Influence of multi-pass friction stir processing on microstructure and mechanical properties of die cast Al-7Si-3Cu aluminium alloy

L. John Baruch[a], R. Raju[b], V. Balasubramanian[c], A.G. Rao[d], I. Dinaharan[e*]

[a]Professor, Department of Mechanical Engineering, Achariya college of Engineering Technology, Villianur 605110, Puducherry, India. E-Mail: johnbaruch1968@gmail.com

[b]Professor, Department of Industrial Engineering, College of Engineering, Anna University, Chennai 600025, Tamil Nadu, India. E-Mail: krrajuin@yahoo.co.in

[c]Professor, Centre for Materials Joining and Research (CEMAJOR), Department of Manufacturing Engineering, Annamalai University, Annamalai Nagar, Chidambaram 608002 Tamil Nadu, India. E-Mail: visvabalu@yahoo.com

[d]Scientist 'B', Marine Materials Division, Naval Materials Research Laboratory, Thane 421506, Maharashtra, India. E-Mail: gourav@nmrl.drdo.in

[e*]Corresponding Author -Post Doctoral Research Fellow, Department of Mechanical Engineering Science, University of Johannesburg, Auckland Park Kingsway Campus, Johannesburg 2006, South Africa. E-Mail: dinaweld2009@gmail.com

Abstract

The influence of overlap multi-pass friction stir processing on the microstructure and mechanical properties, in particular, strength, ductility and hardness of die cast Al-7Si-3Cu aluminium alloy was investigated. It was observed that with the increasing number of overlap passes friction stir processing resulted in significant refinement and redistribution of aluminium silicon eutectic phase with elimination of casting porosities. The microstructural refinement by the friction stir processing not only increases the ultimate tensile strength from 121to 273 MPa, but also increases the ductility as observed by the increase in fracture strain from 1.8% to 10%. Analysis of the fractured surface reveal that microstructural refinement obtained by friction stir processing plays a vital role in transforming the fracture mode from completely mixed mode to ductile mode of fracture with increasing number of passes. Change in the size, shape, morphology and distribution of eutectic silicon particles and elimination of porosities are the main reasons for the increase in tensile strength and ductility due to friction stir processing.

Keywords: Friction Stir Processing, Overlap Multi-Pass, Microstructure, Mechanical Properties

I. INTRODUCTION

Al-Si–Cu alloys are widely used to cast high strength components in aerospace and automobile industries. However, porosity, coarse acicular Si particles and coarse aluminum dendrites in the cast structure reduce the mechanical properties of the castings, particularly the ductility, toughness and fatigue strength [1, 2]. Eutectic modifiers and high temperature heat treatment are widely used to modify the cast microstructure [3, 4]. These processes do not have significant effect on the refinement of silicon particles and elimination of casting porosities. Friction stir processing (FSP), an expansion based on the principle of friction stir welding (FSW) [5], is reported to be an effective route to refine the microstructure, and to eliminate casting porosities and thereby enhancing the mechanical properties of cast Al-Si alloys [6-11]. FSP is a solid state processing technology, in which a rotating tool with pin and shoulder is inserted into a single piece of material and traversed along the desired path to cover the region of interest. A volume of processed material is produced by material movement around the pin. During this process, the material undergoes intense thermo-mechanical deformation, resulting in a generation of fine recrystallized grains with fragmentation and redistribution of second phases particle in the processed region or stir zone. FSP, due to its flexibility is also used for bulk microstructural refinement to produce fine grained alloys [12-15], synthesis of in situ, bulk and surface composite [16-20], metallic foams [21-22], channeling [23], functionally graded materials [24] and modification of electrical conductivity [25].

Process parameters are the key art of Friction Stir Processing. Specifying the tool geometry and the stirring conditions (rotational and translational speeds) are important issues in FSP in order to obtain the desired grain refinement. The rotation of tool results in stirring and mixing of material around the rotating pin and the translation of tool moves the stirred material from the front to the back of the pin and finishes the welding process. The input process/welding parameters influence the heat generation and the flow of the plasticized material and eventually they affect the microstructure and mechanical properties of the processed volume / weldment.

The resulting microstructure is composed of three primary zones: the heat affected zone (HAZ), the thermo mechanically affected zone (TMAZ) and the stir zone (SZ). FSP, imparts property enhancement such as ductility, strength, corrosion, wear resistance and also induces super plasticity [26]. For example, in cast A356 aluminum alloy, FSP resulted in a significant break up of coarse acicular Si particles and the primary aluminum dendrites. This process produces a homogeneous distribution of Si particles in the aluminum matrix and nearly eliminated all casting porosity [27-28]. These microstructural modifications significantly improved the mechanical properties of the cast A356, in particular the ductility and fatigue life [10, 11]. Also, Ma and co workers [27] reported formation of supersaturated solid solution of A356 after FSP with enhanced mechanical properties after post FSP ageing treatment.

Magdy M.El-Rayes and Ehab A.El-Danaf[29] analysed the influence of multi-pass friction stir processing on the microstructural and mechanical properties of aluminum alloy 6082.They found from tensile test results, that there is a good agreement between UTS and the hardness value as well as particle size, where the UTS increases with increasing hardness and reducing particle size. Cui et al. [30] investigated the effects of FSP parameters and in Situ passes on microstructure and tensile properties of Al-Si-Mg casting. They concluded that for the multi-pass FSP, the 2-pass FSP sample exhibited an obvious advantage in the microstructure modification and tensile properties compared with the single-pass sample. The grain refinement of the microstructure and the removal of MIG weld defects, achieved by the friction stir processing, have the major contribution to the improvement of fatigue resistance [31]. Naersh et al. [32] studied a bottom-up approach for optimization of friction stir processing parameters; a study of aluminium 2024-T3 alloy. They found that the proper combination of strength of ductility was obtained with FSP, which is not possible by other Severe Plastic Deformation (SPD) techniques.

Applying FSP on the as-cast LM 13 Al alloy decreases the brittleness significantly and after each pass of FSP the ductility increases [33]. Devinder Yadav and Ranjit Bauri [34] analysed the effect of friction stir processing on microstructure and mechanical properties of aluminium. They concluded that the strength of the FSPed material improved significantly and at the same time the ductility was also retained. Saied et al. [35] produced AA5083/ZrO_2

Nanocomposite by Friction stir processing and concluded that the microstructures in the FSPed specimens with nano- ZrO_2 particles can be refined to a much smaller scale than the parent alloy. They also reported that the recrystalized grains were equiaxed and have a similar size distribution. Friction stir processing has successfully evolved as an alternative technique of fabricating metal matrix composite [36]. FSP is an effective microstructural modification process that produces finer and more homogenous grain structure especially in presence of SiC particles[37].Kumar et al.[38] investigated the microstructure and mechanical behavior of friction stir processed ultrafine grained Al-Mg-Sc alloy. They concluded that FSP resulted into substantial grain refinement of twin-roll cast alloy (80% of the grain size being less than 1μm). They also reported that the increase in yield strength can be mainly attributed to grain refinement during FSP.

From published literature, it is understood that FSP can be effectively used for modifying the microstructure. Most of the published information are focused on single pass FSP and the information on multi-pass FSP is very scant. Hence the present work is aimed to study the effect of multi-pass friction stir processing on microstructural refinement and resulting mechanical properties, of die cast alloy AS7U3G and also to study the effect of post FSP heat treatment response.

2. EXPERIMENTAL WORK

The chemical composition of AS7U3Galloy is presented in Table 1. The alloy used for FSP was cut into rectangular pieces of dimensions 150 X 50 X10 mm. FSP tool was fabricated from high carbon steel having concave shoulder of 18 mm diameter and threaded cylindrical pin of 6 mm diameter and 6 mm length. An indigenously designed and developed FSW machine of 60 kN capacity was used for FSP. The tool rotation and tool traverse speeds were kept constant at 600 rpm and 12 mm/min respectively in all the experiments. Two pass and three pass FSP experiments were performed with 100% overlap over the previous processed zone.

Specimens for microstructural characterization, tensile and hardness testing were machined from the stir zone. ASTM E8M guidelines were followed for fabricating the tensile test specimens. The specimens for tensile tests as shown in Fig.1 were machined from the longitudinal direction parallel to the direction of processing. The specimens were having a gauge length of 25 mm, gauge thickness of 3 mm, grip length of 15 mm and grip width of 24 mm, respectively. Wilson Wolpat make Vickers microhardness testing machine was employed for carrying out the hardness measurement with a load of 0.5 kg and a dwell period of 10 s. Both the base material and the FSPed zones were examined by scanning electron microscopy (SEM) to characterize the extent of microstructural refinement. Image Pro Plus® image analysis software was utilized for quantitative analysis of Al-Si eutectic particles. Specimen for microstructural analysis were initially ground with using various grade of emery papers and 1 μm diamond paste was used for final polishing. The base material and processed zone were etched with
0.5% hydrofluoric acid.

3. RESULTS

3.1 Microstructure

Scanning electron microscopy (SEM) examination was carried out to study the influence of the number of overlapping passes on the microstructure of friction stirred processed region. Fig. 2 illustrates typical SEM micrographs of (a) as cast base alloy, (b) one pass stir zone, (c) two overlap pass stir zone and (d) three overlap pass stir zone. These micrographs distinctly reveal the significant effect of friction stir processing on the size, shape, and distribution of Al-Si eutectic particles with increasing number of passes. However, the size of the Al-Si eutectic particles in the stir zones decreases with the increasing number of overlap FSP passes. Also, the overlap passes not only refines the Al-Si eutectic particles inter connected network but also homogenize the microstructure. Fig.2 (a), (b), (c) and (d) clearly indicates the extent of refinement and the area fraction of Al-Si eutectic particles, increases after each overlap pass, thus having more refined and homogeneous structure in three overlap FSPed alloy.

Fig.2 (a1), (b1), (c1) and (d1) shows the energy- dispersive spectra of base metal and the stir zones of one-pass, two-pass and three-pass FSPed specimens. The energy-dispersive spectra (EDS) of base metal showed the presence of all the alloying elements, but the amount of magnesium quantified is very less. In the stir zones of one-pass, two-pass and three-pass samples, magnesium was not detected by EDS. Similar results were also showed by the work of Ma et al.[27], revealing dissolution of coarse Mg_2Si precipitates in the as-cast A356 sample after FSP. The accelerated dissolution of the Mg_2Si precipitates during a short period of the FSW cycle was attributed to significantly accelerated diffusion rates and shortened diffusion distances of the solutes resulting from intense plastic deformation and material mixing [27]. Because of fast cooling cycle during FSP, majority of solutes were retained in the matrix, thereby, produces super saturated solid solution in FSP processed alloy. Therefore, after three pass FSP the alloy was subjected to artificial aging treatment at 100°C. In the FSPed zone of three pass HT sample, the heat treatment did not change the distribution of Si particles but resulted in significant particle growth [Fig. 3 (a)]. However, after artificial aging it is not possible to reveal the distribution of the precipitates (Mg_2Si & $CuAl_2$) by SEM but the energy dispersive analysis clearly indicate the presence of these precipitates in Fig. 3 (a1).

Table 2 shows the quantitative microstructural characterization result of eutectic Si particle in the cast AS7U3G alloy and after one, two, three overlap friction stir processing and three overlap FSP after artificial aging. The Al-Si eutectic phases are in the form of large interconnected network of acicular shaped particles in the cast alloy (Fig.2a). The size of the Al-Si eutectic particles in base metal are in the range of 1.12 to 23.36 µm, with aspect ratio of 3.70, measured for more than 100 particles. However, after one pass of FSP, the average Si particle size value was drastically reduced to 1.17± 1.00 µm. Further reduction in the average Al-Si eutectic particle size values to 0.86 µm and 0.80 µm were obtained in the case of two and triple overlap pass FSP samples, measured on more than 250 Al-Si eutectic particles. Also, in post FSP precipitation hardening, the average Si particle size and aspect ratio was increased to 1.47 µm and 1.72 µm respectively. This indicates the precipitation hardening has resulted in substantial particle growth. Although the size reduction of the Al-Si eutectic silicon particles from one to three pass FSP was not significant but the decrease in aspect ratio, defined as the ratio of length (L) to width (W) was noticeable. The aspect ratio (Φ) is given by (1).

$$\Phi = \frac{L}{W} \qquad (1)$$

3.2 Tensile properties

The longitudinal tensile properties, such as yield strength, tensile strength and ductility of the FSPed materials were evaluated. Data comparing the tensile behavior of as cast and FSPed materials are presented in Fig. 4.The tensile strengths of the one pass, two pass, and three pass FSPed materials are significantly higher than that of the as cast alloy. The tensile strength of three pass FSPed material is 273 MPa which is 2.25 times higher compared to that of the as-cast alloy of 121 MPa. Generally the increase of strength leads to decrease in ductility but the FSP of this alloy resulted in enhancing the ductility from 1.8% to 10%, due to uniform distribution of fine eutectic precipitates throughout the matrix.

3.3 Hardness

The effect of number of passes on the distribution of hardness across FSP region is presented in Fig.5. Soft spots found in the casting due to porosity and aluminum dendrite cores were eliminated by friction stir processing. The distribution of hardness values also appears narrower in the stir zone. This is consistent with its more uniform microstructure. The average hardness values in one pass, two pass, and three pass FSPed AS7U3G alloy are lower than that of the as cast alloy. Microhardness values indicate a softening of the processed material at the friction stir processed zone due to inherent nature of the process. With an increase in number of passes, an increase in the microhardness values was observed in the processed materials. However, post-FSP precipitation hardening treatment had a significant effect on the hardness of the three-pass sample. Nearly 30% increase was found in average hardness value in three-pass sample after heat treatment. The average hardness value of the three-pass sample after heat treatment was 105Hv, which is around 5% higher compared to the base metal average hardness value of 100Hv.The effect of friction stir processing on the distribution of hardness across FSP region before and after precipitation hardening is given in Fig.6.

3.4 Fractography

The fracture surfaces of tensile tested specimens of friction stir processed aluminum alloy were analyzed using SEM to reveal the morphology of fracture surface. Fig.7a-e displays the fractographs of the unprocessed and the processed materials. The fracture surfaces of the FSPed specimens reveal ductile fracture mode, however the fracture surface of cast alloy exhibit mixed mode fracture with cleavage plane and small amount of dimples. The nucleation and coalescence of voids around brittle cleavage plane is clearly visible from the fractographs.

4. DISCUSSION

4.1 Effect of multiple-pass FSP on microstructure

Multiple pass FSP resulted in significant refinement in the microstructure of the cast alloy. The stirring action of the FSP at the nugget zone fragmented the large interconnected eutectic silicon network into fine globular Al-Si eutectic particles. The stirring action during FSP causes the material movement from the advancing to retracting side and therefore, is responsible for eliminating the casting porosities. Virtually all traces of dendritic solidified microstructure were eliminated throughout the stir zone. With increasing number of FSP passes, the refinement of Si particles increased. Double pass FSP produced a pronounced effect in refining the stir zone microstructure and the break-up of the Si particles is further intensified in the three pass FSP. Three pass FSP produced a remarkable effect on microstructural refinement, homogeneity and densification of Si particles. The reduction in the average size of Si particles after single pass FSP of AS7U3G alloy is 79%, which further refined to 84.6% and 85.6% after two pass and three pass FSP respectively.

In the case of hypoeutectic A356 aluminum alloy, Ma et al. [27] have reported about 86% reduction in the average size of Si particles after one pass FSP. They have also reported that the 50% overlapped multi-pass FSP did not influence the size, aspect ratio and distribution of Si particles.The FSPed grain sizes of 99% and 99.99% pure aluminum were found to be less than 10 µm under all processing conditions; there was little observed difference in grain size between these purity levels [42]. Rao et al. [12] reported that double pass FSP with 100% overlapping on the top of the first pass itself had a pronounced effect on size, shape, and distribution of Si particles.The reduction in the average size of the Si particles after single pass FSP is 98%., which further refined to 99% after second pass. Ranjit et al.[43] reported that in a two pass FSP of Al-TiC in situ composite,the grain size was refined substantially after each FSP pass. Silicon particle reduces considerably, as the pass number increases[33].

Similarly, Nakata et al. [44] produced a fine grain structure of 2–3 μm in ADC12 die casting alloy via multi-pass FSP. However, for AA2219 Al alloy, single-pass FSP resulted in an average grain size of 6.2 μm, but in the subsequent passes (two-pass, three-pass) the average grain size showed a marginal increase, reported by Surekha etal. [45]. Nascimento et al. [46] reported that for AA7022- T6 alloy, single-pass FSP reduced the grain size from 160 μm to an average grain size of 7.1 μm and this remained constant independently of the number of passes and overlap ratios tested. The result of the present study indicated that, with the increase in number of passes, a decrease in size of Al-Si eutectic particles is obtained, which is in agreement with that reported by Ma et al.[25] and Tutinchilar et al.[33].

This proves that FSP with 100% overlap pass continues to homogenize the microstructure in the stir zone. In comparison, the sample processed with three passes with 100% overlapping, exhibited a more homogeneous processed area with average Si particle size of 800 nm.

4.2 Effect of multiple-pass FSP on tensile properties

From the experimental results (Fig. 4), it is very clear that multiple-pass FSP resulted in remarkable improvement in the longitudinal tensile properties of AS7U3G aluminum alloy. Significant microstructural refinement, homogeneity and densification by multiple- FSP in AS7U3G casting resulted in remarkable improvement in the tensile properties. From the above investigation the factors for the increasing the tensile strength for the multiple-pass FSPed materials can be stated as : (1) elimination of casting defects (such as porosity); (2) breaking of eutectic network structure and uniform distribution of the fine Si particles; (3) grain refinement of alpha aluminum matrix. The acicular shaped Al-Si eutectic network provide favorable crack path during deformation once crack is initiated. Whereas, the globular Al-Si eutectic after FSP reduces the stress concentration and acts as barrier to dislocation movement and therefore FSPed material displayed superior tensile properties than the cast alloy. Cui et al. [30] reported that in multi-pass FSP, the two pass FSP sample exhibited an obvious advantage in the microstructure modification and tensile properties compared with the single pass sample.

Usually, cast alloys always show lower ductility as compared to wrought alloys due to the presence of larger grains, porosity and homogeneity of microstructure. All the processed specimens invariably showed considerable increase in ductility compared to the base metal. The elongation of three pass FSPed sample is 10%, which is almost 6 times higher than that of the as cast unprocessed alloy. FSP is an appropriate method to modify the microstructure and mechanical properties of 1050 Al-alloy [47]. By increasing the pass number, both tensile strength and elongation are enhanced due to the decrease in Si particle size accompanied by better particle distribution [33]

Post-FSP heat treatment increased the tensile strength value by around 15% compared to the three pass FSPed material without heat treatment. This is due to the re-precipitation of $CuAl_2$ and Mg_2Si precipitates during the precipitation hardening. The precipitates not only pins the dislocation but also acts as a source for nucleation of dislocations, thereby increasing the dislocation density. This has resulted in improvement of hardness and enhanced tensile properties. The percentage elongation is doubled in the Post-FSP heat treated condition. This can be attributed to the bimodal distributions of eutectic silicon particles and precipitates in the alloy. Elangovan and Balasubramanian [48] reported that uniformly distributed finer strengthening Mg_2Si precipitates, smaller grain size, the lack of a precipitate free zone, and higher dislocation density are the reasons for the superior tensile properties of the artificially aged FSW joints. For the AC8A alloy processed by friction stir processing, a post-FSP aging treatment (448 K-8h) increased the UTS by 15% but decreased the ductility by 42% [49].

After FSP the alloy displays increase in both strength and ductility. Because the alloy after FSP consists of high density of small Al-Si eutectic particles in aluminum matrix, therefore the Al-Si eutectic particles, precipitates and high angle grain boundary will act as obstacles to dislocation movement. The amount of strengthening due to the obstacles will depend on the grain size, Al-Si eutectic particles size and the average distance between the particles. When the average distance between the particles is smaller than the grain size, the particles act as major obstacle to the dislocations movement. With the increasing number of FSP passes the α-grain size as well as Al-Si eutectic particles size were found to decrease simultaneously and the volume fraction of the Al-Si eutectic particles was found to increase. When the small particle pin the mobile dislocations more often than the grain boundaries, the particle size dependence on strength increases. It also confirms that in this case the grain boundary acts as only a secondary obstacle to dislocations. This explanation is valid after FSP, as samples show both higher strength as well as ductility.

4.3 Effect of multiple-pass FSP on microhardness

In general, the hardness of aluminum alloys can be increased by several methods: solid-solution hardening, grain refinement strengthening, work or strain hardening, and precipitation hardening(aging). It was found that the hardness in the FSPedregion increased with an increase in number of passes. The effect of frictional heat on microstructure during single pass FSP results in generation of dynamic recrystallized grains having low dislocation density, reduction of dislocation density having greater effect on softening than the hardening effect of increased grain-boundary area, through dynamic recrystallization. Surekha et al.[50] indicated that the dissolution of second phase particles in the matrix of AA2219 aluminum alloy decreased the hardness value in FSP samples though the grain size is finer compared to the base metal. Santella et al. [51] reported that the thermo mechanical treatment cycle of the friction stir processing had a hardening effect in A319 and a slight softening effect on A356.The subsequent increase in hardness upon two pass FSP and three pass FSP could be due to the significant increase in dislocation density and frequency of sub micron silicon particles in the stir zone. Surekha et al. [45] observed that for AA 2219 aluminum alloy the average hardness values in the nugget region increased with increase in number of passes (up to 3 passes) and they are lower than that of the base metal hardness. Lu et al. [52] reported that the Si particle size decreases and the microhardness increases, as the FSP pass number increases. Hardness increased significantly by increasing the number of FSP passes due to their refining effect and uniformity enhancement of Al_3Ni particles in the treated layer [53].

The average hardness values in both single pass FSP and two pass FSP friction stir processed Al-30Si alloy were lower than that of the base metal [12]. The microhardness behavior of friction stir processed AS7U3G aluminum alloy is consistent with the behavior pattern of Ref[45, 52, 53, 12].Also, in post precipitation hardening the hardness was increased from 80 to 105 Hv in three pass overlap FSP. The main reason for the increased hardness is the precipitation of Mg_2Si and $CuAl_2$ precipitates. These precipitates effectively pins the mobile dislocations and causes the hardening of matrix.

4.4 Effect of multiple-pass FSP on Fracture Surface analysis

Furthermore, the analysis and understanding of the tensile curve will give better insight into the behavior of the alloy. Fig.7 (a) to (e) illustrates the schematic representation of deformation behavior of the as cast alloy and after FSP during uniaxial tensile test. The as cast alloy is characterized by low strength and ductility, owing to the presence of acicular network of Al-Si eutectic particles and porosities as earlier stated. The failure of the as cast alloy exhibits a low energy mixed mode fracture. The alloy showed ductile trans-crystalline mixed fracture, where decohesion takes place on both the aluminum matrix as well as on silicon particles. The surface is characterized by both ductile dimples and brittle cleavage and showed some deformation before fracture as shown in the Fig.7 (a). Fig. 7 (b) to (e) shows the tensile behavior of one to three pass and three pass HT FSPed specimens. The dark phase represents the silicon particles. The mechanism during the deformation is mainly by slip with the nucleation and coalescence of micro voids and dimples. By increasing the FSP pass number, dimples become smaller and deeper as observed by Tutinchilar [33] in a multi-pass FSP of LM13 eutectic Al-Si as cast alloy. The increase in ductility and strength after precipitation hardening treatment is due to more homogeneous structure as revealed and more uniform dimples as shown in the Fig.7 (e).

5. CONCLUSIONS

In this investigation, cast AS7U3G (Al-Si-Mg (Cu)) aluminum alloy was friction stir processed (FSP) with multiple passes (100% overlap) and the following important conclusions are derived;

(i) FSP resulted in the significant break up of acicular networked fibrous Al-Si eutectic particles and aluminum dendrites and led to redistribution of fine and equiaxed Al-Si eutectic particles in the aluminum matrix. Both the size as well as aspect ratio of Al-Si eutectic particles decreased simultaneously with the increase in number of FSP passes.

(ii) The hardness in the friction stir processed region increased with increase in number of passes. However, the hardness after FSP was lower than the cast alloy. This may be due to reduction in dislocation density, which has more effect on matrix hardening rather than grain boundary hardening.

(iii) The tensile strength and ductility of three pass friction stir processed material was remarkably higher compared to that of the cast alloy.

(iv) Post FSP precipitation hardening increased the strength, ductility and hardness. The fracture surface revealed the transition of fracture mode from transcrystalline-ductile tocompletely ductile mode.

ACKNOWLEDGEMENT

The authors are grateful to the Centre for Materials Joining & Research (CEMAJOR), Department of manufacturing Engineering, Annamalai University, Annamalai Nagar, Tamil Nadu, India for extending the facilities of metal Joining Laboratory to carry out this investigation.

REFERENCES

1. D.L. Zhang, L. Zheng, Metall. Mater. Trans. A **27**, 3983 (1996**)**
2. Y.B. Yu, P.Y. Song, S.S. Kim, J.H. Lee, Scripta Mater. **41**, 767 (1999)
3. G. Atxang, A. Pelayo, A.M. Irrisarri, Mater. Sci. Tech. **17**, 446 (2001)
4. K.T. Kashyap, S. Murali, K.S. Raman, K.S.S. Murthy, Mater. Sci. Tech. **9**, 189 (1993)
5. W.M. Thomas, *US Patent Patent Application No. 9125978.8* (1991)

6. R.S. Mishra, Z.Y. Ma, I. Charit, Mater. Sci. Eng. A **341**, 307 (2003)
7. P.B. Berbon, W.H. Bingel, R.S. Mishra, C.C. Bampton, M.W. Mohaney, Scripta Mater. **44**, 61 (2001)
8. A. Tewari, J.E. Spowart, A.M. Gokhale, R.S. Mishra, D.B. Miracle, Mater. Sci. Eng. A **428**, 80 (2006)
9. Z.Y. Ma, S.R. Sharma, R.S. Mishra, Mater. Sci. Eng. A **433**, 269 (2006)
10. Z.Y. Ma, S.R. Sharma, R.S. Mishra, M.W. Mohaney, Mater. Sci. forum **426–432**, 2891 (2003)
11. S.R. Sharma, Z.Y. Ma, R.S. Mishra, Scripta Mater. **51**, 237 (2004)
12. A.G. Rao, B.R.K. Rao, V.P. Deshmukh, A.K. Shah, B.P. Kashyap, Mater. Lett. **63**, 2628 (2009)
13. S. Jana, R.S. Mishra, J.A. Baumann, G.J. Grant, Metall. Mater. Trans. A **41**, 2507 (2010)
14. J.Q. Su, T.W. Nelson, C.J. Sterling, Phil. Mag. **86**, 1 (2006)
15. Z.Y. Ma, S.R. Sharma, R.S. Mishra, Metall. Mater. Trans. A **37**, 3323 (2006)
16. C.F. Chen, P.W. Kao, L.W. Chang, N.J. Ho, Metall. Mater. Trans. A **41**, 513 (2010)
17. K. Liming, H. Chunping, L. Xing, H. Kehui, J. Alloy Compd. **503**, 494 (2010)
18. M. Yang, C. Xu, C. Wu, K. Lin, Y.J. Chao, L. An, J. Mater. Sci. **45**, 4431 (2010)
19. B. Zahmatkesh, M.H. Enayati, Mater. Sci. Eng. A **527**, 6734 (2010)
20. D. Yadav, R. Bauri, Mater. Sci. Eng. A **528**, 1326 (2011)
21. Y. Hangai, H. Kato, T. Utsunomiya, S. Kitahara, Metall. Mater. Trans. A **41**, 1883 (2010)
22. Y. Hangai, T. Utsunomiya, M. Hasegawa, J. Mater. Process. Technol. **210**, 228 (2010)
23. N. Balasubramanian, R.S. Mishra, K. Krishnamurthy, J. Mater. Process. Technol. **209**, 3696 (2008)

24. R.M. Miranda, G.S. Telmo, J. Gandra, N. Lopes, R.J.C. Silva, J. Mater. Process. Technol. **213**, 1609 (2013)
25. G.S. Telmo, R.M. Miranda, P. Vilica, J.P. Teixeira, Int. J. Adv. Manuf. Technol. **57**, 511 (2011)
26. M.A. Garc, A. Bernal, R.S. Mishra, R. Verma, D.H. Silva, Scripta Mater. **60**, 850 (2009)
27. Z.Y. Ma, S.R. Sharma, R.S. Mishra, Metall. Mater. Trans. A **37**, 3323 (2006)
28. Z.Y. Ma, S.R. Sharma, R.S. Mishra, Scripta Mater. **54**, 1623 (2006)
29. M.M.E. Rayes, E.A.E. Danaf, J. Mater. Process. Technol. **212**, 1157 (2012)
30. G.R. Cui, D.R. Ni, Z.Y. Ma, S.X. Li, Metall. Mater. Trans. A **45**, 5318 (2014)
31. J.D.M. Costa, J.S. Jesus, A. Loureiro, J.A.M. Ferreira, L.P. Borrego, Int. J. fatigue **61**, 244 (2014)
32. N. Nadammal, K.V. Satish, S. Suwas, Mater. Des. **65**, 127 (2014)
33. S. Tutinchilar, G.M.K. Besharati, M. Haghpanahi, P. Asadi, Mater. Sci. Eng. A, **534**, 557 (2012)
34. D. Yadav, R. Bauri, Mater. Sci. Eng. A **539**, 85 (2012)
35. S. Shahraki, S. Khorasani, A.B. Reza, Y. Fotouhi, H. Bisadi, Metall. Mater. Trans. B **44**, 1546 (2013)
36. H.S. Arora, H. Singh, B.K Dhindaw, Int. J. Adv. Manuf. Technol. **61**, 1043 (2012)
37. P. Asadi, G. Faraji, K.B. Mohammad, Int. J. Adv. Manuf. Technol. **51**, 247 (2010)
38. N. Kumar, R.S. Mishra, C.S. Huskamp, K.K. Sankaran, Mater. Sci. Eng. A **528**, 5883 (2011)
39. E.O. Hall, Proc. Phys. Soc. B **64**, 747 (1951)
40. N.J. Petch, J. Iron Steel Inst. **174**, 25 (1953)
41. Y. Li, Y.H. Zhao, V. Ortalan, W. Liu, Z.H. Zhang, R.G. Vogt, N.D. Browning, E.J. Lavernia, J.M. Schoenung, Mater. Sci. Eng. A **527**, 305 (2009)

42. T. Morishige, T. Hirata, M. Tsujikawa, K. Higashi, Mater. Lett. **64**, 1905 (2010)

43. R. Bauri, D. Yadav, G. Suhas, Mater. Sci. Eng. A **528**, 4732 (2011)

44. K. Nakata, Y.G. Kim, H. Fujii, T. Tsumura, T. Komzaki, Mater. Sci. Eng. A **437**, 274 (2006)

45. K. Surekha, B.S. Murty, K.P. Rao, Surf. Coat. Tech. **202**, 4057 (2008)

46. F. Nacimento, T. Santos, P. Vilaca, R.M. Miranda, L. Quintino, Mater. Sci. Eng. A **506**, 16 (2009)

47. A. Kurt, I. Uygur, E. Cete, J. Mater. Process. Technol. **211**, 313 (2011)

48. K. Elangovan, V. Balasubramanian, Mater. Charact. **59**, 1168 (2008)

49. F.Y. Tsai, P.W. Kao, Mater. Lett. 80, 40 (2012)

50. K. Surekha, B.S. Murty, K.P. Rao, Mater. Des. **32,** 4502 (2011)

51. M.L. Santella, T. Engstrom, D. Storjohann, T.Y. Pan, Scripta Mater. **53**, 201 (2005)

52. D. Lu, S. Wei, M. Zhou, Y. Jiang, R. Zhou, Adv. Mater. Res. **148-149**, 1689 (2010)

53. A. Shahi, S.M. Hydarzadeh, D. Ahemadkhanila, M. Ghambari, Int. J. Adv. Manuf. Technol. **75**, 1331 (2014)