M. Stadler et al.: Improving the mechanical performance of a resistance spot welded 1200 MPa TBF steel

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Improving the mechanical performance of a resistance spot welded 1200 MPa TBF steel

In the present work different approaches to improve the mechanical properties of a resistance spot welded 1200 MPa transformation induced plasticity-aided bainitic ferrite steel are evaluated. An extension of the welding time results in coarsening of the microstructure of the outer fusion zone and the maximum force derived by the cross tension strength test did not improve significantly. A temper pulse after a long cooling time leads to pronounced softening of the fusion zone, as determined by hardness mapping, which resulted in enhanced weld properties. A recrystallization pulse modifies the shape of the prior austenite grains at the outer fusion zone, which was visualized with electron backscatter diffraction. This also resulted in a significant improvement of maximum force. For all approaches the failure mode improved, which can be attributed to an increased fraction of high angle grain boundaries at the edge of the fusion zone.

Keywords: Resistance spot welding; Double pulsing; Advanced high strength steels; AHSS; TRIP-aided bainitic ferrite

1. Introduction

Third generation advanced high strength steels (AHSS) combine high strength with good formability and are potential candidates for use in body components in the automo-

tive industry due to their superior crash behavior [1, 2]. Promising representatives are the transformation-induced plasticity (TRIP)-aided bainitic ferrite (TBF) steels. Their microstructure mainly consists of carbide-free bainite and a certain amount of retained austenite in order to enable the TRIP-effect. The austenite is stabilized by carbon enrichment during an isothermal heat treatment [2, 3].

Resistance spot welding (RSW) is the dominant technology for sheet metal joining in the automotive industry [4]. Due to the relatively high alloying content of third generation AHSS and the rapid cooling during RSW, the welds are often fully martensitic and therefore hard and brittle. This, combined with the reported tendency of alloying elements such as manganese, silicon and phosphorus to segregate to grain boundaries during solidification, enhances intergranular failure [5]. These circumstances lead to insufficient mechanical properties during the cross tension strength (CTS) test and deteriorate the crash behavior. Therefore, the weldability of third generation AHSS is restricted [4, 6, 7].

In recent years, numerous studies [8–13] focused on the improvement of the mechanical properties of high strength steel spot welds. A simple way to improve the mechanical performance is to increase the load bearing area, namely the fusion zone (FZ), by increasing the heat input [4]. Due to Joule's law of $Q_w = I^2 \times R \times t$, the heat generation Q_w depends on the applied welding current I , the temperature-dependent and therefore dynamic resistance R and the

welding time t . For a given current, the heat input can consequently be increased by extending the welding time. For low carbon steels, the FZ size increases with extended welding times, especially at lower current levels, which leads to an enhanced weld strength [14]. It has been reported that the maximum force during the shear tensile test and the failure mode improved significantly for these steel grades due to longer welding times [15]. An enlargement of the FZ due to an extended welding time and a concomitant improvement of the mechanical properties was also reported for a micro-alloyed steel [16] and for high strength steels [17]. Again, the enlargement of the FZ due to longer welding times was more effective at lower currents since the maximum size is limited by its decreasing dynamic resistance and expulsion [4].

Generally, the mechanical properties of high strength steel welds can be improved by a post-processing heat treatment [18]. Double pulsing is a feasible approach to carry out the heat treatment in-process. Two concepts are suggested in literature. Both rely on a second pulse subsequent to a cooling time, that heat-treats the cast-like, often hard and brittle, FZ.

The first concept relies on quenching the FZ below the martensite finish temperature prior to a second pulse that aims to temper and consequently soften the martensitic FZ, resulting in enhanced toughness. It has been reported that the mechanical performance of TRIP steels can be improved significantly with this approach [19–22]. Especially, the elimination of the unwanted interfacial failure (IF) mode has been observed [23]. The cooling time between the pulses has to be long enough to ensure sufficient cooling of the FZ and the second pulse has to be lower than the first pulse to avoid re-austenitization of the FZ and extensive softening of the upper-critical heat affected zone (UCHAZ) [24].

In contrast, the second concept relies on recrystallizing the microstructure of the outer FZ with the second pulse. According to simulated thermal histories for third generation AHSS welds, the edge of the FZ cools down rapidly and even solidifies during extremely short cooling times between the pulses [10, 25]. Therefore, this concept is characterized by an extremely short cooling time to keep the temperature and therefore the dynamic resistance during the second pulse at a high level. A high-current second pulse is required to ensure sufficient heat input to achieve recrystallization of the outer FZ while the inner FZ re-melts. Therefore, the inner zone is

referred to as the secondary FZ and the initial FZ is termed the primary FZ [10]. According to literature [10, 22], the second pulse destroys the cast-like structure at the edge of the FZ and leads to more equiaxed prior austenite grains (PAGs). EftekhariMilani et al. [10] stated that this equiaxed shape is decisive in terms of the improved mechanical properties and that the recrystallization is accompanied by refinement and reduction of the block width which is reported to affect the mechanical performance in a positive way. Moreover, a second pulse is reported to lead to a refinement of the martensitic packets in the center of the FZ which is assumed to improve the peak load and failure mode during the CTS test [21]. It is also reported that elements such as phosphorus are more evenly distributed, especially after a high current second pulse, which reduces the risk of intergranular failure and improves the mechanical properties [10, 11]. Moreover, improved mechanical performance of a recrystallization pulse welded DP1000 dual-phase steel was attributed to the lowered residual strains at the edge of the FZ and the severe softening of the sub-critical heat affected zone (SCHAZ) [8]. Also, the fraction of high angle grain boundaries in the UCHAZ increased, leading to crack deflection and consequently to enhanced toughness [8].

Up to now, these concepts have never been comparatively studied on a third generation AHSS in order to reveal the microstructural evolution and the influence on the mechanical properties. Hence, in the present work, the described approaches were applied to a TBF steel with a tensile strength of 1 200 MPa. The aim of this study was to investigate the effect of the different double pulse welding sequences on the martensitic features of the FZ, the hardness distribution and consequently the mechanical properties and compare them to conventional and extended single pulse welds for this novel third generation AHSS grade.

2. Materials and methods

A TBF steel with a chemical composition of 0.2C/1.5Si/2.5Mn (wt.%) and a tensile strength of 1 200 MPa was investigated. A detailed microstructural characterization of this material [3, 26, 27] as well as the individual zones in the HAZ after resistance spot welding [24] were carried out in previous works. The nominal sheet thickness was 1.34 mm and the sheets were electrolytically galvanized with a coating thickness of 6.6–8.6 μm per side as specified

Fig. 1. Welding sequences of the (a) conventional single pulse, (b) extended single pulse, (c) temper pulse, and (d) recrystallization pulse.

in VDA 239-100 [28]. RSW was carried out on a Nimak MFDC-1000 Hz pedestal type welding machine, equipped with an AutoSpatz regulator that delivered a constant current. F1-16-20-6 electrodes with a force of 4.5 kN were used, as recommended in VDEh SEP1220-2 [29]. The present study compares samples welded with four different welding sequences, as illustrated in Fig. 1. Prior to the first pulse, a squeeze time of 600 ms was chosen and the hold time after the final pulse was 300 ms. The conventional single pulse is illustrated in Fig. 1a. It consists of a 380 ms lasting pulse with a current of 5.5 kA, which is the current just high enough to produce a FZ that fulfills the quality criterion of a minimum diameter of $4\sqrt{t}$, where t is the sheet thickness. This is the absolute lower limit of current, which is well below the splashing limit of about 6.8 kA for the single pulse weld. This current was chosen for the first pulse of

every sequence. The welding time was prolonged to 810 ms for the extended single pulse weld (Fig. 1b). Figure 1c represents a double pulse weld, where a 380 ms lasting temper pulse with a current of 4.5 kA was added after a cooling time of 1000 ms. Figure 1d illustrates a double pulse weld with a recrystallization pulse of the same time and current as the first pulse after a cooling time of 100 ms.

For light optical microscope (LOM) analyses, cross-sections were ground, polished and finally etched for two minutes with a mixture of 100 ml of cold saturated picric acid, 1 g sodium dodecylbenzenesulfonate and two drops of hydrochloric acid at room temperature. LOM images were taken with an M1M Imager equipped with an AxioCam MRc5 camera, both from Zeiss.

Electron backscatter diffraction (EBSD) measurements were obtained on a scanning electron microscope,

Fig. 2. LOM micrographs of cross-sections welded with the (a) conventional single pulse, (b,c) extended single pulse, (d) temper pulse, and (e,f) recrystallization pulse. The red boxes in (a), (b), (d) and (e) mark the areas where the EBSD measurements were conducted.

VERSA 3D from Thermo Fisher Scientific, equipped with an EDAX Hikari XP EBSD system operating at 20 kV. The working distance was 15 mm and the step size 250 nm. The sample preparation additionally included a final polishing step with an OPU suspension for several minutes to obtain a deformation-free surface. For data evaluation, the software package OIM Analysis 7 from EDAX was used. Grain confidence standardization and grain dilation clean-ups were carried out and data points with a confidence index below 0.1 were disregarded. To reconstruct the PAG boundaries, the ARPGE software package was used [30].

Hardness mappings were carried out with a Qness Q60A+ fully automatic micro hardness tester. The distance between the indents was 150 μm , the load 300 g and the dwell time 10 s.

The mechanical properties of the welds were determined by standard CTS tests performed with a cross-head speed of 10 mm min^{-1} on 150 $\times$ 50 mm² samples. The mechanical performance was evaluated by means of the

maximum force, F_{max} , and the pullout ratio, measured with a caliper after failure. The results represent the average of ten tests.

3. Results

3.1. Light optical microscopy

The influence of the different welding sequences on the microstructure was assessed based on LOM images of the cross-sections etched with picric acid, which are depicted in Fig. 2. The FZ of the conventional single pulse weld (Fig. 2a) shows a typical solidification structure with the dendrites oriented alongside the maximum heat dissipation. The shape of the FZ is rather elliptical with a width of 4.7 mm, indicated by the black arrow. This is in good agreement with the calculated minimum FZ size according to the quality criterion of $4\sqrt{t}$. However, due to the fact that the cross-sections do not always run perfectly through the center of the weld because of inaccuracies during the sample

Fig. 3. IPF maps of the outer FZ of the (a) conventional single pulse, (b) extended single pulse, (c) temper pulse, and (d) recrystallization pulse weld. The regions where the scans were taken are marked with red boxes in Fig. 2. The reconstructed PAGs are highlighted with bold black lines.

preparation, especially during cutting, the size of the FZ was additionally determined on tested samples which led to the same results. By extending the welding time to 810 ms the overall size of the FZ does not increase significantly, as shown by the black arrow in Fig. 2b, but can be subdivided into two zones. The inner zone, indicated by the red arrow, consists of fine dendrites and is surrounded by a zone with coarser dendrites, as can be derived from the detailed image in Fig. 2c. The width of this coarse zone is a few hundred micrometers. Moreover, the shape of the nugget is not as well defined compared to the conventional single pulse weld. By adding a temper pulse, the size of the FZ again does not increase remarkably, as shown by the black arrow in Fig. 2d, and the shape of the FZ is elliptical. The FZ of the sample welded with a recrystallization pulse is also not enlarged significantly and can be subdivided into two zones (Fig. 2e). The inner zone represents the secondary weld nugget (red arrow) and the primary FZ

is indicated by the black arrow. The outer part of the primary FZ undergoes an in-process recrystallization heat treatment during the second pulse. The width of the recrystallized zone is approximately 1 mm on both sides. At the transition zone between the primary and the secondary FZ the etchant reveals the grain boundaries of equiaxed grains, as illustrated in Fig. 2f.

3.2. Electron backscatter diffraction

In order to evaluate the effect of the various welding sequences on the microstructural features of the martensite, EBSD measurements were conducted at the edge of the FZ, as indicated by the red boxes in Fig. 2a, b, d and e. The inverse pole figure (IPF) maps are illustrated in Fig. 3, where the reconstructed PAG boundaries are highlighted with bold black lines. The PAGs of the single pulse weld exhibit a typical cast-like structure with elongated grains

Fig. 4. The misorientation distribution corresponding to the IPF maps depicted in Fig. 3 for the (a) conventional single pulse, (b) extended single pulse, (c) temper pulse, and (d) recrystallization pulse weld.

Fig. 5. Hardness mappings of the (a) conventional single pulse, (b) extended single pulse, (c) temper pulse, and (d) recrystallization pulse weld.

that are oriented alongside the maximum heat dissipation, as Fig. 3a illustrates. The corresponding misorientation distribution of the martensitic microstructure is depicted in Fig. 4a. An extended welding time leads to a distinctive coarsening of the PAGs, while the directional solidification structure is maintained, as can be seen in Fig. 3b. The fraction of high angle grain boundaries, especially with a misorientation near 60° , increases significantly while the fraction of low angle grain boundaries decreases, as illustrated in Fig. 4b. Figure 3c shows that the elongation of the PAGs diminishes. The misorientation distribution, depicted in Fig. 4c, looks similar to the distribution of the extended pulse weld (Fig. 4b) even though the peak near 60° is not as pronounced. The PAGs of the outer FZ of the recrystallization pulse weld, illustrated in Fig. 3d, seem to be coarser compared to the single pulse weld (Fig. 3a) and the cast-like structure with the elongated grains completely disappeared. Figure 4d reveals that a high fraction of 0.37 has a grain boundary misorientation angle of near 60° .

3.3. Hardness mappings

Hardness maps of the FZ and HAZ for all welding sequences are depicted in Fig. 5. The emerging zones are illustrated by means of the single pulse weld in Fig. 5a. A detailed definition and characterization of the zones in a resistance spot weld TBF steel can be found in a preliminary investigation [24]. The hardness increase of the conventional single pulse weld is strongly pronounced (Fig. 5a). The initial hardness of the base metal (BM) of 400 HV rises to over 500 HV in the FZ and reaches a maximum of 550 HV in the UCHAZ. The inter-critical heat affected zone (ICHAZ) shows a similar hardness to the BM. Because of tempering of the BM, the hardness in the SCHAZ drops to 370 HV. An extended welding time leads to an even harder inner part of the FZ (550 HV) surrounded by a slightly softer layer, as de-

picted in Fig. 5b. The SCHAZ is widened and at 320 HV the hardness drop is more pronounced. An implemented temper pulse softens the FZ and parts of the UCHAZ extensively, as shown in Fig. 5c. The hardness of the inner part of the FZ is approximately 370 HV and rises from the inside out reaching a maximum of 500 HV in the outer part of the UCHAZ. Softening of the SCHAZ is similar to the conventional single pulse. A recrystallization pulse again softens the SCHAZ but does not alter the hardness of the other zones significantly, as shown in Fig. 5d.

3.4. Cross tension strength tests

In order to evaluate the influence of the various welding sequences on the mechanical performance of the welds, CTS tests were carried out. The mechanical performance of the samples is hereinafter represented by the maximum force, $F_{\max}$, and the failure mode which is quantified by means of the pullout ratio in percent. A fraction of pullout of 0 % represents an interfacial failure (IF) and a fraction of pullout of 100 % represents a pullout failure (PF). Values between these limits represent a partially interfacial failure (PIF). As Fig. 6a shows, the single pulse welds bear an average load of 4.0 kN and the failure can be classified as PIF with a pullout ratio of 30 %. By extending the welding time to 810 ms the average force slightly increases to 4.7 kN with an average pullout ratio of 73 %. With 8.3 kN the temper pulse samples bear significantly higher loads than the single pulse samples. The pullout ratio is 55 %. For the recrystallization pulse the maximum force is 7.1 kN with a pullout ratio of 72 %. Representative load–displacement curves for each welding sequence are depicted in Fig. 6b. The curve for the single pulse (black) and the temper pulse weld (blue) drops abruptly to zero after reaching the maximum force, while it gradually drops for the extended pulse (red) and the recrystallization pulse weld (green).

Fig. 6. (a) Average maximum force and pullout ratio during CTS tests ($n = 10$), and (b) representative load displacement curves of the samples welded with different sequences.

4. Discussion

The aim of the present work was to compare different approaches to improve the mechanical performance of a resistance spot welded 1 200 MPa TBF steel. The mechanical performance of the single pulse weld is poor, as the average $F_{\max}$ of 4.0 kN and the PIF failure mode with a low average pullout ratio of 30 % (Fig. 6) indicate. Generally, a larger weld nugget provides a broader load bearing area, which results in a higher $F_{\max}$ at a given strength. Since the selected current is well below the splashing limit of 6.8 kA, it would be possible to increase the single pulse current to get a larger nugget, but the aim of this work was to compare the mechanical properties at the absolute lower limit of the welding current. Literature suggests that the FZ size can also be enlarged with an extended welding time, especially at lower current levels, while this effect diminishes at higher currents due to the risk of expulsion [14–16]. In addition to the increase of the bearable load during mechanical testing, the shift of the failure mode from IF to PF was reported for several steel grades due to an enlarged FZ [14–17]. Consequently, the first approach was to increase the heat input by extending the welding time and potentially enlarge the FZ. While $F_{\max}$ during the CTS test only increases slightly to 4.7 kN for the TBF steel under investigation, the failure mode due to the extended welding time improves significantly to a pullout ratio of 73 %, as can be seen in Fig. 6a. This improved failure mode can also be derived from the load–displacement curve in Fig. 6b because it gradually drops to zero, which indicates that the crack arrests. However, as Fig. 2b indicates, the FZ is not enlarged due to the extended welding time. Consequently, the improvement of the mechanical performance has to be attributed to another phenomenon. As Fig. 2b illustrates, the appearance of the outer FZ differs from the conventional single pulse weld (Fig. 2a). The magnified image in Fig. 2c shows that there is an outer FZ of a few hundred microns that consists of a much coarser dendritic microstructure than the inner FZ. Since nugget growth in the lateral direction seems to be finished after a conventional single pulse, this coarse zone must evolve during the additional 430 ms due to a slower solidification rate resulting from the interplay of heat generation on the one hand and heat extraction from the cooled electrodes on the other hand, as suggested by Krajcarz et al. [31]. The inner FZ stays liquid and solidifies rapidly during the final cooling step. Consequently, the inner FZ is finer and noticeably harder than the more slowly solidified outer FZ, as Fig. 5b shows. The EBSD results in Fig. 3b confirm that the PAGs of this zone are much coarser compared to the PAGs of the conventional single pulse weld in Fig. 3a, while the cast-like structure is still present. Furthermore, the extension of the welding pulse, and therefore a greater heat input, leads to a significant increase of the high grain boundaries near 60°, as the comparison of Fig. 4b and Fig. 4a reveals. The increase in the toughness of the weld of a multi-phase pipeline steel was attributed to the increased number of high angle grain boundaries due to an increased and optimized heat input by

You et al. [32]. Moreover, Chabok et al. [8] investigated the crack path through the recrystallized zone of a double pulse resistance spot welded DP1000 steel and observed that the crack is predominantly deflected at high angle grain boundaries with a misorientation of over 50°. Consequently, the high number of high angle grain boundaries may be responsible for crack deflection at the outer FZ leading to a more favorable failure mode for the samples welded with an extended single pulse. Additionally, the softening of the SCHAZ is more pronounced compared to the conventional single pulse weld (Fig. 5a), a circumstance that was reported to be a key reason for the improvement of the mechanical properties of a double pulse welded high strength dual-phase steel [8].

In general, the poor mechanical properties of third generation AHSS spot welds can mainly be attributed to the combination of a cast-like structure and the hardness increase in the FZ due to the relatively high alloying content [4]. Hence, the goal of both double pulsing approaches is to eliminate one of those factors. A tempering heat treatment of the welds is generally a capable way to improve the mechanical performance [18]. In this work an in-process tempering heat treatment was achieved by means of a second pulse subsequent to a long cooling time. As Fig. 5c illustrates, the hardness of the FZ decreases to a hardness similar to the BM of about 400 HV at the edge of the FZ because of the second pulse. In contrast, the softening of UCHAZ is not as pronounced and this zone is therefore more rigid than the tempered FZ. As the bearable load strongly increases to 8.3 kN with an average pullout ratio of 55 % (Fig. 6), this combination of a soft and therefore tough FZ and a still hard and therefore strong UCHAZ seems to be ideal in terms of the mechanical performance, as suggested in a previous work [24]. However, the parameters have to be chosen very carefully. On the one hand, the second pulse has to be strong enough to enable tempering. On the other hand, the heat input of the second pulse must not be too high so that re-austenitization of the FZ and unwanted excessive tempering of the UCHAZ are avoided [24]. The tempering leads to an increase in the fraction of high angle grain boundaries (Fig. 4c), which is presumed to promote crack deflection, as discussed above. The drawback of this approach is the more than doubled process time compared to the conventional single pulse weld.

The concept of the recrystallization pulse relies on a short cooling time after the first pulse, where solidification of the FZ takes place. By an immediately following second pulse of the same current, the inner part of the FZ re-melts and the outer part recrystallizes during the second pulse. The LOM image of the cross-section (Fig. 2e) shows that the FZ can indeed be subdivided into the secondary FZ that re-melted during the second pulse and the surrounding part of the primary FZ that underwent the desired heat treatment. The etching reveals a non-dendritic grain structure at the transition zone between secondary and primary FZ, as illustrated in Fig. 2e. Moreover, as the highlighted PAG boundaries in Fig. 3d show, the recrystallization leads to equiaxed PAGs close to the pre-crack. The equiaxed shape of the PAGs is assumed to be one of the main reasons for enhanced mechanical prop-

erties of double pulse welded AHSS steel sheets as it impedes the fracture path through the nugget centerline [10, 22]. This was also observed in the framework of the present research. Moreover, the recrystallization modifies the arrangement of the grain boundaries, resulting in a significant increase of high angle grain boundaries near 60° , as shown in Fig. 4d. The hardness mapping (Fig. 5d) illustrates that the softening of the SCHAZ is more pronounced compared to the single pulse weld, which is seen as beneficial for the mechanical properties [8], as mentioned above. However, a softening of the recrystallized zone, as reported in literature [8, 9], was not observed. Figure 3d indicates that the recrystallization pulse also leads to a coarsening of the microstructure at the edge of the FZ, which is attributed to grain growth due to the high temperature during the second pulse. This seems to be contrary to the results of Sajjadi-Nikoo et al. [21] and Eftekharimilani et al. [11], which both reported grain refinement as a result of double pulsing. This different grain growth behavior can be attributed to the lower second pulse currents they applied in their studies. In addition, Sajjadi-Nikoo et al. [21], applied a longer cooling time between the pulses, which resulted in lower heat input and therefore inhibited grain growth compared to the present work. At a higher second pulse current, Eftekharimilani et al. [11] also observed grain growth due to the higher temperature. Besides the modification of the morphology of the PAGs and the softening of the SCHAZ, the homogenization of phosphorus due to the second pulse is considered as another main benefit. A correlation between improved mechanical properties and a homogenization of phosphorus, detected via electron probe microscopy analyses (EPMA), has been established for third generation AHSS welds [11, 13]. Within the framework of this study, EPMA measurements were conducted as well, without observing noteworthy differences in the phosphorus distribution. Due to the recrystallization pulse the mechanical performance during the CTS test is improved significantly, as shown in Fig. 6. The maximum force reaches 7.1 kN with a pullout ratio of 72 %. Consequently, the mechanical performance is distinctively enhanced compared to the single pulse welds, with the advantage of a much shorter process time compared to the temper pulse sequence.

5. Conclusions

In the present work three different approaches to improve the mechanical performance, according to CTS testing, of a resistance spot welded 1 200 MPa TBF steel were evaluated and compared with a conventional single pulse weld. The following conclusions can be drawn:

1. The conventional single pulse weld possesses poor mechanical properties during the CTS test, with an $F_{\max}$ of 4.0 kN and an unfavorable failure mode with a pullout ratio of 30 %. Its outer FZ consists of elongated PAGs that are oriented alongside the maximum heat dissipation.
2. An extended welding time does not enlarge the FZ but leads to a distinctive coarsening of the PAGs of the outer FZ and to an increase in the fraction of the high angle

grain boundaries near 60° . The mechanical performance regarding the maximum force during the CTS test only improves slightly to 4.7 kN, but the failure mode, quantified by the pullout ratio, improves to 73 % which is mainly attributed to the increased fraction of high angle grain boundaries.

3. Double pulsing with a low current temper pulse following an extended cooling time of 1 000 ms between the pulses leads to pronounced softening of the FZ and parts of the UHAZ due to tempering which results in a high $F_{\max}$ of 8.1 kN. A refinement of the microstructure and an increase in the fraction of high angle grain boundaries near 60° at the edge of the FZ can be observed which leads to an average pullout ratio of 55 %.
4. Double pulsing with a recrystallization pulse of the same current as the first pulse following a very short cooling time of 100 ms successfully recrystallizes the edge of the FZ. The martensitic microstructure is much coarser but the PAGs are equiaxed and the fraction of high angle grain boundaries near 60° increases significantly. The resulting crack deflection results in an improved mechanical performance during the CTS test to a maximum force of 7.1 kN with an average pullout ratio of 71 %.

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