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Mechanical Properties of Thin Wall Ductile Iron Cast in Moulding Sand/ Aluminium Dross Mix

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Abstract: *Moulding sand thermal characteristics is vital to defining the solidification mechanism of a cast part, which in turn influences evolving microstructure and mechanical properties. Thin wall ductile iron (TWDI) castings are a viable substitute for lightweight applications for energy saving in automotive industries. Carbide precipitation and non-nodular graphite in the structure of TWDI remains a production challenge in many foundries. Hitherto, charge material composition and liquid treatments were considered important in the production of sound TWDI castings. Literature is very scanty on the strategy for modifying the thermal properties of moulding sand for cooling rate and under-cooling controls for preventing carbide precipitation and non-nodular graphite in TWDI castings. This study investigates the effect of incorporating 2-12 wt. % aluminum dross (AlDr) on the thermal properties of moulding sand and on the microstructure and mechanical properties of as-cast TWDI parts. Microstructural and mechanical property characterisation of TWDI cast samples using sand-aluminum dross mix reduced BHN values from 179, 185 and 123 BHN to 67, 54 and 71 BHN, UTS values from 248, 300 and 389 MPa to 208, 168 and 221 MPa for 0 and 12 wt. % AlDr (2, 3, 4 mm thick samples, respectively). However the percent elongation increased up to 7.3% for the 3 mm thick sample. The results showed that aluminum dross used as a moulding sand additive reduced the hardness and ultimate tensile strength values but significantly improved percent elongation.*

Keywords: *Mould materials, sand mix, cooling rate, mechanical properties, thermal conductivity*

1. Introduction

The mechanical properties of ductile iron depend primarily upon the microstructures developed during solidification (Sheikh, 2008). The manufacture of thin wall ductile iron (TWDI) sand castings presents unique problems. The high surface area to volume ratio in the thin sections results in very high solidification rates and can lead to incomplete filling or other casting defects, undesirable microstructures (poor nodularity and nodule count) and mechanical properties. In recent years, many researchers such as Bockus et al (2008) and Fraś et al (2013) considered TWDI as a substitute for steels and light alloys owing to its high strength; good ductility; good castability; machinability; with high wear and fatigue resistance. However the literature identifies some drawbacks with TWDI castings: the presence of massive carbide precipitates (see Figure 1); and poor graphite shape characteristics (Figure 2) (Li et al 2000), which cause poor functional properties such as reduced ultimate tensile strength (UTS), low ductility, poor crack propagation resistance and machinability (Bockus et al., 2008; Ochulor et al, 2015). To date, most methods used to produce thin wall castings focus on metal chemistry, inoculation and gating practice. Few practical methods have been developed to control cooling and the reduction of solidification rates in convectional sand moulds. However, improvement in the heat capacity and thermal conductivity of the mould and core materials may have the potential to reduce casting wall thickness, more than all the other factors combined. By adjusting the density and thermal properties of individual mould and core components or inserts, the mould/core package can be engineered to give optimum flow and cooling characteristics (Afterheide and Showman, 2003).

During casting, heat transfer occurs between the hot liquid metal and the mould and the temperature decreases from that of the cast to the surrounding temperature. The process involves three successive stages: the cooling of the liquid metal; solidification; and finally cooling of the solid metal (Abed, 2011). The properties of the mould sand have an influence on the solidification process and behaviour of the liquid metal in it.

Figure 1. Microstructure of TWDI showing carbide precipitate
Source: Ochulor et al. (2015)

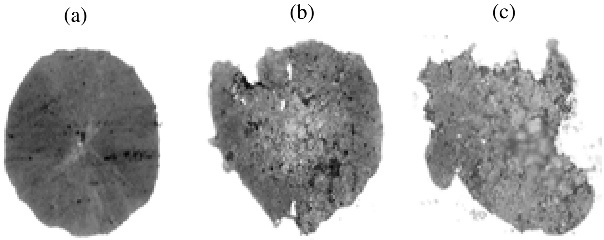


Figure 2. Types of graphite shapes (a) Spherical/nodular, (b) Slightly nodular and (c) Non-nodular
Source: Abstracted from Li et al. (2000).

The process of solidification—the change of liquid to solid metal after pouring into the mould—is the defining event in the life cycle of the casting (Rihan, 2010). The time involved in this transition may be as short as a few seconds or as long as hours, depending upon the casting process; the size of the casting; the chemical composition of the metal being cast; the manner in which solidification occurs; and the subsequent solid state treatment which determines the ultimate microstructure and properties (mechanical and physical) of the casting (Schmidt, 2010).

The heat exchange in the metal mould system is essential to the kinetics of cooling and solidifying of a casting, especially in TWDI casting, which starts to solidify during mould filling, and determines the cooling rate (Gorny, 2009). The goal here would be to control the solidification event so that the desired microstructure (nodularity and nodule count, and matrix type) of the final product with enhanced mechanical properties is obtained. The ultimate physical and mechanical properties of the cast metal will depend on one hand on intrinsic factors, such as chemical composition; cooling rate during solidification; and heat and mechanical treatments after solidification. On the other hand, it will depend on extrinsic factors, namely metal cleanliness; additives for microstructure control; casting design; riser and gating design; solidification rate control; and temperature control subsequent to solidification, which are both present (extrinsic and intrinsic) in each casting event and processing event subsequent to casting (Cantor, 2003; Kalpakjian, 2008). The cooling rate is largely determined by the size of the casting in its cross-section. Heat treatment may be used to overcome the difficulty, but this is usually undesirable because of cost and the extra processing steps required (Bockus and Zalgarys, 2010).

Ruxanda et al. (2002) in their study of the microstructural characterisation of TWDI castings, observed that high solidification cooling rates, the presence of carbide forming elements in the charge materials, low carbon equivalent and/or silicon content, low nodule count (poor inoculation) and poor nodularity as some parameters responsible for carbide formation. The main constituents of the matrix of TDWI castings are ferrite, pearlite and carbides, if any; their actual ratio is highly dependent on the processing parameters which include cooling rate, liquid treatment, chemical composition, and pouring temperature. The thermo-physical property of the mould is a crucial variable that affects the chilling tendency of TWDI castings (Stefanescu et al., 2002). Moulds with high thermal conductivity remove heat faster from the molten metal, causing it to solidify earlier. Moulds with high heat diffusivity transfer heat faster from the molten metal, causing it to stop flowing so that solidification occurs faster.

Aluminium dross, a by-product of aluminium smelting, is a mixture of metallic aluminium and non-metal mostly aluminium oxide. It usually forms on the surface of molten aluminium or its alloys by oxidation. In this study it is used as a moulding sand constituent and this study investigated its effect on the thermal characteristics of moulding sand and consequently on the microstructure and mechanical properties of TWDIs cast from the mould mix. The aim was to impart some level of thermal insulation into the mould material using the refractory properties of Al_2O_3 and SiO_3 present in the dross: This approach was predicated on the reduction in moulding sand thermal conductivity and finally on cooling rate of the melt.

2. Methodology

2.1 Aluminium Dross Additive to Moulding Sand on TWDI castings

The dross used was collected from Aluminium Rolling Mills, Ota, Nigeria, after a recovery process was carried out to remove valuable aluminium. Table 1 shows the chemical composition of the Aluminium Dross. Sieve analysis was carried out on the dross and only particles sizes between 250-300 μm were used. This ensured that the particle size is similar to that of the silica moulding sand used, as good surface finish is required in TWDI castings.

The chemical composition of cast the TWDI sample is shown in Table 2, and a control composition of the green moulding sand used is shown in Table 3. This control composition is used to cast 2, 3 and 4 mm plates so as to compare its properties with that of the other sand mixes, containing varied wt. % of the aluminium dross.

Table 1. Chemical Composition of Aluminium Dross

Consti.	Al_2O_3	SiO_2	MgO	NaO	K_2O
Wt. %	43.38	3.12	0.12	9.84	0.72

Consti.	CaO	Fe_2O_3	Sulphate	Chloride	Al
Wt. %	1.57	0.70	0.60	1.98	37.97

Table 2. Chemical Composition of cast TWDI sample

Element	Fe	C	Si	Mn	P	S	Cr
Compo (Wt. %)	92.47	3.44	3.21	0.32	0.057	0.071	0.025

Table 3. Control Composition of the green moulding sand

S/No	Materials	Weight Composition (wt. %)
1	Silica Sand	96.4
2	Bentonite	2.2
3	Starch	0.8
4	Water	0.4

The sand constituents are mixed using a Rhino model IRM-500 sand mixer with a mixing time of 5 minutes. Using this standard composition of moulding sand, six other different compositions of the moulds were prepared by adding varying weight percentages of aluminium dross (AlDr) to the moulding sand as in Table 4. The choice of the weight percentages used is based on a preliminary trial test conducted on 600g of moulding sand. The result helped determine the upper limit (i.e. 12 wt. % AlDr) of the dross to be used. Higher weight percentages had an adverse effect on the moulding sand properties. The moulding sand property test was conducted to ensure that the sand/AlDr blend had the required properties necessary for ductile iron casting in the foundry. This was vital to preparing dense moulds with sufficient strength for close dimensional accuracy of the samples.

Table 4. Sand Specimen with wt% of Aluminium Dross

S/No	1	2	3	4	5	6	7
Specimen	D	D1	D2	D3	D4	D5	D6
Wt% of AlDr	0	2	4	6	8	10	12

The thermal properties of importance in this work are (1) thermal conductivity and (2) heat/ thermal diffusivity. These thermal properties of the sand-Al dross blend were determined after moulding just before coupling, using the KD 2 Pro Thermal Conductivity Meter (see Figure 3a). Both the TR-1 (see Figure 3b) and SH-1 (see Figure 3c) sensors were used to measure thermal conductivity and thermal diffusivity respectively at 28.83 ^{0}C read temperature. The charge composition is shown in Table 5.

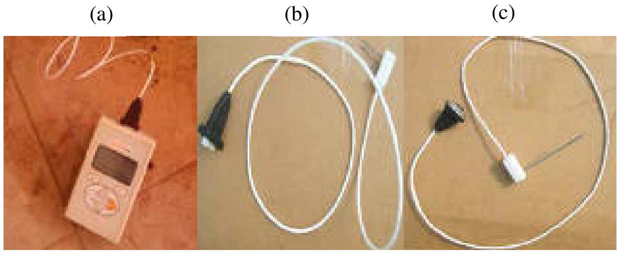


Figure 3. (a) KD 2 Pro Thermal Conductivity Meter, (b) TR-1 sensor (c) SH-1 sensor

Table 5. Chemical composition of charge materials

Charge	wt. % (Kg)	% of Charge	C (Ch. Comp.%)	Si (Ch. Comp.%)	Mn (Ch. Comp.%)
Mild Steel	300	60	0.1	0.1	0.2
Ductile Iron Returns	80	34	0.1	0.1	0.2
Ferro Silicon	7	1.4	0.00	70	0.00
Graphite	23	4.6	70	0.00	0.00
Charge	wt. % (Kg)	% of Charge	C (Ch. Comp.%)	Si (Ch. Comp.%)	Mn (Ch. Comp.%)

2.2 Microstructural Characterisation of Experimental TWDI Castings

The samples (of 2, 3 and 4 mm thicknesses) were cast using the standard casting procedure after melting the charge materials. Samples for microstructural analysis were cut from the centre; ground; and polished according to the standard procedure outlined in ASTM Standard E3 for metallographic analyses. The prepared samples were viewed in their unetched and etched (using 2% nital solution) conditions using a CETI Optical Metallurgical Microscope Model No. 0703552 at a magnification of X100.

2.3 Mechanical Property Testing

The Brinell hardness test was carried out using a 10/3000kg indenter ball in accordance with the ASTM E10 standard. The results are shown in Table 5. A tensile property test was carried out on a test piece sample 2 mm in thickness, as shown in Figure 4 in accordance with ASTM E8 standard.

Table 6. BHN results for the samples cast with moulding sand-aluminium dross mix

Wt.% Al.Dr	0	2	4	6	8	10	12
2	179	48	37	26	55	47	67
3	195	63	33	30	52	52	54
4	123	69	48	25	63	47	71

Figure 4. Dimension for Tensile Test Sample

3. Results and Discussion

3.1 Effect of Aluminium Dross addition on Moulding Sand Thermal Characteristics

The effects of the aluminium dross addition on the thermal conductivity and diffusivity of the sand mixes are presented in Figures 5 and 6 respectively. The thermal conductivity of the sand mix, shown in Figure 5, increased significantly from that of the control mix up to 6 wt. % AlDr, after which it dropped progressively with further increases in weight percent of AlDr from 8-12wt. % AlDr. This can be attributed to high initial thermal conductivity imposed by aluminium in sand mix i.e., 2-6 wt. % aluminium dross, then as the weight percent of additive is increased i.e., 6-12 wt. % the insulating properties of both alumina and silica became evident causing reduction in thermal conductivity (see Table 1).

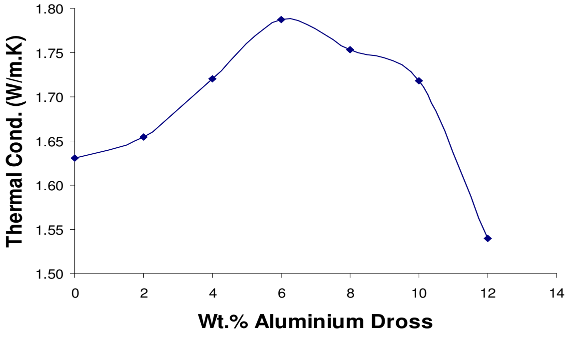


Figure 4. Moulding sand thermal conductivity with weight % Al dross in sand mix

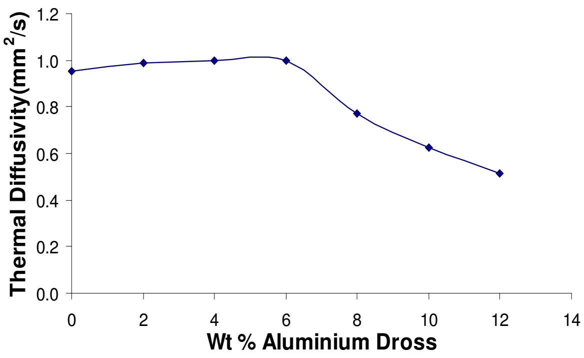


Figure 5. Moulding sand thermal diffusivity with weight % Al dross in sand mix

This indicates a faster cooling/heat transfer rate for the TWDI samples up to 6 wt. % AlDr. This faster cooling rate implies that there is insufficient time for graphite segregation i.e. formation of graphite nodules. It then reduced on further AlDr addition to the sand mix, thereby aiding thermal insulation which is the desired property here. The reduction in thermal conductivity from 6 wt. % AlDr implies that there is more time for graphite segregation but it should be noted that these values of 1.787, 1.753, 1.718 W/m K for 6, 8 and 10 wt. % respectively (except that of 12 wt. % AlDr of 1.540 W/m K) are still lower than that of the control sand mix of 1.631 W/m K. The thermal diffusivity which is a function of thermal conductivity increased only slightly from 2 to 6 wt. % AlDr, after which it dropped significantly from 8 to 12 wt. % AlDr, reaching 0.514mm^2/s for 12 wt. % (see Figure 5). This implies that the solidification of samples is delayed when cast in these moulding sand/aluminium dross sand mix. This is expected to aid proper graphite segregation (carbon diffusion) in melt solidification, enhancing better nodularity and nodule count.

3.2 Microstructural Analysis of Sand – Aluminium Dross Cast Samples

All the optical micrographs (see Appendix 1, Plates 1-21) of the samples cast using an aluminium dross additive showed that this additive yielded undesirable graphite characteristics i.e., low nodularity and nodule count, and consequently undesired mechanical properties of cast TWDI samples. The control samples showed good nodularity, good nodule count and control of carbide precipitates. Non-nodular graphite and poor matrix structure were observed in the samples cast using the moulding sand-aluminium dross blend. Plates 1-3 shows micrographs of samples cast without the use of moulding sand-AlDr blend (control samples). The samples show good nodularity and nodule count. The matrix constituents are mainly ferrite and pearlite exhibiting the bull-eyed structure. The graphite nodules were mainly of type IV and V.

The microstructures of samples cast using 2wt. % AlDr show poorly formed graphite nodules for all thicknesses. In addition to non- nodular graphite, there is the presence of a dark phase which is suspected to be a reaction product formed by reactions between elements in the melt (see Table 5) with aluminium, alumina or sulphur from sulphate in the moulding sand mix (see Table 1). Thermal conductivity increased slightly from 1.631 to 1.654 W/m K thereby reducing the time for nucleation of graphite nodules (Plates 4-6). Due to the reduction in solidification time, insufficient time is available for graphite nucleation leading to carbide precipitates in TWDI matrix.

Plates 7-9 for 4 wt. % AlDr show these dark reaction product phases, poor nodularity and nodule count with carbide precipitates in the structure. Plates

10-12 show samples cast from 6 wt% AlDr. This corresponds to the highest thermal value of 1.787 W/m K, indicating a high heat transfer rate. The samples also exhibited poor nodularity and nodule count; undesirable reaction products were created and the resultant matrix structure is not clearly defined. The same is also observed for Plates 13-15 where thermal conductivity started dropping, the structure here also shows the presence of a ferrite phase. The thermal conductivity was further reduced, though it is still higher than that of the control sand mix. Increased thermal conductivity drops resulted in better nodularity and nodule count. The matrix type is ferrite-pearlite for the three thicknesses as shown in Plates 16-18. The shape characteristics of formed nodules improved significantly for 12 wt. % AlDr sand mix (see Plates 19-21). Thermal conductivity dropped to 1.540 W/m K, which was lower than that for control sand mix of 1.631 W/m K. This is responsible for a better but not desired microstructure observed in these plates. The matrix is still ferrite-pearlite.

3.3 Hardness Characteristics of TWDI Castings Produced in Al Dross-Sand Mould

The chemical composition of cast TWDI sample is shown in Table 2. The variation of Brinell hardness number (BHN) with weight percent aluminium dross is shown in Figure 7. The hardness values were highest for the control samples 179, 195 and 123 for 2, 3 and 4 mm thick samples, indicating that casting using the AlDr as a moulding constituent did not produce the required hardness. However, the BHN values increased from 2-12wt% aluminium dross, dropping slightly again at 10wt%. AlDr. These lower BHN values observed in samples cast from moulding sand-aluminium dross mix can be attributed to the reaction product formed; this compound had a softening effect on the matrix of the samples.

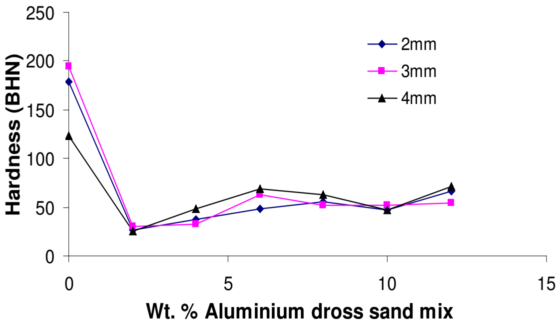


Figure 7. Variation of BHN with weight % Al Dross in sand mix

3.4 Tensile Characteristics of TWDI Castings Produced in Al Dross-Sand Mould

The variation of ultimate tensile strength (UTS) with weight percent aluminium dross is shown in Figure 7. The UTS responses show that aluminium dross addition to sand mould negatively affected the UTS of the cast samples. The control samples that were cast in sand mould without AlDr addition gave the best UTS of 248, 300 and 389 MPa. The lowest UTS values occurred at 2wt. % AlDr corresponding to the second lowest thermal conductivity value. This pattern is similar to that obtained for hardness responses. The percent elongations at fracture are higher from 8-12wt. % AlDr.

The highest values of 4.5, 7.3 and 4.7 % at 12wt. % AlDr for 2, 3 and 4 mm thicknesses, respectively, were observed (see Figures 9). Thus, the percent elongations of cast samples were high, indicating that the dross-sand mould positively impacts ductility, while sacrificing tensile strength. As mentioned previously the suspected reaction product nucleated in the melt during solidification had a softening effect on the matrix of TWDI samples, also as thermal conductivity dropped from 6-12 wt. %, the cooling rate is reduced and further softening of matrix is suspected as the percent elongation values were highest for all thicknesses investigated at 12 wt. % aluminium dross (see Figure 9).

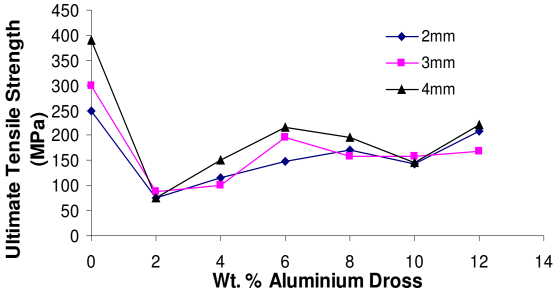


Figure 7. Variation of UTS with weight % Al Dross in sand mix

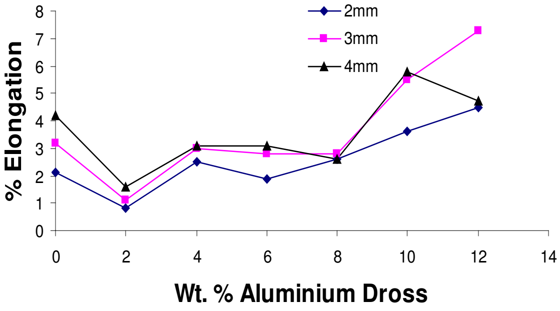


Figure IX. Variation of % elongation with weight % Al Dross in sand mix

Regression analysis was used to correlate the effect of weight percent aluminium dross in moulding sand on percent elongation of samples. The analysis shows that the percent elongation follows a quadratic relationship according to equations 1, 2 and 3 for 2, 3 and 4 mm thick samples, respectively.

$$\%_{\mathrm{Elong.}}(2_{\mathrm{mm}}) = 0.0301(\mathrm{AlDr}_{\mathrm{Wt\,\%}})^2 - 0.1304(\mathrm{AlDr}_{\mathrm{Wt\,\%}}) + 1.7905 \quad R^2 = 0.8328 \tag{1}$$

$$\%_{\text{Elong.}}(_{3mm}) = 0.0711(AlDr_{Wt\,\%})^2 - 0.4804\,(AlDr_{Wt\,\%}) + 2.8548 \qquad R^2 = 0.8849 \tag{2}$$

$$\%_{\text{Elong.}}(_{4mm}) = 0.0446(AlDr_{Wt\,\%})^2 - 0.5107(AlDr_{Wt\,\%}) + 4.2829 \qquad R^2 = 0.8940 \tag{3}$$

4. Summary of the Findings

The study shows that the thermal conductivity of aluminium dross-sand mix is not favourable for casting TWDI as it causes a high heat transfer/cooling rate and this hinders equilibrium transformation. Thermal conductivity increased for all sand mixes except for 12wt. % AlDr. Samples cast from the aluminium dross sand mix are structurally defective both in graphite shape characteristics and matrix type formed. It was difficult to determine the nodularity and nodules count, as the graphite structures formed were mostly non-nodular/ deformed in shape. The matrix was also not clearly defined due to the presence of a reaction product. However, the percent elongation increased at the expense of tensile strength and hardness properties of these samples. The highest elongation values of 4.5, 7.3 and 4.7 were observed for 2, 3 and 4mm samples respectively at 12 wt. % AlDr, this can be attributed to the suspected matrix softening effect of both the reaction product and the lowest thermal conductivity value obtained at 12 wt. % Al dross.

5. Conclusion

This work has shown that aluminium dross addition to moulding sand mix caused a reduction in mould thermal properties (thermal conductivity and diffusivity); undesirable nodule characteristics; and a reduction in hardness and tensile strength of TWDI cast samples. However, samples show good percent elongation values reaching 7.3 for 3mm thick sample cast using 12wt. % aluminium dross in the sand mould. Although, this sand mix may not be a suitable mould for components requiring high strength and hardness, it can be used to cast profiles or automobile parts requiring considerable elongations and mild strength.

Acknowledgement:
The authors gratefully thank the Management and Staff of Nigerian Foundries Ltd, Lagos, Nigeria, for the use of their facilities. The contributions of Staff of Metallurgical Laboratory of the Department of Metallurgical and Materials Engineering, University of Lagos are also recognised.

Appendix 1: Optical Micrographs of Samples

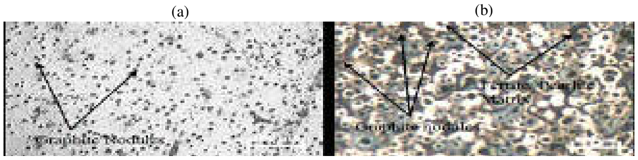


Plate #1: Optical micrograph of 2mm thick section
(a) unetched (b) etched of D

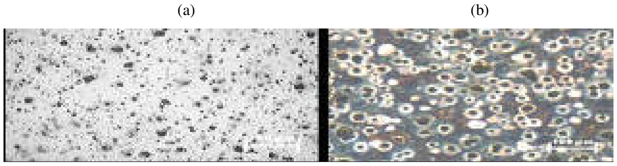


Plate #2: Optical micrograph of 3mm thick section
(a) unetched (b) etched of D

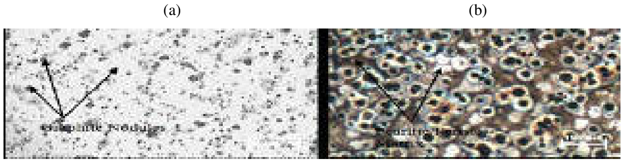
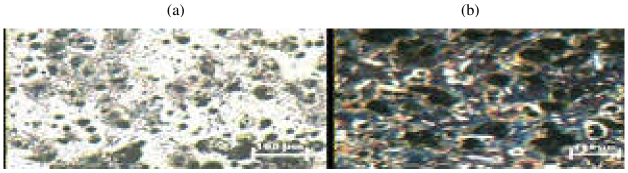


Plate #3: Optical micrograph of 4mm thick section
(a) unetched (b) etched of D



Plates #4: Optical micrograph of 2mm thick section
(a) unetched (b) etched of D1

Plate #5: Optical micrograph of 3mm thick section
(a) unetched (b) etched of D1

Plates #6: Optical micrograph of 4mm thick section
(a) unetched (b) etched of D1

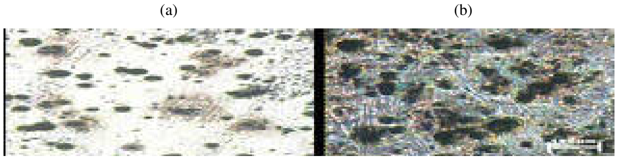


Plate #7: Optical micrograph of 2mm thick section
(a) unetched (b) etched of D2

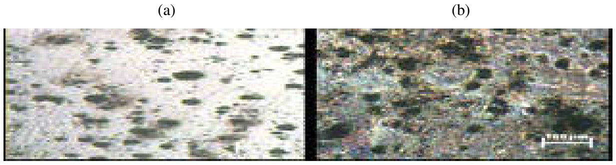
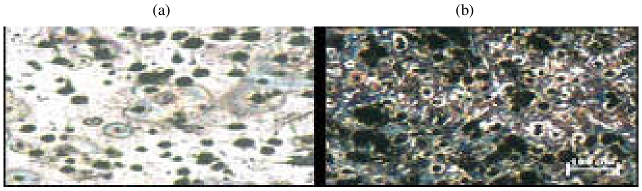


Plate #8: Optical micrograph of 3mm thick section
(a) unetched (b) etched of D2



(a) unetched (b) etched of D2

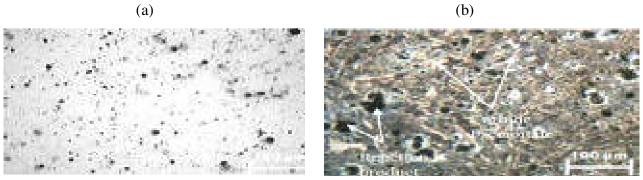


Plate #10: Optical micrograph of 2mm thick section
(a) unetched (b) etched of D3

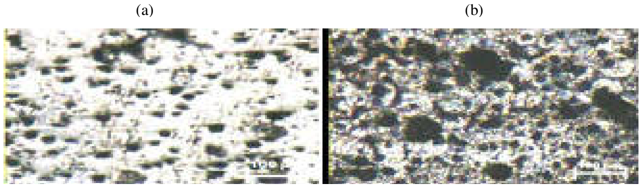


Plate #11: Optical micrograph of 3mm thick section
(a) unetched (b) etched of D3

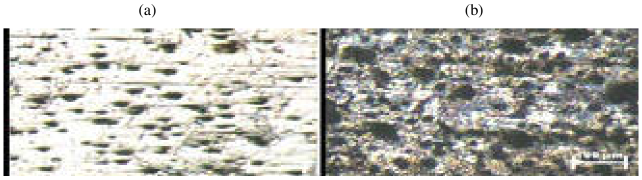


Plate #12: Optical micrograph of 4mm thick section
(a) unetched (b) etched of D3

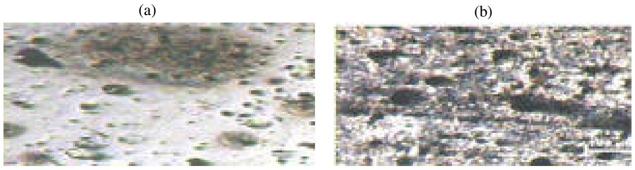


Plate #13: Optical micrograph of 2mm thick section
(a) unetched (b) etched of D4

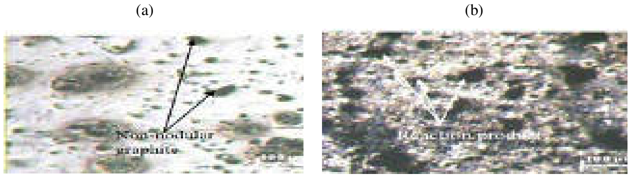


Plate #14: Optical micrograph of 3mm thick section
(a) unetched (b) etched of D4

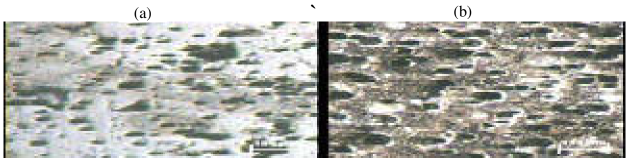


Plate #15: Optical micrograph of 4mm thick section
(a) unetched (b) etched of D4

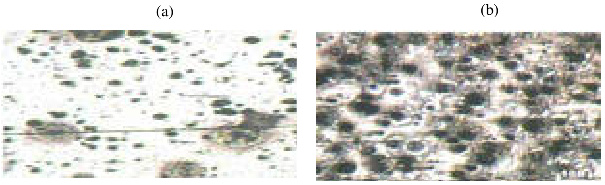


Plate #16: Optical micrograph of 2mm thick section
(a) unetched (b) etched of D5

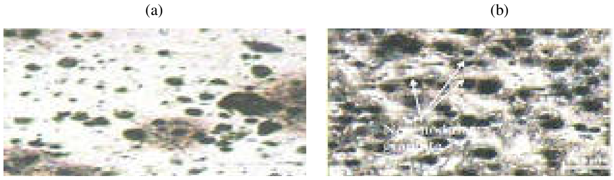


Plate #17: Optical micrograph of 3mm thick section
(a) unetched (b) etched of D5

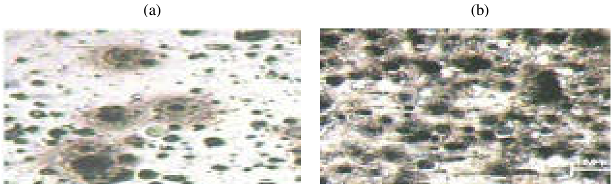


Plate #18: Optical micrograph of 4mm thick section
(a) unetched (b) etched of D5

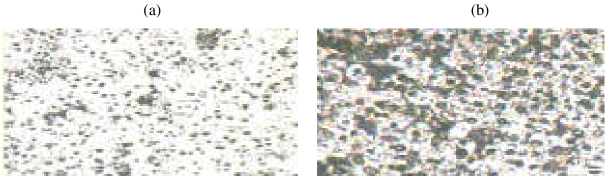


Plate #19: Optical micrograph of 2mm thick section
(a) unetched (b) etched of D5

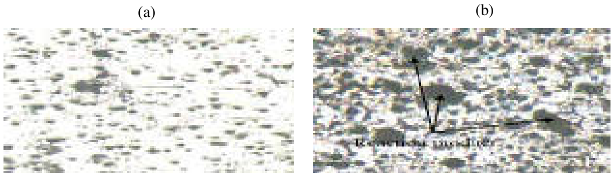


Plate #20: Optical micrograph of 3mm thick section
(a) unetched (b) etched of D6

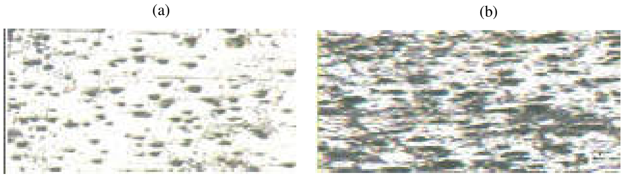


Plate #21: Optical micrograph of 4mm thick section
(a) unetched (b) etched of D6

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