Multipass Friction-Stir Processing and its Effect on Mechanical Properties of Aluminum Alloy 5086

K.N. RAMESH, S. PRADEEP, and VIVEK PANCHOLI

Twelve-pass friction stir processing (FSP), with 50 pct overlap was carried out on aluminum alloy 5086-O rolled plates to obtain total area of 40 × 150 mm^2. Two methods of friction-stir processing, intermittent multipass friction stir processing (IMP), and continuous multipass stir processing (CMP) were carried out, and their effect on the mechanical properties of the processed material was studied. The results revealed that material subjected to IMP showed better mechanical properties compared with the material subjected to CMP. Also, a variation in mechanical properties was observed with an increase in the tool traverse speed for single-pass, CMP, and IMP types of processing.

DOI: 10.1007/s11661-012-1232-3

I. INTRODUCTION

FRICTION-STIR processing (FSP) is a new, solid-state processing technique for microstructural modification,[1,2] which was developed based on the principle of friction-stir welding (FSW).[3] A rotating, nonconsuming tool with a pin and shoulder is inserted into the material and traversed along the desired path. Because of the frictional heat generated, the material undergoes severe plastic deformation, resulting in significant microstructural changes in the processed zone. FSP creates a region called the ''stir zone'' or ''nugget zone,'' where the microstructural refinement takes place producing equiaxed ultrafine grains with high-angle grain boundaries.[4,5] A single-pass FSP with a pin diameter of 6 mm may produce a processed zone 6 to 8 mm wide and a depth depending on the length of the tool pin. Such a narrow processed zone is not suitable for practical engineering applications. The extension of FSP to multipass FSP addresses this issue, whereby the overlapping of passes can be used to produce bulk-processed material.[6]

The study on the possibility for fabricating large bulk ultrafine-grained materials through multipass FSP in commercial 7075 aluminum reported that the grains of the multipass FSP regions exhibited the same characteristics as the grains in the center region of single-pass FSP sample.[6] Johannes and Mishra[7] investigated the effect of multipass FSP on the superplasticity of 7075 Al rolled plate by using mini tensile specimens cut from the center of each stir zone on the staggered pass samples. The result show good superplastic ductility in each stir zone of the multipass FSP 7075 Al samples. The study also indicated that overlapping FSP passes is a feasible method to create a large, fine-grained aluminum alloy plate. Ma *et al.*[8] studied the effect of multipass FSP on the microstructure and tensile properties of a cast aluminum-silicon alloy A356. The work reported that in the multipass processed material, the strength of the previously processed zones was lower than that of the subsequent processed zones because of an overaging from the thermal cycles. Nakata *et al.*[9] reported an improvement in mechanical properties of an aluminum die casting alloy subjected to 14 pass FSP. The average tensile strength in the parallel direction was higher than in the perpendicular direction. However, ductility was almost the same in both directions.

It is clear from the available literature that the multipass FSP heating cycle of one pass affected microstructure and mechanical properties of other passes. In this work, multipass FSP of Al 5086-O alloy was done using two different variants of the processL intermittent multipass FSP (IMP) and continuous multipass FSP (CMP). Details are provided in Section II. The objectives of the study were (1) to evaluate the room-temperature mechanical properties of the multipass friction-stir processed alloy compared with the single pass and parent material and (2) to study the effect of two different multipass FSP methods (IMP and CMP, performed using five different traverse speeds) on the mechanical properties of the processed material.

II. EXPERIMENTAL DETAILS

In this work, 6-mm plates of commercial AA 5086-O alloy were used for single and multipass friction stir processing. The plates were cut into 150 × 110 mm^2 and subjected to FSP. A nonconsumable hot die steel tool with a flat shoulder of 24 mm diameter, a cylindrical pin of 6 mm diameter, and 3 mm length was used. The direction of processing was parallel to the rolling direction. The separation between the subsequent passes during multipass FSP was 3 mm, which resulted in 50 pct nugget overlap. A total of 12 passes was carried

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Manuscript submitted September 28, 2011.
Article published online May 26, 2012

out on each plate. The FSP resulted in processed material of 3 mm depth and an area of 150 × 40 mm^2. The processing of the plates was carried out at a fixed tool rotational speed of 1025 rpm and five traverse speeds of 30 mm/min, 50 mm/min, 80 mm/min, 110 mm/min, and 150 mm/min, respectively. An indigenously designed and developed vertical milling machine was used for FSP. A specially designed and developed fixture was used to hold the plate firmly in position during FSP. A mild steel backing plate was used in this process. In this study, two types of processing methods were adopted: (1) IMP, in which the material was allowed to cool back to room temperature after each pass of FSP and then the subsequent pass was carried out and (2) CMP, in which the FSP was continuously performed for 12 passes without allowing any cooling time between passes. For each of these processing methods, four combination of processing conditions were obtained: one rotational speed and five different traverse speeds.

Optical metallography was carried out using LEICA DMI 5000M (Leica Microsystems, Buffalo Grove, IL). The metallographic examination and hardness measurement were carried out on the section normal to processing direction. Specimens for metallographic examination were prepared using a standard polishing technique. Electron backscattered diffraction (EBSD) scans were performed on the same section as used for optical metallography. EBSD scans were carried out using TSL-OIM data acquisition system (EDAX Inc., Mahwah, NJ) fitted on FEI-Quanta 200 field-emission scanning electron microscope (SEM; FEI Corporation, Hillsboro, OR). EBSD data were analyzed using TSL-OIM version 5.2 analysis software. The samples for the EBSD analysis were prepared by electropolishing after mechanical polishing. Electropolishing was carried out for a duration of 1 minute in a mixture of 80 pct methanol and 20 pct perchloric acid, at a voltage of 11V and temperature of 258 K (–15 °C).

Vickers hardness and tensile tests of the base material and multipass friction-stir processed materials were performed at room temperature for evaluating mechanical properties. A Vickers hardness tester (FIE-VM50 PC) was employed for measuring the hardness distribution on the transverse cross section of the processed material using an indentation load of 5 kgf and dwell time of 15 seconds. The tensile specimens were prepared as per the dimensions specified for a subsize specimen in ASTM E8 M-08. The schematic diagram of tensile test specimens is shown in Figures 1(a) through (c). The tensile tests were carried out on the base material, and single and multipass FSP material samples were processed at different traverse speeds. The multipass tensile samples were obtained from material processed both under IMP and CMP conditions. The tensile test specimens were cut parallel and perpendicular to the FSP direction from the processed material.

Tensile tests were carried out using a 25 KN, electromechanically controlled universal testing machine (H25 K-S; Hounsfield Test Equipment, Ltd., Surrey, UK). A minimum of two good reproducible tests was performed for each processing condition in both directions. The yield strength, ultimate tensile strength, and ductility (pct elongation at failure) were evaluated from the load and deformation data obtained from the tensile tests.

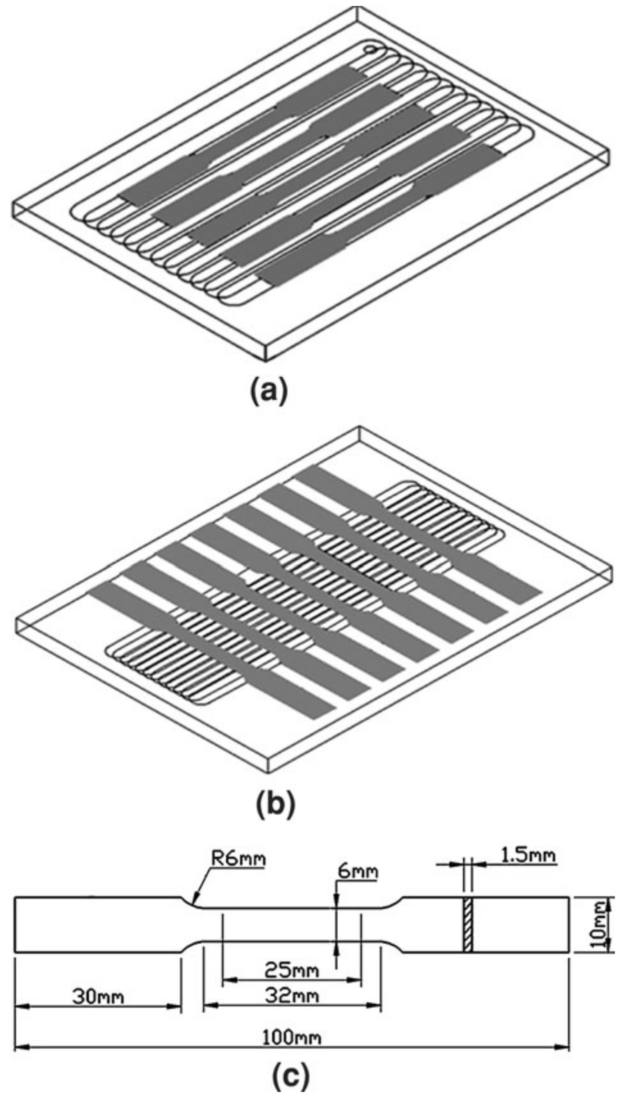

Fig. 1—Schematic diagram of (*a*) longitudinal tensile test specimens, (*b*) transverse tensile test specimens, and (*c*) tensile test specimen dimensions.

III. RESULTS AND DISCUSSION

A. *Macrostructure and Microstructure*

A typical macrograph of multipass processed sample with the entire 12 pass is shown in Figure 2. Various microstructural regions of FSP like the nugget zone thermomechanical affected zone (TMAZ) are distinctly visible from the macrograph. The material has been processed approximately up to a depth of 3 mm, which is the length of the tool pin. The transition regions between two FSP passes appear darker and are distinctly separable from the nugget zones of both the adjacent passes. The curly nature of the various zones of FSP material in the macrograph shows the complex nature of material flow during FSP. Figure 3 shows the sectioned macrograph obtained for IMP and CMP samples processed at different traverse speeds.

It is clear from the macrographs that after IMP processing, different zones are (nugget and transition) clearly visible, whereas after CMP processing, the distinction between different zones is not clear. Apparently, material flow is more complex after CMP processing than IMP processing. From the macrographs of samples processed using IMP at different traverse speeds, it is observed that with increase in traverse speed, the shape and size of nugget and transition zone is changing from curly at low speed to a ''petal'' shape at high speed.

The grain size of the base material was found to be 48 μm. A significant reduction in grain size was observed after processing. Optical micrographs obtained from the nugget zone of different passes of the FSP sample processed by IMP variant at traverse speed of 30 mm/min are shown in Figure 4. The optical micrographs of nugget zones of FSP sample processed by CMP variant at traverse speed of 30 mm/min are shown in Figure 5. In the material processed using IMP variant, grain size seems to increase from 1st pass to 12th pass. In contrast, after CMP processing (Figure 5), the grain size seems to be same irrespective of the number of passes. Therefore,

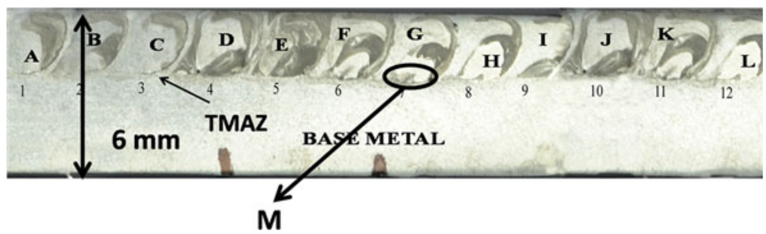

Fig. 2—Typical macrograph of multipass friction-stir processed sample showing nugget and transitional zones of 12-passes labeled as A, B, C, D, E, F, G, H, I, J, K, and L.

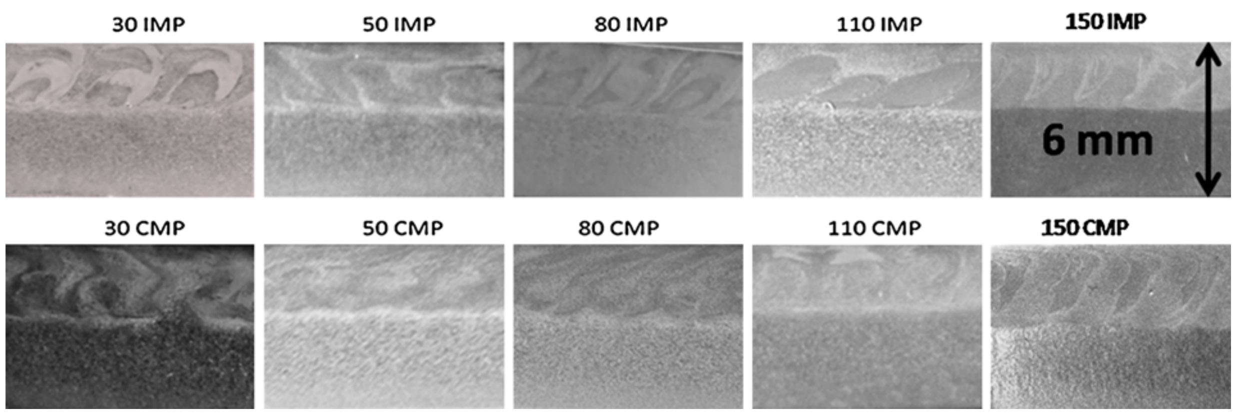

Fig. 3—Comparison of macrographs of FSP samples processed at different traverse speeds.

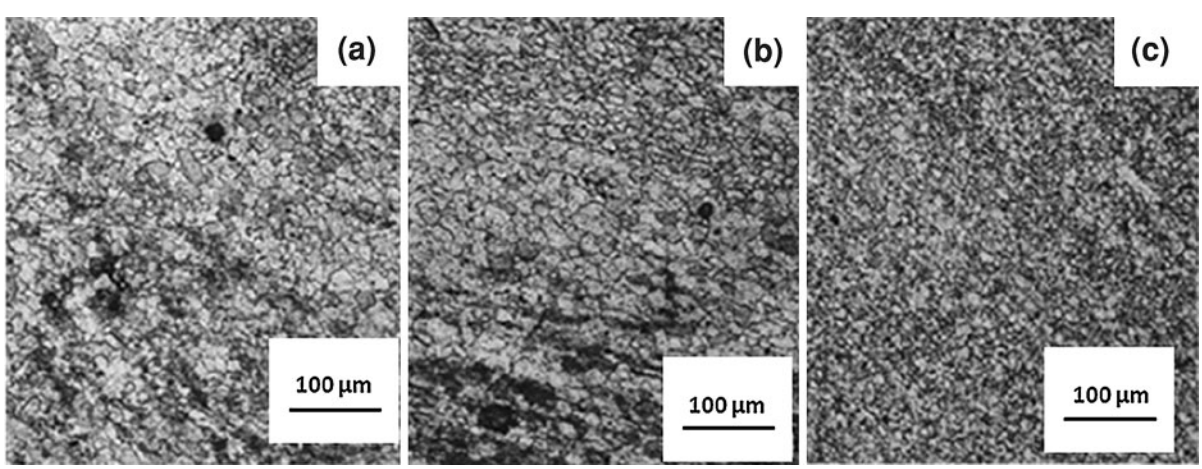

Fig. 4—Optical micrographs of nugget zone of multipass FSP sample processed by IMP FSP under a tool rotational speed of 1025 rpm and traverse speed of 30 mm/min: (*a*) 1st pass, (*b*) 4th pass, and (*c*) 12th pass (locations A, D, and L in Fig. 1).

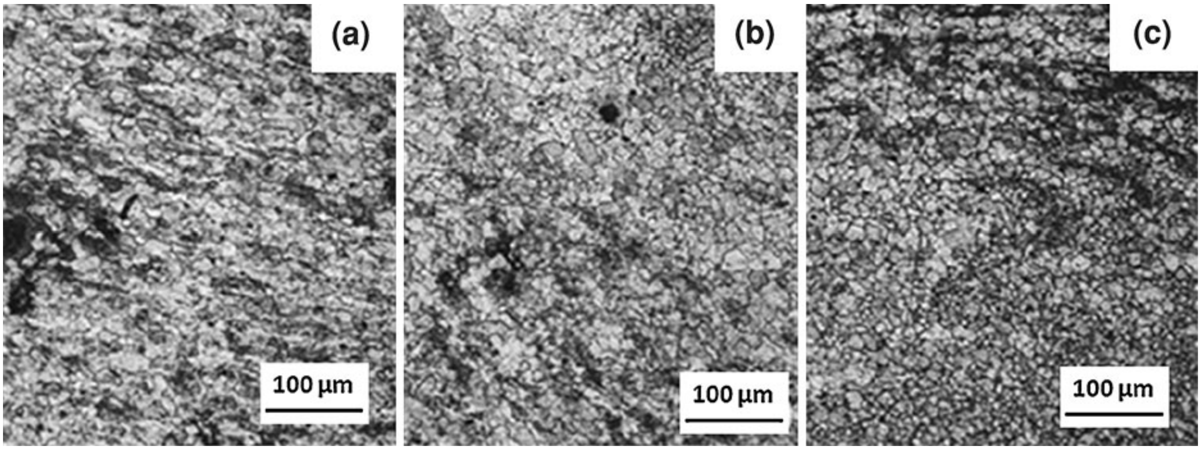

Fig. 5—Optical micrographs of nugget zone of multipass FSP sample processed by CMP FSP under a tool rotational speed of 1025 rpm and traverse speed of 30 mm/min: (*a*) 1st pass, (*b*) 4th pass, and (*c*) 12th pass.

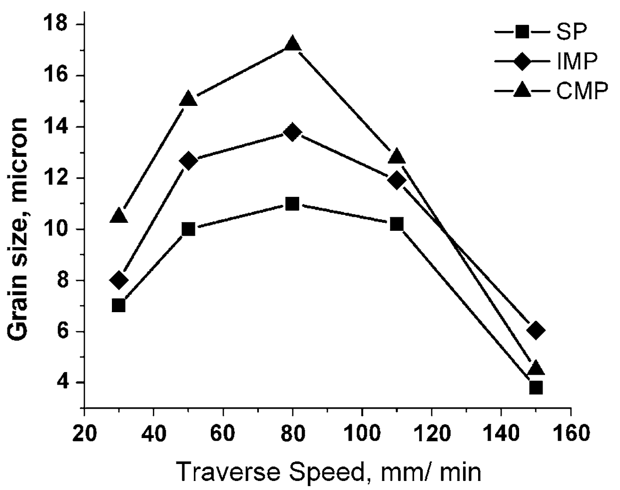

Fig. 6—Variation in grain size with traverse speeds for different FSP conditions.

IMP and CMP processing have different effects on microstructural evolution, which may be attributed to different thermal cycle. Figure 6 shows effect of traverse speed on grain size in the nugget zone after IMP, CMP, and single-pass processing. The grain size is found to increase with a traverse speed of up to 80 mm/min and then start decreasing at a higher speed. It is interesting to note that the pattern of variation in grain size is similar under all variants of processing. Up to the traverse speed of 110 mm/min, the grain size obtain after CMP is coarser than IMP and single-pass processing. However, after processing using a traverse speed of 150 mm/min, the grain size obtained for all the processing variants lies within a narrow range. This clearly brings out the effect of thermal cycle on microstructure after multipass using IMP and CMP variants.

Figure 7 exhibits microstructural inhomogeneity after multipass processing. It is clear that a significant variation in microstructure is present within a small area in the two zones. The average grain size in the transition zone is much lower than in the nugget zone. However, high-angle grain boundary fraction is found to be more than 70 pct in both zones.

B. *Hardness*

Figure 8 exhibits a variation in Vickers hardness values as a function of traverse speed. For the samples processed up to the traverse speed of 110 mm/min, the hardness values obtained for IMP and single-pass processed samples were found to be higher than the values obtained for the CMP processed samples. This observation might occur because the grain size obtained after IMP and single-pass processing is lower than that obtained after CMP processing. However, the hardness values for the material processed at traverse speed of 150 mm/min using all the three variants are very close, clearly bringing out the effect of grain size. It is also observed that the hardness values in the processed samples showed variation within the sample depending on the location where the indentation was done. The hardness values in the transition zone were higher than that obtained from the nugget zone. Similarly, there is a variation in hardness values in the nugget zone of different passes. The hardness values increased marginally from 70.4 for first pass to 74 for the 12th pass.

C. *Tensile Properties*

Mechanical properties like ultimate yield strength, tensile strength, and percentage elongation obtained after different processing conditions are shown in the Figures 9 through 11, respectively. To study the effect of multipass on the tensile properties it is compared with the properties of single pass and base material. It is observed from Figures 9(a) and (b) that the yield strength values of multipass FSP samples (both IMP and CMP) in both longitudinal and transverse directions is inferior to that of the base material. Subsequent yield strength is found to drop continuously in the longitudinal direction with increasing tool traverse speed up to 110 mm/min and then increased substantially at 150 mm/min for both CMP and IMP processed

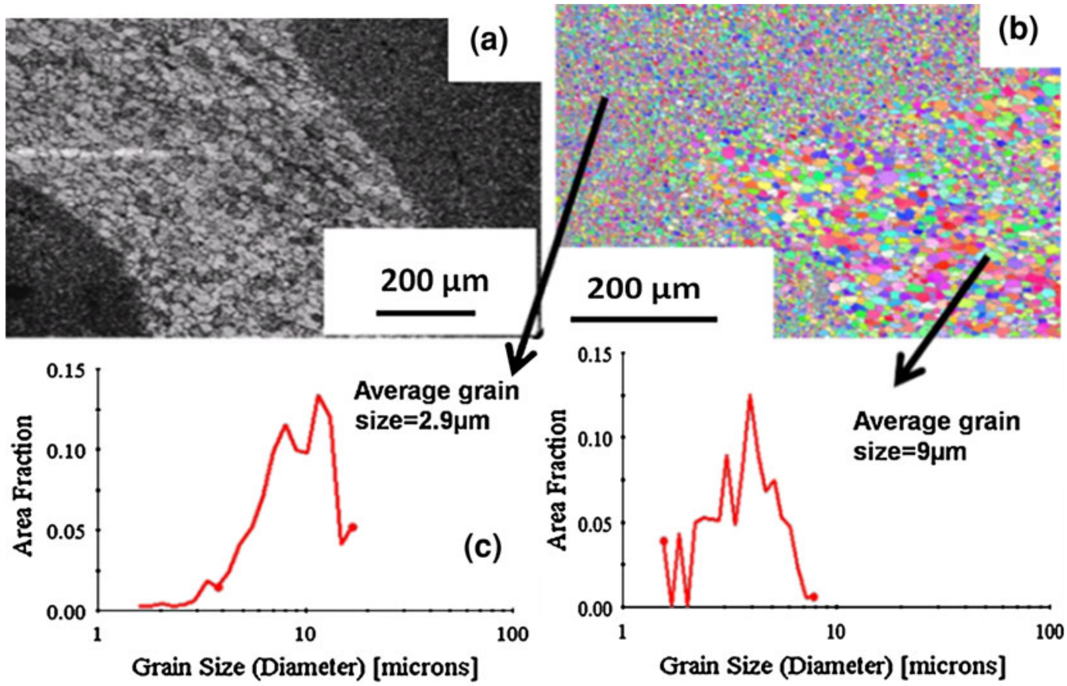

Fig. 7—Microstructure after multipass FSP in plane perpendicular to processing direction: (*a*) and (*b*) optical micrograph and EBSD of the region M circled in Fig. 2, coarse grain in nugget and fine grain in the transition is clearly visible, and (*c*) grain size distribution obtained from EBSD scan in the two zones.

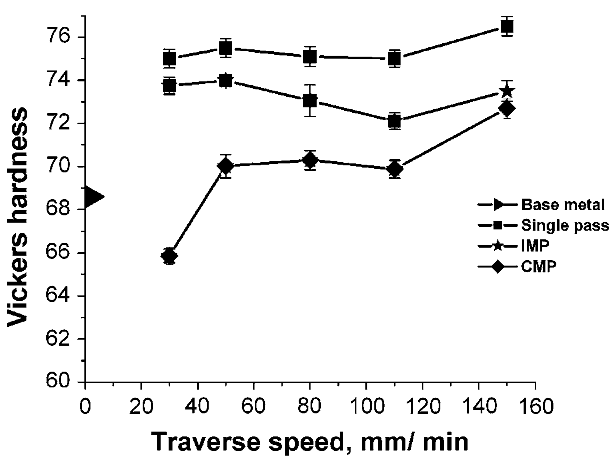

Fig. 8—Variation in Vickers hardness values with traverse speeds of different FSP conditions.

material. For the transverse direction, the yield stress shows an increasing trend after an earlier decline up to traverse speed of 80 mm/min (Figure 9(b)). The yield strength of single pass processed material in longitudinal direction showed a value close to that of the base material (Figure 9(a)). The yield strength of single-pass processed material in the transverse direction is substantially lower than the base material (Figure 9(b)).

Figures 10(a) and (b) exhibit ultimate tensile strength (UTS) in longitudinal and transverse directions after processing. It is observed that UTS in longitudinal direction after multipass processing is lower than the base material except for a traverse speed of 30 and 150 mm/min. In the transverse directions, the UTS is closer to a base material at speed of 30 mm/min but showed a decreasing trend at higher speeds except for the material processed using a CMP variant. In CMP processed material, the UTS show an increasing trend after a traverse speed of 80 mm/min. A single pass shows better UTS in the longitudinal direction and is almost equal to the base material strength at all traverse speeds used with a maximum strength at 80 mm/min. But in the transverse direction, UTS is below that of the base material at all the traverse speed used. Figures 11(a) and (b) show a variation of ductility with traverse speed for longitudinal and transverse directions, respectively. Percentage elongation to failure values of multipass FSP samples (both IMP and CMP) in both longitudinal and transverse directions was observed to be greater than the base material under all processing conditions except for traverse speed of 110 mm/min in longitudinal direction for CMP processing. It is also observed that the ductility of IMP processed samples exhibited better values to CMP processed samples. However, for CMP variant, the ductility shows a downward trend with an increase in traverse speed, except at 150 mm/min in longitudinal direction. Single pass shows elongation above the base metal at all traverse speeds in both longitudinal and transverse directions and comparable with the IMP processed material.

IV. DISCUSSION

Friction-stir welding is a well-established technique especially for the welding of Al alloys. In recent years, concepts of friction stir are applied for processing material as a tool for microstructural modification.[10]

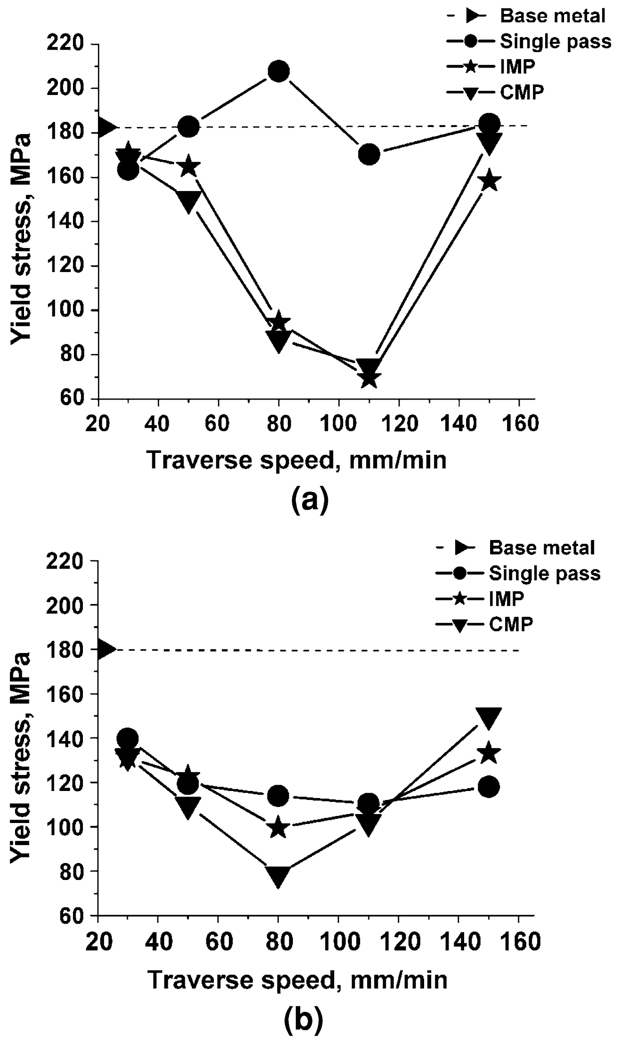

Fig. 9—(*a*) Yield strength as a function of traverse speed for different processing conditions in longitudinal direction. (*b*) Yield strength as a function of traverse speed for different processing conditions in transverse direction.

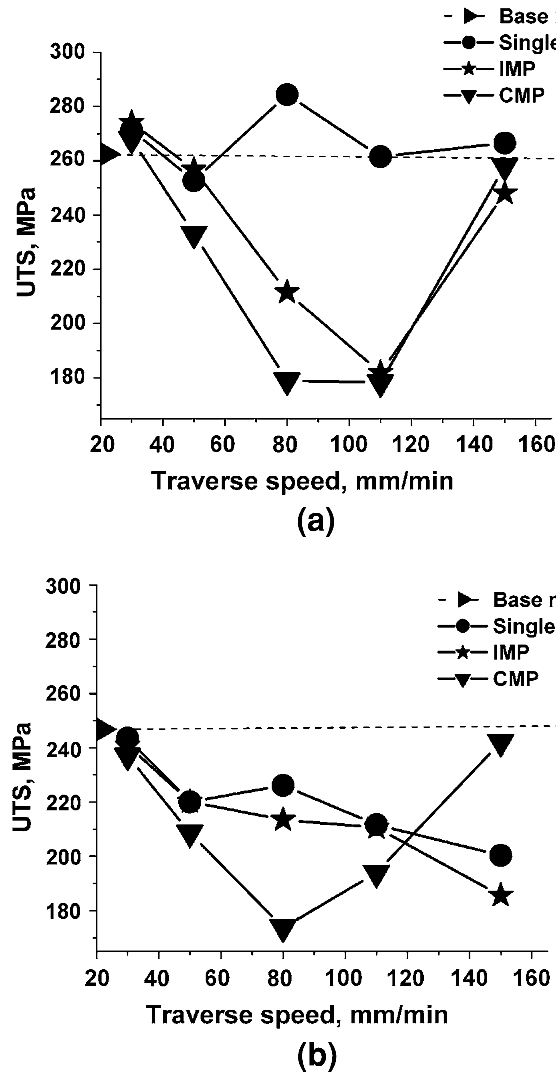

Fig. 10—(*a*) Ultimate tensile strength as a function of traverse speed for different processing conditions in longitudinal direction. (*b*) Ultimate tensile strength as a function of traverse speed for different processing conditions in transverse direction.

Limited work has also been initiated by several groups on the feasibility of extending single-pass processing to multipass for bulk processing. However, mechanical properties after multipass are generally reported to be inferior to single-pass processing. The decrease in mechanical properties is observed even though the microstructure does not show any significant variation between single and multipass processing.

A. *Effect of Processing Variant*

In this study, two multipass friction-stir processing variants are tried: (1) continuous multipass and (2) intermittent multipass. In the literature on multipass, this processing variable is usually not specified. The study of this variable is important for processing bulk material economically. The macrostructure and microstructure obtained after processing using these two variants are found to be distinct because the temperature distribution and profile are expected to be different in CMP and IMP processing. The peak temperature is reported to be 673 K to 773 K (400 °C to 500 °C) close to the shoulder in different alloys depending on the processing conditions; however, the temperature drops to a value of 423 K to 473 K (150 °C to 200 °C) after 50 to 100 seconds.[11] The temperature also varies as a function of the distance from tool pin and drops to a value of 523 K to 573 K (250 °C to 300 °C) at distance of 11 mm and 423 K (150 °C) at distance of 40 mm away from the edge of the nugget.[12,13] In CMP processing, the time between each pass was not more than 120 seconds; hence, each successive pass was performed under a preheated condition of at least 473 K (200 °C). Because the processed area is approximately 40 mm in the current work, the temperature experienced by the material where passes are completed will also be in excess of 423 K (150 °C). The total time for CMP decreased from approximately 80 minutes at the lowest traverse speed to 30 minutes at the highest speed used. Hence, it is safe to assume that the material

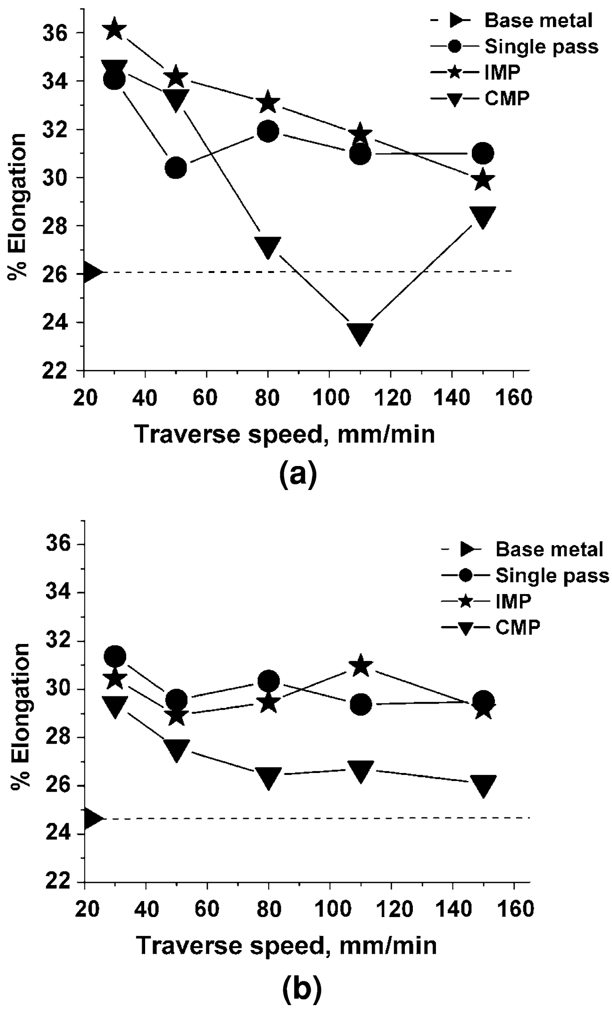

Fig. 11—(*a*) Ductility as a function of traverse speed for different processing conditions in longitudinal direction. (*b*) Ductility as a function of traverse speed for different processing conditions in transverse direction.

processed in initial passes at a low traverse speed is exposed to a temperature of $0.3T_m$ 473 K (200 °C) for a sufficiently long time and may cause grain growth in the processed material. This may be the reason for a higher grain size in the CMP processed material at lower speeds. In contrast, in IMP processing, the material was cooled to room temperature before the next pass, and hence, it does not experience any preheating of the processed area. This variation in temperature between IMP and CMP is reflected in the grain size obtained in nugget zone at different traverse speeds. Because material is not exposed to heat input from other passes during single pass processing, the grain size is finer than for both variants of multipass.

Unlike any other severe deformation process, friction-stir processing has the potential to develop as a bulk processing method for grain refinement. In this work, it was explored whether the CMP variant can be used as continuous process to enhance productivity. The hardness, tensile strength, and ductility values in both longitudinal and transverse directions at lower traverse speeds of processing are inferior in the CMP processed material compared with IMP. However, at the highest speed of processing used in this study, the hardness and tensile strength in the material processed using CMP variant are comparable with IMP variant. A variation in hardness and strength properties is showing strong correlation with the variation in grain size of the material processed using CMP and IMP processing variants. It should be noted, however, that substantial microstructural inhomogeneity exist in the processed material. The effect of inhomogeneity is reflected when the mechanical properties of the processed material are compared with single-pass FSP and base metal. Bulk properties like yield strength and UTS showed a significant reduction after multipass FSP compared with single pass and base metal. However, the hardness values after single pass and multipass FSP are found to be higher than the base material. The reduction in strength after friction-stir welding or processing is usually reported in the literature.[12] The primary reason for reduction is the dissolution of precipitates in precipitation-hardened alloys.[14] It is also shown that postweld/processed heat treatment restores properties in the material.[15] Because the current alloy is not precipitation hardened, the hardness values did not drop after processing, and the effect of grain size reduction is noticed. It is interesting to note that strength values after single-pass FSP are better than the base metal, CMP, and IMP processed materials. Therefore, microstructural inhomogenity caused by multipass processing is the primary reason for the decrease in strength compared with base metal and single-pass FSP. Therefore, it is important to understand material flow and microstructure in the nugget and transition zones in multipass processed material to use FSP successfully for bulk processing.

B. *Effect of Traverse Speed*

The material processed using IMP multipass FSP with different traverse speeds showed distinct macrostructure as shown in Figure 2. The macrostructure consists of nugget and transition zones. As shown in Figure 3, the shape of the transition zone is changing from curly shaped at lower traverse speed to petal shaped at a higher traverse speed. At lower traverse speeds, the shape of the zones seems to define the vertical flow of material; however, at higher speeds, the nugget and transition zones are separated horizontally. The development of macrostructure is the result of overlapping of complex material flow in each pass of multipass processing.[16] The flow of material usually occurs from the top surface, which is in contact with the shoulder, toward the bottom.[17] It is shown by experiments and modeling that the vertical mixing of material increases at lower weld pitch (ratio of traverse speed to rotation speed).[18] The enhanced mixing is probably caused by a higher viscosity of the material prompted by a higher surface temperature obtained at a lower weld pitch.[19] The maximum temperature at the shoulder drops with increase in traverse speed; however, a drop in temperature away from the shoulder is more pronounced at a higher traverse speed.[13] This finding implies that temperature variation between the surface and some distance away from the surface will be greater at a higher traverse speed than at a lower speed. The variation in temperature at different location of processed material as a function of traverse speed will affect viscosity and material flow, which can be observed in the form of a variation in shape of the two zones. The material processed using CMP multipass FSP, however, did not show a distinct macrostructure development. The shape of the nugget and transition zones is a zigzag pattern. The shape of the two zones did not show any significant variation with traverse speed. Higher temperature is expected to be attained by material because of continuous processing in CMP. This may result in a similar shape and pattern of the two zones at different traverse speed because of similar material flow at all traverse speeds studied in this work. The nature of the variation of grain size with a traverse speed after single pass, CMP, and IMP is interestingly found to be same, *i.e.,* increasing up to 80 mm/min and then decreasing. The effect of traverse speed on microstructure irrespective of the processing variant used is still not clear and definitely requires more work.

The effect of traverse speed on the mechanical properties keeping other parameters of FSP/FSW constant is given less priority in the available literature. However, the effect of traverse speed in combination with rotation speed is widely reported. The mechanical properties are studied as a function of the ratio of rotation speed to traverse speed (ω/v), which indicates heat input to the material.[20] With a decrease in rotation speed or an increase in the traverse speed, heat input to the material decreases. In the current study, the ω/v ratio decreased from 34.1 r/mm (1025 rpm, 30 mm/min) to 6.8 r/mm (1025 rpm, 150 mm/min). Therefore, the heat input to the material is decreasing with an increase in the traverse speed. The other effect of varying the rotation or traverse speed is the variation in strain rate of deformation. At higher rotation and traverse speeds, the strain rate will increase.[21] The combined effect of the temperature and strain rate can be studied using Zener-Hollomon parameter $Z = \dot{\varepsilon}\exp(Q/RT)$, where $\dot{\varepsilon}$ is the strain rate, T is the temperature, Q is the related activation energy, and R is the universal gas constant.

In the current work, the yield and ultimate tensile strengths were found to decrease up to the traverse speed of 110 mm/min and then increase at 150 mm/min. The variation in strength correlates with the variation in grain size of the nugget region. At a traverse speed of 150 mm/min, lower heat input and higher strain rate (high Z value) result in grain refinement and hence better strength. A word of caution: The preceding argument is only based on grain size in the nugget region. However, during FSP, the material flow is very complex and variety of nugget and transition zones was observed as a function of the traverse speed. The effect of nugget and transition zones is more pronounced when the material is tested in the direction transverse to the processing direction. The strength properties in transverse direction are lower than the base material at all the conditions of processing. The effect of different zones in multipass processed material on properties will be clearer if the properties of single pass processed material are compared. The strength is more than base material in longitudinal direction at all traverse speed but lower in transverse direction. The material processed using single pass in longitudinal orientation will contain predominantly nugget zone, whereas the sample from transverse direction will contain nugget, TMAZ, and HAZ, which may result in a decrease in strength.[12] In multipass, however, there is overlap of nugget zone in each pass and there is no clear distinction between the different zones identified in single pass. However, gauge section of tensile sample will contain both nugget and transition zones in longitudinal as well as transverse directions. Significant improvement in ductility after both IMP and CMP is observed at all conditions of processing in both longitudinal and transverse directions. It is clear that the integrity of material is not affected by multipass processing.

V. CONCLUSIONS

Two different variants for multipass friction-stir processing were introduced in this work. The effect of these processing variants, at different traverse speeds, on microstructure and mechanical properties were studied and compared with single-pass processing and base material. The main conclusions of the study are as follows:

1. Macrostructure contains nugget and transition zones wherein the nugget contains coarse grains and transition zone contains fine grains. The shape and size of the two zones was found to vary with traverse speed from a curly shape at a lower speed to a petal shape at a higher transverse speed.
2. Significant reduction in grain size is observed after friction-stir processing. The grain size reduced from 48 μm in base material to 4 to 6 μm at the traverse speed of 150 mm/min. The grain size is found to increase first as a function of traverse speed up to 80 mm/min and then decrease irrespective of the processing variant used.
3. The effect of grain size variation is observed on the hardness values of the material after processing. The hardness of the processed material is higher than the base material. Similarly, the hardness value of single-pass processed material is higher than both IMP and CMP processed materials.
4. The yield strength and UTS values are lower in multipass processed material than base material and single-pass processed materials for the processing conducted at a lower traverse speed. At the highest speed of 150 mm/min used in the current work, the yield and tensile strength after CMP is comparable with the base material. The CMP process shows promise to be used for application because it is a continuous process and is showing better properties at a higher traverse speed.
5. Ductility values are found to be better in multipass and single-pass processed material than the base material under all processing conditions used.

ACKNOWLEDGMENTS

The authors gratefully acknowledge support from Department of Science and Technology, India under fast track scheme for young scientists, Grant No. SR/FTP/ETA-44/2007, used for conducting out this research.

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