used in this investigation.

Results

The effect of Mn additions on the strength of the alloys can be seen in Figure 2, in which there is a slight reduction in strength as the Mn level is raised. These data are consistent with the known effect of Mn-containing dispersoids in this alloy type on "quench sensitivity", such that precipitation of β'-Mg_2Si occurs on the dispersoids during cooling (air quenching) of the extrudate. Thus, the removal of Mg and Si from solid solution lowers the overall volume fraction of the precipitation hardening phase (β''-Mg_2Si) developed during final ageing. The increased strength of the alloy containing no deliberate addition of Mn (AA6005) may, to some extent, be explained by the addition of Cu (0.11 wt.%) to this alloy, which was not present in those alloys containing Mn (see Table 1).

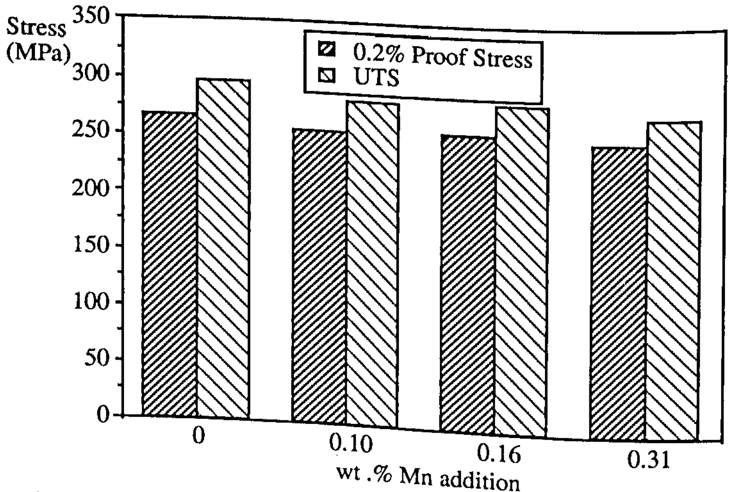

Figure 2 - The effect of Mn content on the tensile strength of peak aged AA6005(A) alloys.

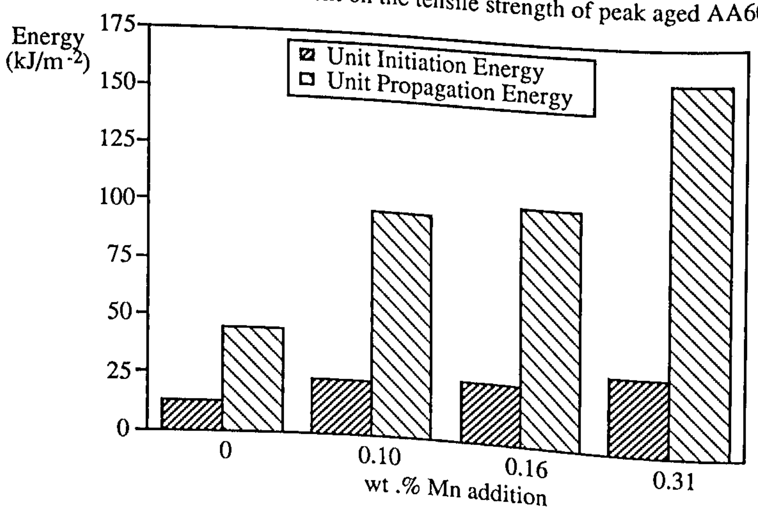

Figure 3 - The effect of Mn content on the Kahn tear energies of peak aged AA6005(A) alloys.

hn tear test results for the same material are shown in Figure 3. From these data, it is it that as the Mn content increases, both the unit initiation energy (U.I.E.) and unit ition energy (U.P.E.) increase.

ect of Mn additions to an AA6005 alloy on the D.E.N.T. test results can be seen in Figure rial containing no deliberate addition of Mn can be seen to have a value of R (work of) of 28 kJm^{-2} and a shallow, almost horizontal, slope, indicating that little plastic ation occurs prior to failure. Small additions of Mn to AA6005 (i.e. AA6005A containing % and 0.16 wt.%Mn) have the effect of slightly increasing the value of R to 35 kJm^{-2}, but antly increase the slope. A further addition of Mn to a level of 0.31 wt.% gives a able increase in the R value to approximately 81 kJm^{-2}, and the data have the same slope as material containing the lower levels of Mn. These changes in the specific work of fracture the slope are shown graphically in Figure 5.

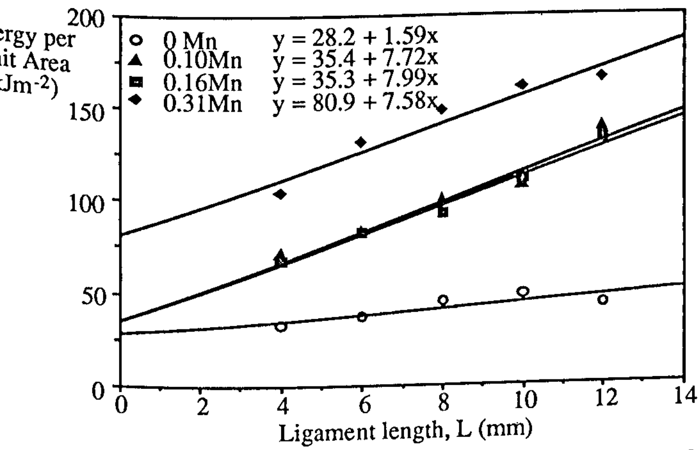

Figure 4 - The effects of ligament length and Mn content on the D.E.N.T. performance of peak aged AA6005(A) alloys.

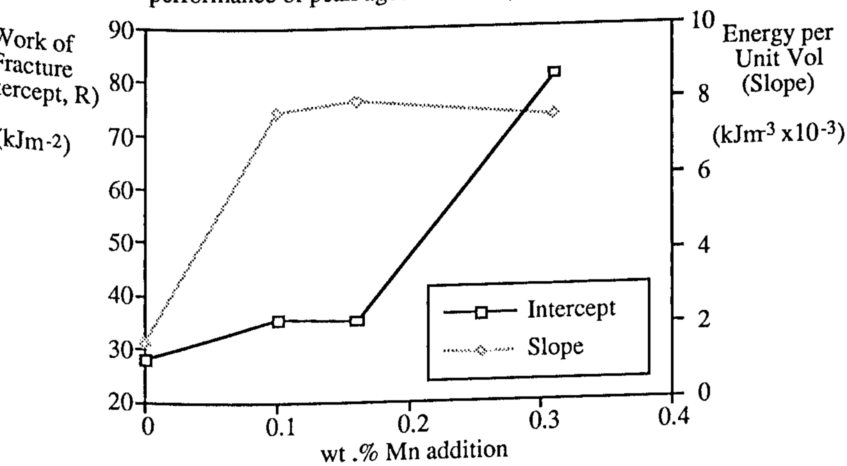

Figure 5 - The effect of Mn content on the D.E.N.T. parameters of peak aged AA6005(A) alloys.

Examination of the fracture surfaces of the D.E.N.T. samples (Figure 6(a-d)) show that in the AA6005 alloy (0 wt.% Mn), failure is highly faceted and obviously intergranular (Figure 6(a)). On increasing the Mn content to either 0.10 wt.% or 0.16 wt.%, the failure appearance changes to that associated with a mixed intergranular/transgranular mode (Figures 6(b) and (c) respectively) and finally to a transgranular mode at 0.31 wt.% Mn (Figure 6(d)). It is of interest to note that although the toughness of the 0 wt.% Mn alloy has been identified [2,3] as being structurally unacceptable, owing to the apparently "brittle" nature of the fracture surface, the intergranular failure is locally ductile; however, the fracture energy from the D.E.N.T. test indicates that little energy is absorbed by such a fracture mode. Detailed examination of the fracture surfaces of this alloy shows that failure is due to coalescence of voids formed by highly localised plastic deformation at grain boundary precipitates. The ductile cusps arise from fracture of material within the grain boundary precipitate free zone (P.F.Z.) and consequently are limited in height. In contrast, failure of the alloys containing Mn occurs primarily by ductile voiding at coarse Fe-bearing, intragranular constituent particles. These provide more surface relief on fracture surfaces such that the ductile, transgranular failure is more readily recognised.

(a) (b) (c) (d)

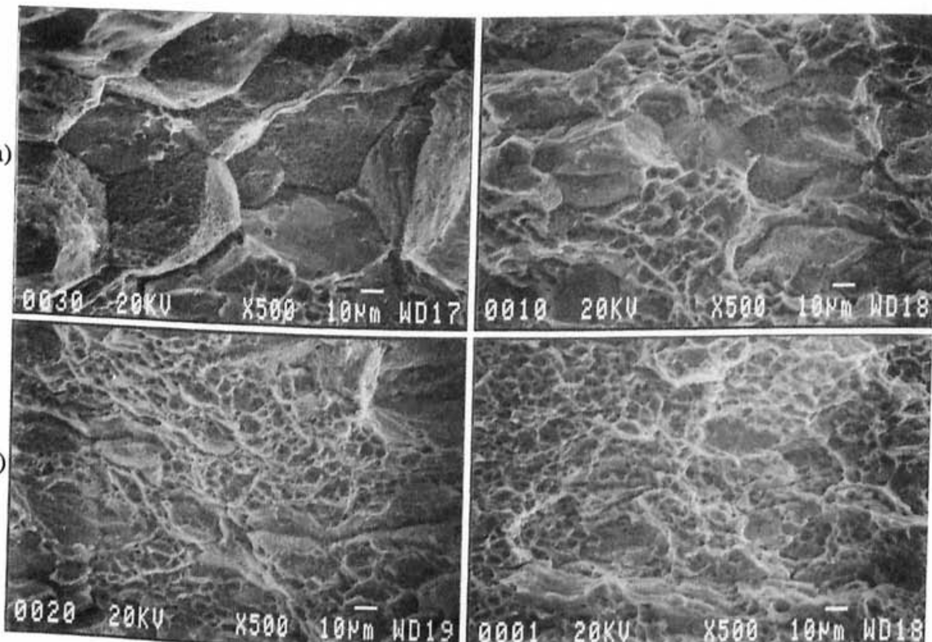

Figure 6 - Scanning Electron Micrographs showing the effect of Mn content on the fracture surfaces of peak aged AA6005(A) alloys containing: (a) 0 wt.% Mn, (b) 0.10 wt.% Mn, (c) 0.16 wt.% Mn, and (d) 0.31 wt.% Mn.

Discussion

From the results presented in the previous section, it is clear that any fundamental interpretation of a material's sensitivity to failure in the presence of cracks is difficult to accomplish from a consideration of the Kahn tear data alone, since the measured Kahn tear energies contain contributions from many sources, amongst which are fracture, plastic deformation at both the fracture surface and the loading holes and plastic buckling. However, by considering the D.E.N.T. data in parallel, it is possible to provide a more rigorous interpretation of the behaviour, and thereby identify the applicability of Kahn tear approaches to a true ranking of the toughness behaviour of materials.

Material containing 0 wt.% Mn has an unacceptable value for U.P.E. [2] and this corresponds to both a low intercept (work of fracture) and low slope (work of plastic deformation prior to fracture) in the D.E.N.T. analyses. Additions of 0.10wt.% and 0.16 wt.% Mn increase the U.P.E. values to a level which, from experience, is deemed to be "just acceptable" for structural applications (i.e. approximately 100 kJm^{-2}), and relate to material in which only a slightly higher intercept and markedly higher slope are recorded in the D.E.N.T. test analysis. A further increase in the level of Mn to 0.31 wt.% results in an increases in U.P.E. to a value considerably greater than 100 kJm^{-2} and is associated with further significant increases in the intercept of the data measured in the D.E.N.T. test, whilst the slope remains approximately the same. Hence, it can be seen that the increases observed in the Kahn tear U.P.E. values with increasing Mn content are reflected in the changes to both the intercept (fracture energy) and slope (plasticity prior to fracture) observed in the D.E.N.T. testing (see Figure 4).

From earlier analyses of the D.E.N.T. test [8-11], it is possible to identify that Mn has two effects on the material's behaviour that are significant in terms of toughness. First, adding Mn to a level of 0.10wt.% or 0.16 wt.% increases the material's resistance to crack initiation by increasing the specific work of fracture from 28 kJm^{-2} to 35 kJm^{-2}. Secondly, and perhaps more significantly, is the ability of the material to deform plastically prior to fracture. From the D.E.N.T. data it can be seen that additions of 0.10wt.% or 0.16 wt.% Mn give rise to a change in the plastic deformation energy from 1.6×10^3 kJm^{-3} to $\sim 8 \times 10^3$ kJm^{-3}. Thus, the observed increase in Kahn Tear U.P.E. energy with increasing Mn content arises from a combination of both the increased resistance to crack initiation and the increased plastic deformation prior to fracture. However, in view of the significant increase observed in the plastic deformation associated with the fracture process, it is most likely that the increase in material toughness measured using the Kahn tear approach is dominated by the plastic deformation component of the material's toughness at this level of Mn addition. Therefore, although the Kahn tear test cannot separate these two aspects of behaviour, the responses measured in this test can provide an appropriate ranking of material behaviour.

The changes in the energy required to fracture material noted above are associated with changes in the fracture path. At 0 wt.% Mn, the "brittle" appearance of the fracture surface is associated with localised, ductile failure of the grain boundaries, which progressively changes as Mn is added, to a truly ductile, and more importantly, high energy, failure process involving void formation and coalescence at coarse, Fe-rich intermetallic particles. These observations are consistent with those made of increased toughness with increasing Mn content in thicker section sizes, in which more conventional fracture toughness tests were used [4]. In this previous work, Mn was reported to increase the elastic/plastic initiation toughness J_{1c} and increase the tearing resistance of the material [4]. In this respect, the same trend in behaviour is observed in the present work on thin sections, with the specific work of fracture (intercept, R) identifiable with the elastic/plastic initiation toughness J_{1c}, and the remote plastic work (slope) related to the tearing resistance. Furthermore, this change in behaviour was related to the increased slip homogenisation occurring with increased dispersoid level [4]. It was argued that increasing slip homogenisation gave rise to a more blunt crack tip, thereby reducing the stress concentrating effect of the crack and increasing the toughness; effects which are again reflected in the D.E.N.T. data. First, slip homogenisation delays grain boundary failure until fracture occurs in the matrix at coarse, Fe-containing intermetallic particles and an increased specific work to fracture arises. In this respect, the size and distribution of the grain boundary Mg_2Si precipitation formed during cooling of the extrudate will be important in controlling the cohesive strength of the grain boundaries. Secondly, slip homogenisation leads to activation of slip over a larger number of grains and an increased spread of plasticity arises. This is reflected in the change in the slope of the D.E.N.T. data, since this is associated with the deformation occurring prior to fracture.

The present work has demonstrated that fracture analyses conducted using the D.E.N.T. approach can be used to provide a more quantitative understanding of the factors which influence the toughness of 6XXX extrusions. Additions of Mn to AA6005 type alloys result in increases in the material's toughness which are due to changes in both the energy required to fracture and the deformation energy associated with remote plastic work prior to fracture. From the data generated, it is apparent that both of these components can be influenced by additions of Mn to AA6005. At low levels of added Mn, the most significant parameter affected is the remote plastic work prior to fracture. However, on increasing the level of Mn, the energy absorbed during fracture is also increased significantly. From a structural viewpoint, this information can be used to aid material selection by reflecting the ability of the material to respond to the failure requirements of the component. For true structural applications, in which cracking may represent the major failure mechanism, it may be important to select materials which have both a high specific work of fracture and a high degree of plasticity prior to failure, and alloys with high levels of Mn would be most suitable. In contrast, for applications where the structure may be subject to severe deflections, a lower crack initiation (fracture) resistance may be tolerated provided the material displays a high capacity to absorb plastic deformation prior to fracture; consequently, material with lower levels of Mn may be used in such applications.

Conclusions

1. The D.E.N.T. test can be used to provide a more fundamental measure of toughness in thin section 6XXX series extrusions by enabling the energy of fracture to be separated from the energy associated with plastic deformation remote from the fracture process zone.

2. Both the D.E.N.T. test and the Kahn tear test can provide a ranking of material toughness, but the latter test combines fracture and plastic deformation energies.

3. Additions of Mn to AA6005 initially increase the work of plastic deformation prior to failure, although, if added in sufficient quantity, can also increase the work of fracture (R).

4. Fracture of AA6005 has been observed to be macroscopically brittle, with grain boundary facets in evidence. However, on a microstructural level failure is ductile with small dimples present on the faceted surfaces. At high Mn additions (AA6005A), this fracture behaviour is replaced by a high energy, ductile fracture mode involving void formation and coalescence at coarse, Fe-containing intermetallic particles.

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