Melting Phenomena in Solid State Welding Processes

The microstructure of ultrasonic and explosive welds studied by transmission electron microscopy yields considerable evidence that bonding is achieved by melting of the interface while, in friction welding, only isolated areas may reach the melting point

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ABSTRACT. Different aluminum and copper alloys with a well defined microstructure are joined by ultrasonic, explosion and friction welding. Transmission electron microscopy is used to study the microstructure within the bonding area of the welded joints. From the change in microstructure, as compared to the material in its original state, conclusions are drawn on the bonding mechanism of these welding processes.

In ultrasonic welding, bonding occurs predominantly by a short time melting of a narrow surface layer (less than 1 μm thick) followed by rapid cooling. In explosion welding, melting phenomena are not only found in the well known melt pockets of wavy interfaces; even plane interfaces of similar alloy welds show evidence of melting within a 0.5 to 4 μm thick zone. During the friction welding of two dissimilar aluminum alloys used in this investigation, the temperature exceeds the melting point only within isolated areas along the interface up to 15 μm in size.

Introduction

Ultrasonic, explosion and friction welding are commonly referred to as solid state welding processes, mainly because metallographic investigation of the bonding area does not show evidence of melting[1]. Nevertheless, melting of the interface on a submicroscopic scale has been considered as a possible bonding mechanism, and considerable effort has been spent to determine the maximum temperature achieved during the welding process[2-9]. This has been mainly carried out either by thin thermocouples placed as close as possible to the bonding area, or utilizing the thermocouple effect by measuring the voltage produced between the two dissimilar metals being joined. In nearly all instances, the resulting temperature values were well below the melting point.

However, since both methods are only capable of determining the average temperature over the welded area, localized melting as a possible bonding mechansim cannot be ruled out by these results.

Table 1—Heat Treatments Used to Produce Well Defined Microstructures in the Base Metals of this Investigation

	Base metal	Heat treatment
A	Cu 99.99	1 h 850 C (1562 F)/H_2O
B	Cu2Co	1 h 1050 C (1922 F)/H_2O + 1 h 700 C (1292 F)/H_2O
C	Al 99.5	1 h 540 C (1004 F)/H_2O
D	Al3Cu	2 h 520 C (968 F)/H_2O + 20 h 300 C (572 F)/H_2O
E	AlCuMg 1	4 h 540 C (1004 F)/H_2O
F	AlCuMg 1	4 h 540 C (1004 F)/H_2O + 33 h 300 C (572 F)/H_2O
G	AlMgSi 1	2 h 540 C (1004 F)/H_2O
H	AlMgSi 1	2 h 540 C (1004 F)/H_2O + 1 h 260 C (500 F)/H_2O

In the following reported investigation a different method was used to study the bonding mechanism. Since a distinct change of the microstructure can be expected if the temperature in the bonding zone exceeds the melting point, a microstructural analysis of the bonding area by transmission electron microscopy (TEM) can clarify whether or not melting at the interface takes place during the bonding process.

Experimental Procedure

The aluminum and copper alloys used for this investigation are given in Table 1. The ultrasonic spot welds have been made from 0.4 mm (0.016 in.) thin sheets. Explosion welding was carried out with 6 × 150 × 200 mm (0.236 × 5.91 × 7.87 in.) plates, while 20 mm (0.787 in.) rods 100 mm (3.94 in.) long have been used for friction welding. Before welding, the materials were heat treated in different ways to produce a well defined microstructure. For all three welding processes preliminary tests were carried out to find suitable welding parameters. The welds chosen for further investigation did not break at the interface in tensile testing and did not show any excessive heating effect under the optical microscope. Microstructural analysis by TEM was carried out on welded joints of the following materials (Table 1):

Paper presented at the AWS 57th Annual Meeting held in St. Louis, Missouri, during May 10-14, 1976.

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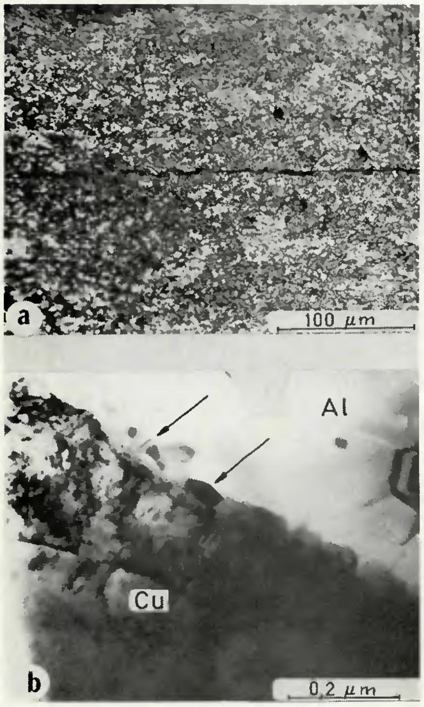

Fig. 1—Microstructure of ultrasonic welds. (a) A/A (light optical micrograph). (b) A/C (TEM micrograph) arrows point to small new grains along the interface

Ultrasonic: A/A, B/B, C/C, A/C, B/C
Explosion: D/D, A/E, E/F
Friction: C/C, E/F, E/G, F/H

To prepare thin foils for TEM, 0.2 mm (0.008 in.) thick discs with a 3 mm (0.118 in.) diameter were mechanically cut from the bonding area and thinned down by electrolytic jet polishing and/or ion milling. Areas less than 0.5 μm thick can be transmitted by the electron beam. More details on the welding parameters and the preparation technique for TEM foils have been described elsewhere[10,11].

In addition, the influence of a short time heat treatment (1 to 3 s in a salt bath) on the microstructure of plastically deformed samples of the base metal and the stability of the microstructure of welded joints with respect to a postweld heating were investigated by means of TEM. The results have been used to facilitate the interpretation of the microstructure observed within the bonding area.

Results

Ultrasonic Welding

The bonding zone of spot welds made from similar alloys (A/A, B/B, C/C) was found to be less than 1 μm thick. The grains within these areas have a size of only 0.05 to 0.2 μm. In the case of B/B welds the cobalt rich particles formed during annealing for 1 h at 700 C (1292 F) prior to welding had been dissolved within the bonding zone during the welding process. In the copper to aluminum welds (A/C, B/C) the bonding area also contained small newly formed grains. No intermetallic compounds could be detected by electron diffraction of these grains. Figure 1 shows an optical micrograph of an A/A weld and an electron micrograph of an A/C weld respectively. The arrows in Fig. 1b point to the extremely small grains along the interface. Only 10-15% of all samples examined did not show such small grains.

For comparison, the grain size of the base metals varied between 5 and 50 μm. The grains formed by recrystallization during short time annealing of heavily rolled base metal, carried out at different temperatures below the melting point, always turned out to be ≥ 3 μm.

Explosion Welding

The heat treatment for the base metal D, given in Table 1, was chosen to form thin plates of the θ' phase on (100) planes of the matrix. These plates up to 0.8 μm in size and a few hundred angstroms thick are semicoherent with the surrounding matrix, as shown in Fig. 2a. During plastic deformation of the material they deform together with the matrix. The material E and F as a technical alloy contains large incoherent particles with a shear modulus about 10 times as high as the matrix. These particles cannot be deformed by plastic deformation. In the F material, in addition to the incoherent particles, small θ' plates have been formed by the 300 C (572 F) heat treatment, as shown in Fig. 2b.

Figure 3 is an optical micrograph showing the bond line and plane bonding area typical for the E/F and D/D welds used in this investigation. Details of this microstructure have been revealed by TEM. The bonding area of the D/D and E/F welds consists of a 0.5 to 4 μm wide zone with small grains of only 0.1 to 0.3 μm size, Fig. 4a. In D/D welds on both sides of this zone and on the F-side in E/F welds within an area 5–8 μm wide, the θ' plates are aligned parallel to the interface and elongated by a factor of 5 to 10 compared to the original size, Fig. 4b,c. Between the θ' plates single elongated grains formed by recrystallization during welding can be seen in Fig. 4b. The degree of alignment of the θ' plates and, therefore, the amount of deformation then decreases continuously.

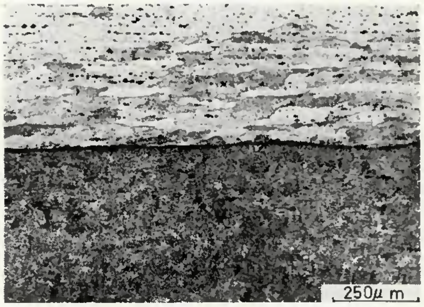

Fig. 3—Bond line of an E/F explosive weld (optical micrograph)

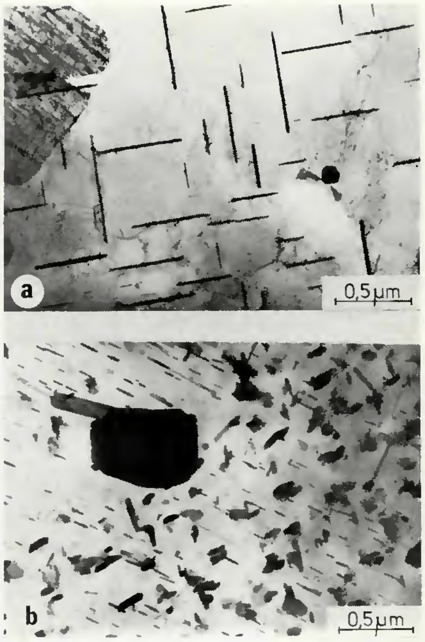

Fig. 2—Microstructure of the material used for explosion welding (TEM). (a) Alloy D containing θ' plates. (b) Alloy F containing large incoherent particles and small θ' plates

In a distance of more than 40 to 80 μm from the interface no alignment can be observed. In the E/F welds within the material F, close to the interface, the flow of the soft matrix around the incoherent particles is made visible by the small θ' plates. At the interface of large particles, new small grains have also been formed—Fig. 5.

The short time heating of welded joints at different temperatures below the melting point causes recrystallization of the highly deformed areas containing the aligned θ' plates. During this recrystallization, the grain growth perpendicular to the interface is impeded by fragments of the θ' plates. Therefore, the recrystallized grains also become elongated parallel to the interface.

Friction Welding

Examination of the C/C, E/F, F/H welds with an optical microscope revealed a fine grained structure in the bonding area—Fig. 6. In some areas of the welds made from dissimilar alloys, bands of material from one component within the region of the other weld component have been formed by turbulence at the interface during welding—Fig. 6c. TEM investigation of

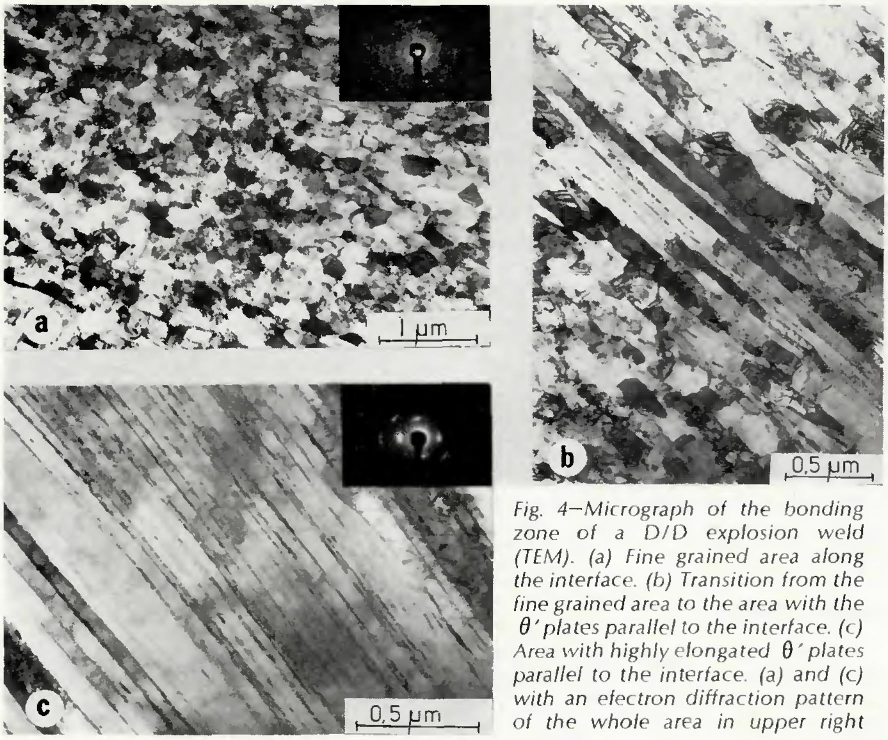

Fig. 4—Micrograph of the bonding zone of a D/D explosion weld (TEM). (a) Fine grained area along the interface. (b) Transition from the fine grained area to the area with the θ' plates parallel to the interface. (c) Area with highly elongated θ' plates parallel to the interface. (a) and (c) with an electron diffraction pattern of the whole area in upper right corner

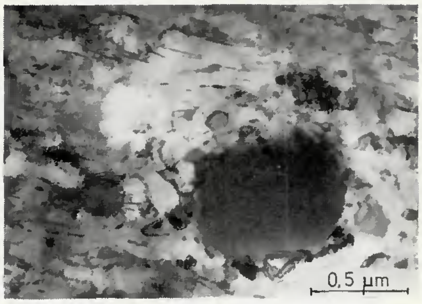

Fig. 5—Formation of new grains at the interface of large incoherent particles in E/F welds. The distance of this particle from the center of the bond line is about 6 microns

the bonding area of the E/F and F/H welds indicated that particles of θ' and Mg_2Si phases were dissolved within a 5-7 mm (0.197-0.276 in.) wide zone of the bonding area—Fig. 7a.

After heating the welds for 1 h at 260 C (500 F) particles of θ' and Mg_2Si phases could be found again in the E, F and G, H components respectively. Within a 2 to 5 μm wide zone at the interface of E/G and F/H welds both types of particles were found, marking the distance of interdiffusion of copper and silicon, Fig. 7b,c. Occasionally these areas become up to 15 μm wide. At the interface of isolated bands, shown in Fig. 6c, the distance of interdiffusion varies between 1 and 3 μm. For comparison cold pressure welds of E/G have been made and annealed for 1 h at 260 C. In this case the width of the zone containing both types of particles was in the range of ≤ 1 μm.

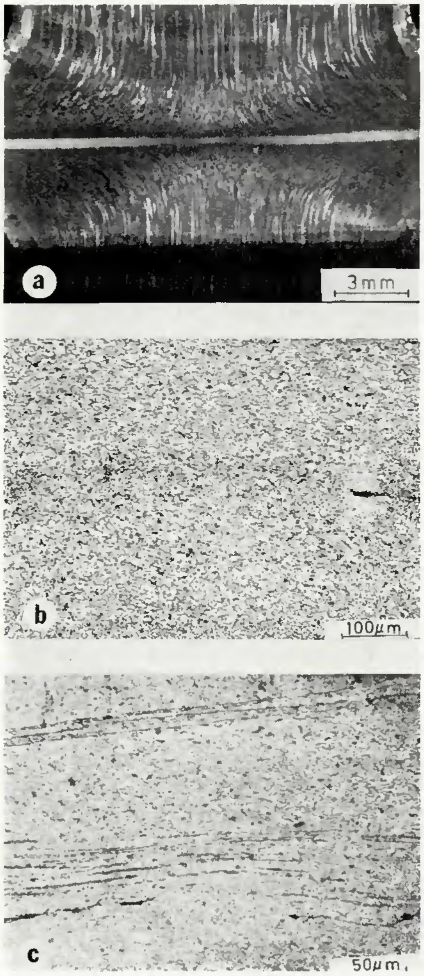

Fig. 6—Microstructure of different friction welds (optical micrograph). (a) C/C, (b) E/F and (c) F/H, the latter showing bands of material H within the area of F

Discussion

TEM studies of the bonding area at high magnification have revealed a considerable change of the microstructure during welding. Formation of new grains was found in all three welding processes investigated. To explain this change, both recrystallization of heavily deformed material and short time melting have to be considered.

During recrystallization the dislocations produced by plastic deformation first rearrange to form dislocation networks and subgrain boundaries. The minimum size of new grains then formed from the subgrain structure is always a few times larger than the diameter of the subgrains. So far, the smallest recrystallized grains found after short time heating of deformed samples have had a size of about 3 μm[12,13].

On the other hand new grains formed by rapid cooling from the melt can be as small as a few hundred angstroms, depending on the cooling rate[14]. Therefore, the small grains found at the interface of ultrasonic and explosion welds indicate that melting has occurred during the bonding process. The comparatively large grain size in the bonding area of friction welds cannot be used as an indication for the bonding mechanism. However, further details of the observed microstructure can be used to analyze the bonding mechanism.

In ultrasonic welding, it is not only the small grain size that indicates a melting process during bonding. The cobalt rich particles in the base metal B become unstable when the temperature exceeds 900 C (1650 F). The time necessary for a dissolution of the particles at a temperature below the melting point can be calculated from the diffusion data available in the literature[15,16]. This time turns out to be longer than the total welding time. Therefore, dissolution of these particles within the newly formed grains along the interface of B/B welds also indicates a melting of this area during welding.

In addition the absence of intermetallic compounds indicates that heat transfer to the surrounding areas provided a very rapid cooling rate in the bonding zone. The frictional heat generated at the interface during welding is obviously sufficient to raise the temperature within a thin surface layer above the melting point of at least one component. These findings are contrary to the results obtained by other authors[2-6]. The disagreement can be explained by the fact that any temperature measurement with thin thermocouples or using the thermocouple effect can give only average values over the bonding area. The actual temperature at the interface must be higher than these values.

In explosion welding, the high impact pressure causes high amounts of plastic deformation in the bonding area. Simultaneously, the heat developed by this plastic deformation and by adiabatic compression of gases between the plates raises the temperature. An increase in hardness of the material in the bonding zone has been reported by several authors[7,17]. There is also clear evidence for melting in the vortex areas of wavy interfaces. In *dissimilar* metal welds, especially after high collision energies, molten layers of about 50 μm thick can be found along the interface[7,18,19]. However, since structural features resulting from melting are generally not found in *similar* metal explosion welds, melting is not considered to be essential in explosion welding[7].

Some electron microscopy studies of wavy copper-to-copper and steel-to-steel welds have already indicated that melting may well occur along the interface of similar metal welds[17,20]. The microstructure of the interface of D/D and E/F welds examined in this investigation was found to consist of small grains of only 0.1 to 0.3 μm in size. This fine grained area was observed in all samples taken from plane and wavy bonding zones as a continuous layer with a variable thickness between 0.5 and 4 μm. The existence of the small grains indicates a melting of this area during the welding process. Recrystallization of the highly deformed material as a possible mechanism for the formation of the small grains can be excluded for three reasons:

1. In no instance have such small grains been detected in a material deformed by conventional methods and annealed for recrystallization.
2. Since grain growth perpendicular to the interface is impeded by elongated θ' plates or the fragments thereof, new grains formed by recrystallization are also always elongated parallel to the interface. This has been proved by studying the recrystallization behavior of welded samples in the highly deformed areas adjacent to the fine grained area. The small grains in the bonding zone, however, are equiaxed.
3. Within the fine grained area, fragments of undissolved particles are concentrated at the corners of grain boundaries as is typical for solidified melts containing non-dissolvable particles.

Therefore, the observed microstructure can only be interpreted as a result of short time melting of thin surface layers followed by rapid cooling.

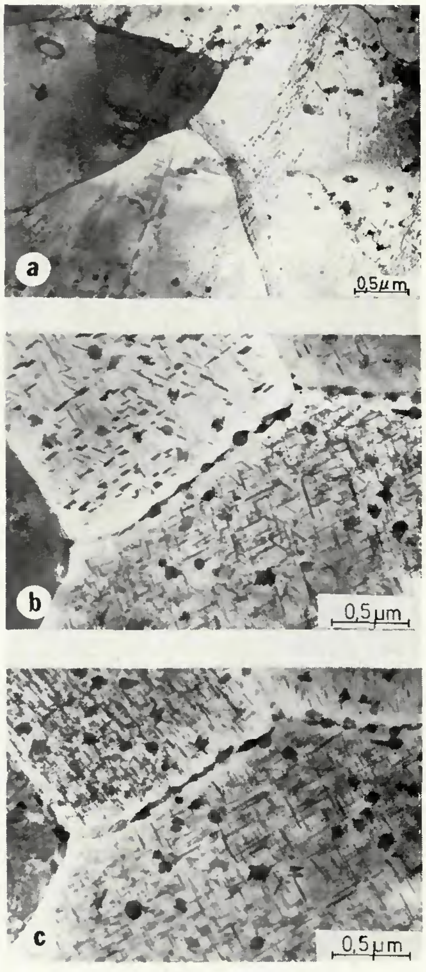

Fig 7—Microstructure of the bonding zone of friction welds (TEM). (a) E/F as-welded, (b), (c) F/G weld annealed for 1 h at 260 C (500 F). Same area under different contrast to show precipitates of both phases θ' plates and Mg$_2$Si rods

In friction welding, temperature measurements using the thermocouple effect can be expected to be more reliable than in ultrasonic welding. Because of the relatively long welding time of several seconds and, therefore, a comparatively wide heat affected area at the interface, the difference between local peak temperatures and the average temperature integrated over the whole contact area becomes smaller. In nickel to steel welds, even the integrated temperature has been found to exceed the melting point during the welding process[9].

There are no specific features in the microstructure of the friction welded joints analyzed by TEM in this study which could be attributed directly either to melting or to thermally activated processes in the solid state alone. However, the interdiffusion distance of different atoms in dissimilar metal welds may be used for further information on the bonding process. After heat treatment of the E/G and F/H welds, this distance becomes decorated by a simultaneous precipitation of θ' and Mg$_2$Si particles. The diffusion distance of copper atoms into aluminum after 5 s at a temperature just below the melting point is about 2 to 3 μm ($D = 10^{-8}$ cm^2/s). For the same period of time above the melting point, this width may increase by a factor of about 100. A comparison with interdiffusion distance obtained by TEM may lead to the assumption that bonding occurs in the solid state.

However, spreading of a molten film across the interface, not more than 1 to 3 μm thick, must also be considered as a possible bonding mechanism. The solidification of such a film should lead to a typical microstructure within this area, quite different from the adjacent material. Yet, none of the samples investigated showed such a microstructure. Therefore, only the isolated areas along the interface up to 15 μm wide and containing both types of particles can be interpreted as molten areas. These findings are supported by more recent TEM studies on AlCuMg1/Al3Cu friction welds[21].

In general, melting at the interface may not be desirable because of the weakness associated with cast structures. However, in ultrasonic and explosion welding the very rapid cooling rate of the material in the bonding zone leads to the formation of extremely fine grains. According to the Hall-Petch relation, the mechanical strength of the observed fine grained structure can be expected to be about 2 to 3 times higher than the strength of the base metal, without an embrittling effect[22]. In friction welding, the molten areas at the interface are strengthened by plastic deformation during cooling.

Conclusion

In ultrasonic, explosion and friction welding, the welding occurs within a very short time, and only extremely small areas of the material become affected by the process. Therefore, measurements of the temperature during the welding process, no matter how carefully they are carried out, must be problematic. Since the structure of a material changes considerably when subjected to a temperature above the melting point for a short time, an analysis of the microstructure by means of transmission electron microscopy can be used to study melting phenomena even on a submicron scale.

1. In ultrasonic welding, 85 to 90% of all samples investigated had a continuous layer of very fine grains (0.05 to 0.2 μm) along the contact area. The formation of these grains could

only be referred to a short time melting and rapid cooling of thin surface layers during the welding.

2. In explosion welding, all samples prepared from the bonding zone of similar and dissimilar metal welds, with both plane and wavy interfaces, had a 0.5 to 4 μm thick area along the interface with a grain size of 0.1 to 0.3 μm. The existence of these grains again refers to a short time melting followed by rapid cooling during the welding process. A zone with heavy isotropic flow of the material during the welding process but no melting phenomena, was found adjacent to the fine grained area. The flow of the material is decorated by the semicoherent θ' plates, which have been deformed together with the surrounding material. Since all samples had the fine grained zone along the interface, melting of thin surface layers may be considered to be essential in explosion welding.

3. In friction welding, a 2 to 5 μm wide area along the interface was found to contain alloying elements of both aluminum alloys welded. Occasionally, this area became up to 15 μm wide. The distance of interdiffusion could be decorated by simultaneous precipitation of two different phases during a postweld heat treatment. These findings indicate that bonding occurs in the solid state and only isolated areas along the interface may exceed the melting point.

Acknowledgment

The author is grateful to Dr. U. Richter, Dynamit Nobel, Dipl.-Ing. K. Thomas of the University of Braunschweig, and The KLN Ultraschall Co., Heppenheim, for making the welds. The investigation was conducted by the author at the Institut für Werkstoffe, Ruhr-University, Bochum.

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