Effect of tool materials on tensile properties of friction stir welded AZ31B Magnesium alloy

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ABSTRACT

In this investigation, an attempt was made to study the effect of tool materials on tensile properties of friction stir welded AZ31B magnesium alloy. Tools made of five different materials were used to fabricate the joints. Tensile properties of the joints were evaluated and correlated with the weld zone microstructure and hardness. From this investigation, it is found that the joint fabricated using the tool made of high carbon steel exhibited superior tensile properties compared to their counterparts. The absence of defects in weld region, presence of very fine equiaxed grains in the weld region and higher hardness in the weld region are the main reasons for superior tensile properties of these joints.

Keywords: Magnesium alloy; Friction stir welding; Tensile properties; Tool material

INTRODUCTION

Magnesium alloys have many attractive properties, such as low density and high specific strength. It is predicted that the application of magnesium alloys will grow rapidly in the near future, especially in the transport industry [1]. With fast development and wide applications, the welding of magnesium alloys becomes a main concern. The drawbacks associated with the fusion welding include: (a) complex thermal stresses and severe deformation, (b) the presence of porosity and crack in the fusion zone, (c) the excess eutectic formation [2].

Friction stir welding (FSW) is capable of joining magnesium alloys without melting and thus it can eliminate problems related to the solidification. As FSW does not require any filler material, the metallurgical problems associated with it can also be eliminated and good quality weld can be obtained [3]. FSW involves complex material movement and plastic deformation. Welding parameters, tool geometry, and joint design exert significant effect on the material flow pattern and temperature distribution, thereby influencing the microstructural evolution of material. Tool geometry is the most influential aspect of process development. [4]. Tools consist of a shoulder and a probe which can be integral with the shoulder or as a separate insert possibly of a different material. Clearly, the variations in tool design are infinite and combinations of shoulder diameter, shoulder profile, probe length, diameter and profile, are all important parameters in determining the speed of welding and the quality of the finished weld. Another important parameter in the determination of the suitability of a tool for a particular application is the tool material itself. Welding is carried out around 70 90% of the material melting point so it is important that the tool material has sufficient strength at this temperature otherwise the tool can twist and break. [5] Several studies [6 12] reported the effect of tool geometry on mechanical and metallurgical properties of FSW joints. But, there is no information available on the role of tool materials on tensile properties of friction stir welded joints in open literature. The tool requires all of the following characteristics: (1) as simple a shape as possible to reduce the cost; (2) sufficient stirring effect to produce sound welds similar to an ordinary tool for aluminium alloys. With conventional aluminium alloys tools made of tool steel give good results but with the softer alloys such as magnesium may give good results with other tool materials. Hence, the present investigation was carried out to study the effect of tool materials on tensile properties of friction stir welded AZ31B magnesium alloy and the results are reported in this paper.

EXPERIMENTAL WORK

The rolled plates of 6 mm thickness, AZ31B magnesium alloy were cut into

Table 1a Chemical composition (wt %) of base metal AZ31B magnesium alloy

Al	Mn	Zn	Mg
3.0	0.20	1.0	Bal

Table 1b Mechanical properties of base metal AZ31B magnesium alloy

Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation (%)	Reduction in cross-sectional area (%)	Hardness (Hv) at 0.05 kg load
172	215	14.7	14.3	69.3

the required size (300×100 mm) by machining process. Square butt joint configuration, was prepared to fabricate FSW joints. The initial joint configuration was obtained by securing the plates in position using mechanical clamps. The direction of welding was normal to the rolling direction. Single pass welding procedure was used to fabricate the joints. Non-consumable tools made of five different materials (mild steel, stainless steel, armour steel, high carbon steel, high speed steel) were used to fabricate the joints. The chemical composition and mechanical properties of base metal are presented in Table 1. The tool nomenclature is presented in Table 2. An indigenously designed and developed FSW machine (15 hp; 3000 rpm; 25 kN) was used to fabricate the joints. The welded joints were sliced and then machined to the required dimension (as shown in Fig. 1), according to the ASTM E8M-04 standard for sheet type material (i.e., 50 mm gauge length and 12.5 mm gauge width). The tensile specimens were prepared to evaluate yield strength, tensile strength and elongation. Tensile test was carried out in 100 kN, electro-mechanical controlled universal testing machine (Make: FIE-Bluestar, India; Model: UNITEK-94100). The 0.2% offset yield strength and the percentage of elongation were evaluated. Vicker's microhardness testing machine (Make: SHIMADZU, Japan; Model: HMV-2T) was employed for measuring the hardness of the weld region with 0.05 kg load for 20 sec. The specimens for metallographic examination were sectioned to the required size and then polished using different grades of emery papers. A standard reagent made of 4.2 g picric acid, 10 ml acetic acid, 10 ml diluted water and 70 ml ethanol was used to reveal the microstructure of the welded joints. Macro and micro structural analysis was carried out using a light optical microscope (Make: MEIJI, Japan; Model: MIL-7100) incorporated with an image analyzing software (Metal Vision).

RESULTS

Tensile properties

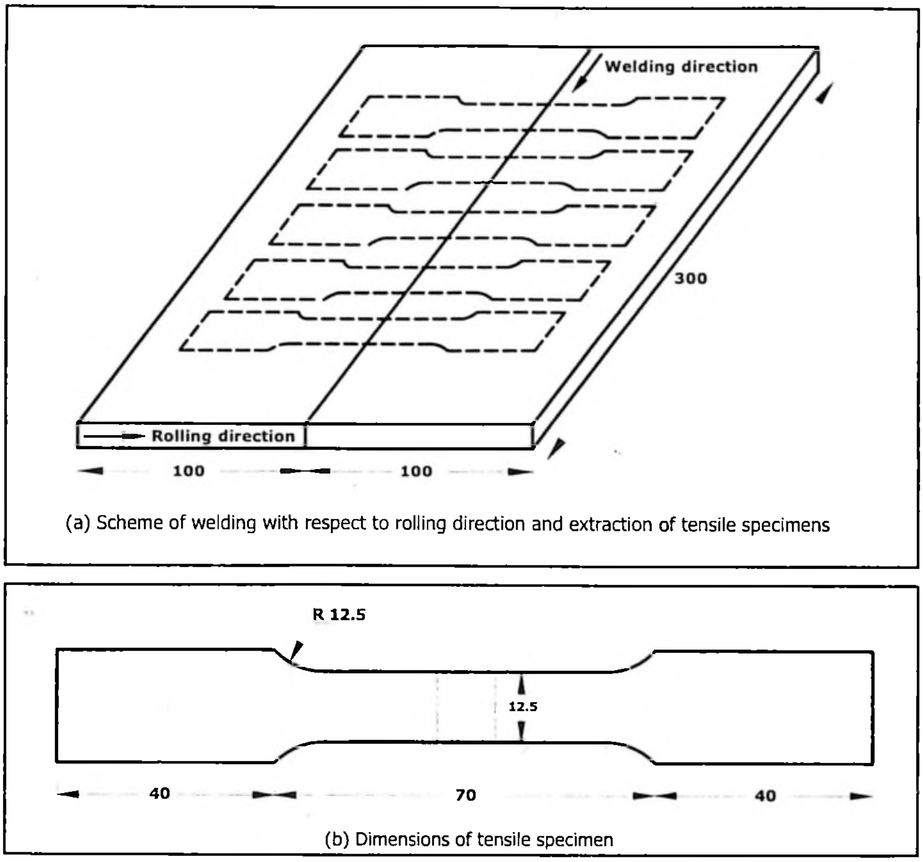
The transverse tensile properties such as yield strength, tensile strength, percentage of elongation, percentage of reduction in cross-sectional area and joint efficiency of friction stir welded AZ31B magnesium alloy joints were evaluated. In each condition, three specimens were tested and the average of three results is presented in Table 4. The joint fabricated with high carbon steel tool showed superior tensile properties compared to the joints fabricated by other tool materials.

Macrographs

In fusion welding of magnesium alloys, the defects like porosity, hot crack etc. deteriorates the weld quality and joint properties. Usually, friction stir welded joints are free from these defects since there is no melting takes place during welding and the metals are joined in the solid state itself due to the heat generated by the friction and flow of metal by the stirring action. However, FSW joints are prone to other defects like pinhole, tunnel defect, piping defect, kissing bond, cracks, etc. due to improper flow of metal and insufficient consolidation of metal in the FSW region [8]. Hence, all the joints fabricated in this investigation were analyzed at low magnification (10X) using optical microscope to reveal the quality of FSW region and they are presented in table 5. The joint fabricated using high carbon steel and super HSS are completely free from the defects. Invariably, all joints show wider upper surface than the lower surface because the upper surface experienced an extreme deformation and frictional heat caused by contacting weld specimens with a cylindrical tool shoulder [13].

Microhardness and Microstructure

The hardness was measured across the weld at mid thickness region using Vicker's microhardness testing machine and the values are presented in Fig. 2. The hardness of base metal (unwelded parent metal) is 69 Hv. The joint fabricated using high carbon steel tool exhibited higher nugget zone hardness (77 Hv) compared to their counterparts. If the joints are defective, then the failure was along the defect (Table 5). The location of failure in the defect free joints are along the TMAZ region. Very low hardness was recorded in the TMAZ region (64 Hv). This is also one of the reasons for failure in TMAZ region of defect free joints during tensile test. The optical micrographs taken at nugget zone of all the joints are displayed in Fig. 3. From the micrographs, it is understood that there is an appreciable variation in average grain diameter and the coarse grains (20 µm) of base metal are changed into fine grains in the



(a) Scheme of welding with respect to rolling direction and extraction of tensile specimens

(b) Dimensions of tensile specimen

Fig. 1 Dimensions of joint and tensile specimen

Table 2 Details regarding FSW process parameters and tools

Rotational speed (rpm)	1600
Welding speed (mm/sec)	0.67
Axial force (kN)	3
Tool shoulder diameter, D (mm)	18
Pin diameter, d (mm)	6
D/d Ratio of tool	3.0
Pin length, L (mm)	5.7
Tool inclined angle (deg)	0
Shoulder deepness inserted into the surface of base metal (mm)	0.2
Pitch (mm) and included angle (deg) of threaded pin	1 and 60

nugget region. Hence, an attempt was made to measure the average grain diameter of the weld metal region (nugget zone) of all the joints by applying Heyn's line intercept method [14] and measured grain sizes were presented in Table 4.

The joint fabricated with high carbon steel tool contain very fine grains (6 μm) in the nugget region compared to their counterparts. The presence of very fine equi axed grains in the nugget region, more amount of subgrains and very clear grain boundaries are the reasons for better tensile properties of these joint compared to their counterparts. To identify, the reason for failure in TMAZ region, the detailed microstruture was taken in TMAZ region of both advancing and retreating side (Fig.4). From the micrographs, it is understood that there is an appreciable difference in grain size (average grain diameter) in the nugget and thermo mechanically affected zone (TMAZ). The grain size of TMAZ is coarser than the nugget region, because of insufficient deformation and thermal exposure [15]. Also relatively smaller grains (12μm) were observed in the retreating side compared to advancing side (16μm) (Fig.4 b). This is caused by the greater straining expected in this location. The similar observation was made by pareek et al. [16] in friction stir welding of AZ31B magnesium alloy. This is also another reason for failure along the TMAZ region in the advancing side of defect free joints.

4.0 DISCUSSION

From the literature review, it is understood that friction stir welding of aluminium alloys was mostly carried out using either high carbon steel or high speed steel material. These tool steel materials are giving very good results for aluminium alloys. However, the magnesium alloys are much softer than aluminium alloys and hence, sometimes, they may not require harder tool steel materials.

To understand the influence of tool materials on tensile properties of the FSW AZ31B magnesium alloy joints, four more tools were fabricated using mild steel (MS), stainless steel (SS), armour

Table 3 Chemical composition and hardness of tool materials

Tool materials	C	Si	Mn	Cr	P	S	Mo	Ni	V	W	Fe	Hardness (HRc)
MS	0.22	0.3	-	-	0.04	0.05	-	-	-	-	Bal.	30
SS	0.06	0.32	1.38	18.4	0.4	0.28	-	8.17	-	-	Bal.	40
AS	0.315	0.239	0.53	1.29	0.018	0.009	0.451	1.54	-	-	Bal.	58
HCS	0.75	0.25	0.32	-	-	-	-	-	-	-	Bal.	66
HSS	0.86	0.45	0.40	3.80	0..03	0.03	4.70	-	1.70	6.00	Bal.	73

*MS - Mild steel; SS - Stainless steel; AS - Armour steel; HCS - High carbon steel; HSS - High speed steel

Table 4 Effect of tool materials on joint properties

Tool Material	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation in 50 mm gauge length (%)	Reduction in cross -sectional area (%)	Joint efficiency (%)	Stir Zone hardness (Hv)	Stir zone grain diameter (µm)
MS	130	162	5.0	5.1	75.5	72	10
SS	128	160	3.5	4.8	74.5	73	11
AS	127	159	3.0	4.3	74.1	73	12
HCS	166	207	7.3	5.5	96.3	77	6
HSS	142	178	4.0	4.8	82.5	75	8

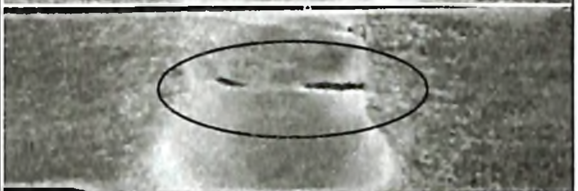
steel (AS) and high speed steel (HSS) materials. Threaded pin profile and a shoulder diameter of 18 mm were maintained for all the tools. In FSW process, the tool plays an important role and decides the quality of the joints. The pin initiates the process by plunging into the base metal. The tool shoulder generates the heat and makes the base metal to attain plastic state. Again, the pin stirs the plasticized base metal to flow around it and pave the way for dynamic recrystallisation and weld metal consolidation. The friction between rotating tool shoulder and the metals to be joined at the abutting surfaces generates the heat required to cause the material to flow plastically. If the co-efficient of friction (µ) is higher, then heat generation will be higher. The co-efficient of friction exist between the tool and the base metal is controlled by the hardness of the tools. The hardness of the tool is influenced by the chemical composition of the tool materials. The chemical composition and hardness of tool materials are presented in Table 3. The tool material hardness was measured and it is found that the hardness is in the ascending order of mild steel, stainless steel, armour steel, high carbon steel and high speed steel.

Carbon content and other alloying elements present in the tool material influence the hardness. The lowest hardness of 30 HRc was recorded for mild steel and this is mainly because of low carbon content (0.22 wt %). Even though, the carbon content in stainless steel is lower (0.06 wt %) compared to mild steel, the other alloying elements such as chromium, nickel, molybdenum enhances the hardness value to 40 HRc.

Similarly, higher carbon content and other alloying elements along with quenched and tempered treatment yields higher hardness of 58 and 66 HRc for armour steel and high carbon steel respectively. HSS contains higher amount of carbon (0.86 wt %), along with other alloying elements such as tungsten, chromium and vanadium and shows a hardness value of 73 HRc.

The friction between pin and the plasticized metal is also influenced by the tool material hardness. The plasticized material under the tool shoulder is pulled from advancing side and redeposited on the retreating side. During this period, the plasticized metal flows around the tool pin and behaves like an extruded metal under the forging action of tool shoulder. If the friction between tool pin and the extruded metal is less, then the metal flow will be free and smooth. The resultant microstructure will be coarse and elongated in the extrusion direction. If the friction between tool pin and the extruded metal is high, then the metal

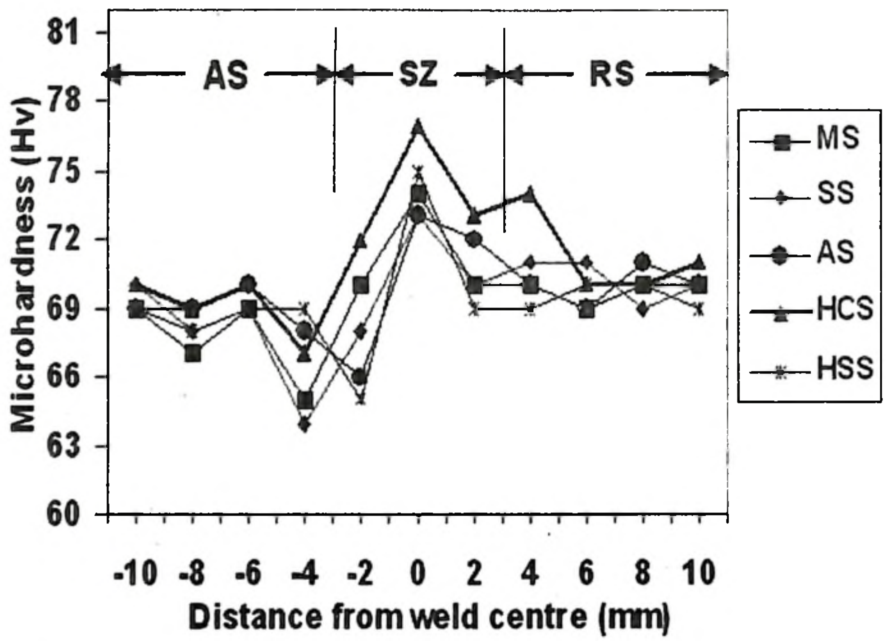
Table 5 Effect of tool materials on macrographs of FSW zone

Tool Material	Weld cross-section Shows defect location (AS — RS)	Probable reasons for defect	Location of failure during tensile test
MS		insufficient heat generation	along the defect
SS		insufficient heat generation	along the defect
AS		insufficient heat generation	along the defect
HCS		defect free	TMAZ
HSS		defect free	TMAZ

flow will not be as smooth as in the previous case. This will lead to severe plastic deformation, breaking of old grains and recrystallisation of smaller grains. Further, the pulling of metal from advancing side is also affected by the friction existing between tool pin and the plasticized metal. If friction between pin and plasticized metal is less, then the magnitude of inward force acting towards the pin centre will be less and subsequently the plastic working (pulling) of metal will be less.

On the other hand, the friction between pin and plasticized metal is high, then the magnitude of inward force acting towards the pin is high and subsequently the amount of plastic working (pulling) in the weld zone is relatively higher. Based on the above discussion, it is understood that the lower hardness of mild steel, stainless steel and armour steel led to the low friction condition between pin and the plasticized metal, subsequently, insufficient metal working resulted in defect formation and inferior tensile properties. However, the higher hardness of HCS and HSS led to the high friction condition between pin and the plasticized metal, subsequently, sufficient metal working resulted in defect free nugget region and superior tensile properties.

The tool material, which possesses higher hardness, will generate higher heat input due to higher co-efficient of friction. If this is the case, then the HSS tool should have generated higher heat input compared to their counterparts. However, the thermal (heat) conductivity of HSS tool is higher compared to HCS due to the presence of tungsten, chromium and vanadium. Though heat generated by HSS is higher than HCS, some amount of heat is dissipated to the tool shank due to higher thermal conductivity. Hence, the net heat flow in to the base metal is appreciably lower in the case of HSS compared to HCS. This lead to the insufficient working and poor consolidation of plasticized metal in the nugget region, which was evident from hardness measurements and tensile properties evaluation. The hardness of



AS - Advancing side
RS - Retreating side

Fig 2 : Effect of tool materials on hardness

mild steel, stainless steel and armour steel is much lower compared to HCS and HSS and hence the heat generation is not sufficient to cause the metal to flow plastically. This led to the formation of defects in the nugget region and subsequently exhibited poor tensile properties.

CONCLUSIONS

In this investigation, an attempt was made to study the effect of tool materials on friction stir welded AZ31B magnesium alloy. From this investigation, the following important conclusions are derived:

1. The joints fabricated by high carbon steel (HCS) tool exhibited superior tensile properties (14% higher joint efficiency than the joint fabricated by HSS tool) compared to their counterparts.

2. The absence of defects in nugget region, presence of very fine equiaxed grains in the nugget region and the formation of very clear grain boundries in nugget region are the main reasons for higher hardness and subsequently for the superior tensile properties of the above joints.

ACKNOWLEDGEMENTS

The authors are grateful to the Department of Manufacturing Engineering, Annamalai University, Annamalai Nagar, India for extending the facilities of Metal Joining Laboratory and Material Testing Laboratory to carryout this investigation. The authors wish to place their sincere thanks to Science and Engineering Research Council (SERC), Department of Science and Technology (DST), New Delhi for financial support rendered through a R&D project no. G5/9167/2005.

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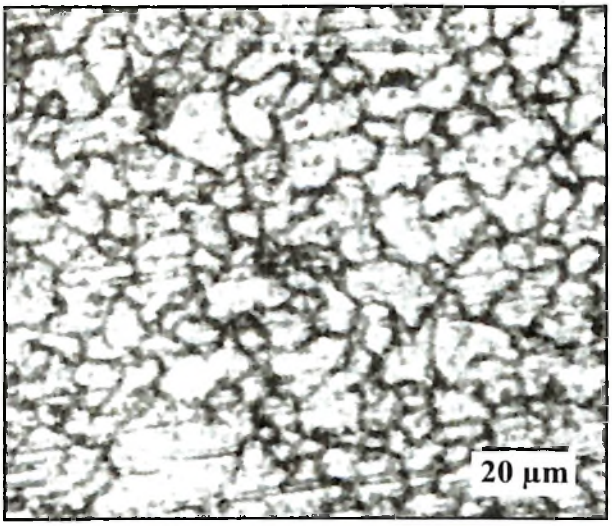
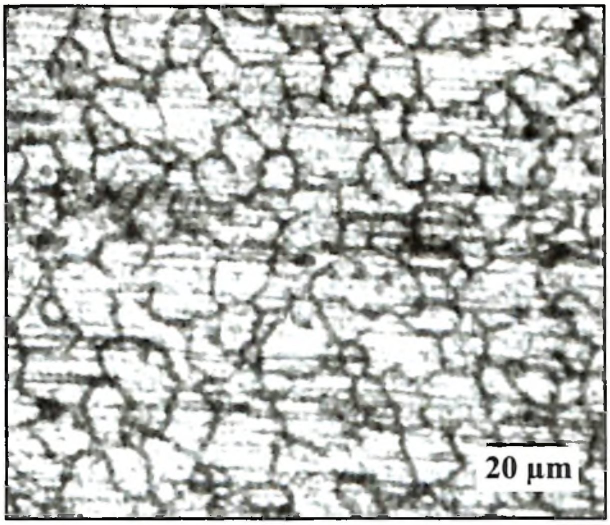
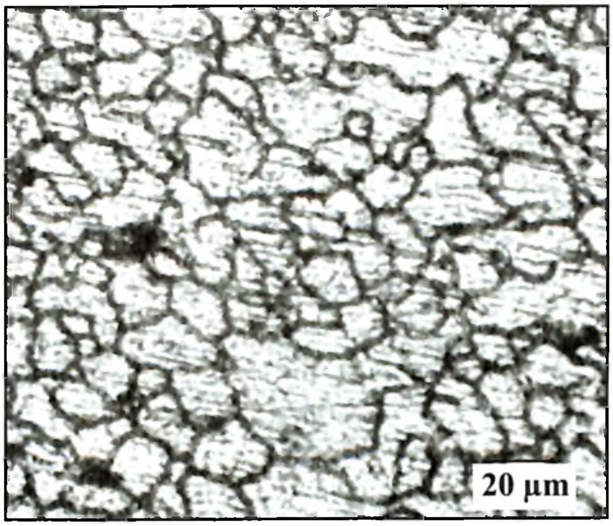
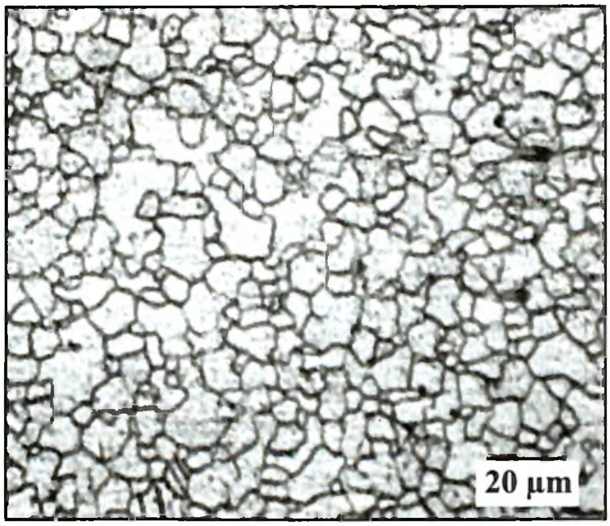




(a) Mild Steel

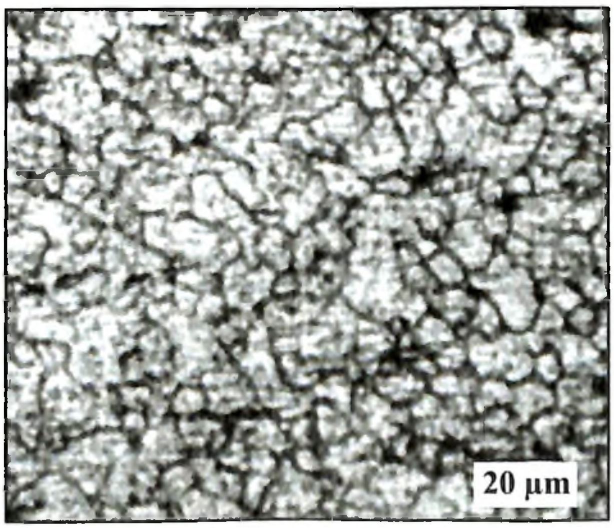
(b) Stainless Steel

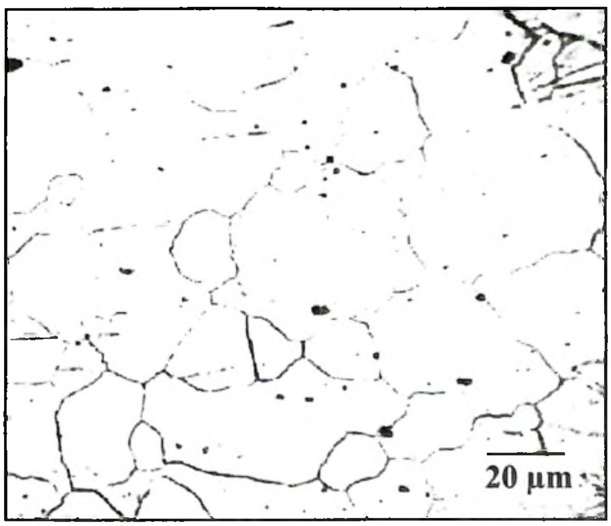




(c) Armour Steel

(d) High Carbon Steel



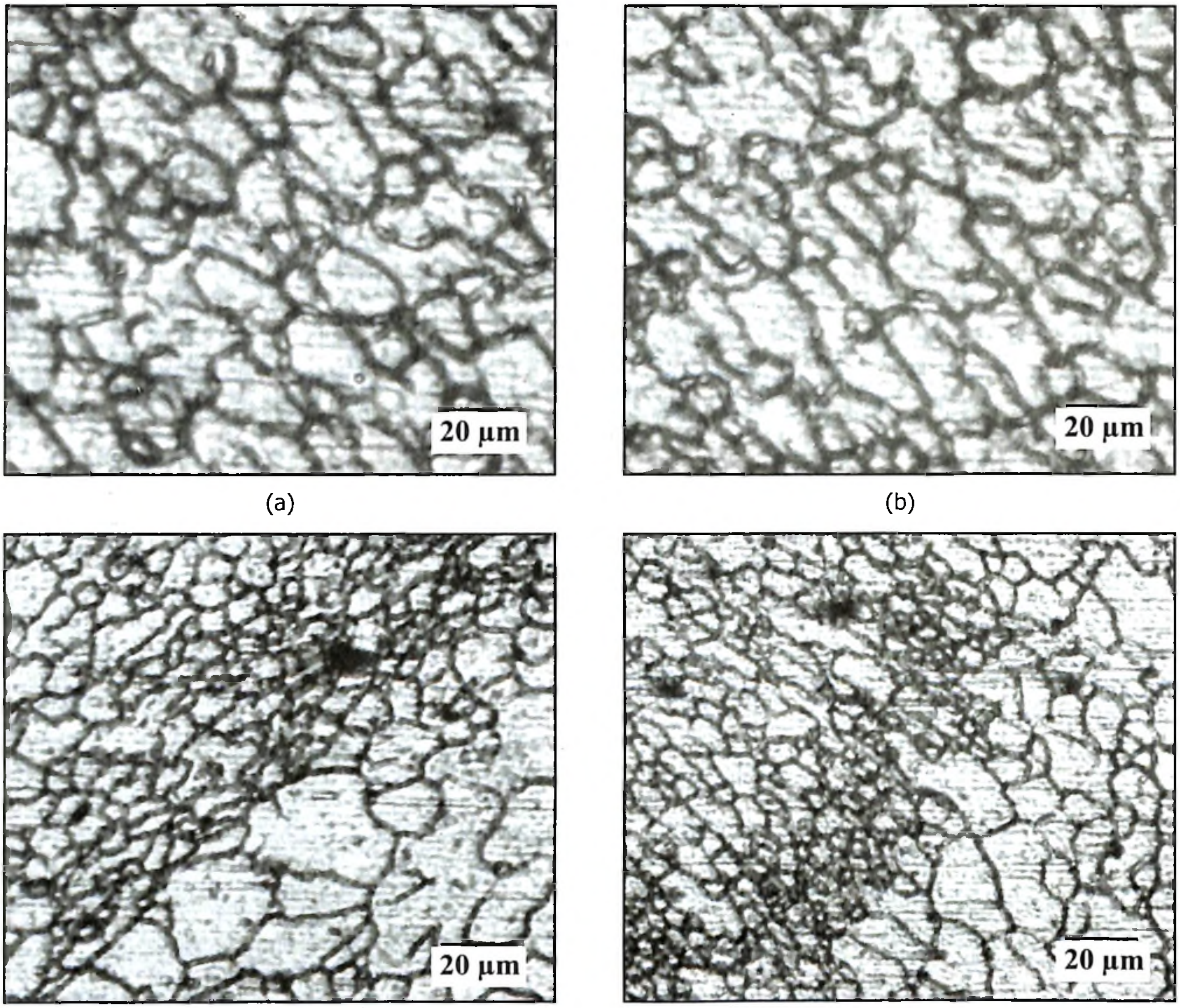


(e) HSS

(f) Base Metal

Fig. 3 Effect of tool materials on stir zone microstructure

Advancing Side **Retreating Side**



(a) (b)

(c) Transition between SZ and TMZ (d) Transition between SZ and TMZ

Fig.4 Optical micrographs of TMAZ region

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