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THE EFFECT OF GRAIN REFINEMENT ON MECHANICAL BEHAVIOUR AND WEAR CHARACTERISTICS OF LOW CARBON STEEL PROCESSED BY MULTI-AXIAL FORGING

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ABSTRACT

The present work comprises of the study of the microstructure, mechanical behavior and dry sliding wear characteristics of low carbon steel when subjected to Multi-axial forging (MAF). With increasing forging passes, grain refinement of samples was evident from microstructures, which was confirmed by grain size analysis of the samples. Grains with initial size of 80 µm were refined to the final size of 11.9 µm. Mechanical behavior of MAF steel was checked for hardness by Rockwell hardness testing machine, tensile strength by Universal testing machine and toughness by Charpy impact testing machine. Increase in hardness of nearly 130% was observed in sample with maximum forging passes from 127 HV for 0 pass material to 285HV for 9 forged pass materials. Tensile strength was increased from 509 N/mm^2 for original material to 777.8 N/mm^2 for 9 pass forged samples. The toughness of the original material increased from 16J to28J for the 9 pass forged samples. Wear rate and wear volume for same sliding distance at same load had lower values for 9 pass forged steel when compared to the original material.

***Keywords:** Multi-axial forging; Grain refinement; Microstructure; Wear; Low carbon steel.*

I. INTRODUCTION

Over the year's grain size control has been a key area of interest for researchers to control the properties of steel with the aim of achieving higher strength to weight ratio, higher hardness, and adequate toughness and better wear properties. The foundation which leads to inclination towards this interest was laid by the Hall-Petch equation which says that the strength of material also, depends on grain size and is inversely proportional to the square root of the grain size. In pursuit of this interest, several grain refinement techniques were developed which include severe plastic deformation (SPD), thermo-mechanical processing, alloy addition, powder metallurgy etc. Out of these methods, the main area of focus is the newly developing SPD methods because of their ability to overcome the shortcoming of other methods such as loss of ductility, loss of toughness, poor weldability, porosity etc.

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Severe plastic deformation (SPD) involves application of very high plastic strain on a sample avoiding any significant change in a sample's geometry resulting in refinement of grains in sample. These processes are modification of already known metal forming processes such as forging, rolling, extrusion etc, with the aim of achieving grain refinement by applying large strain rate with very short span of time thereby minimizing possibilities of grain coarsening. The SPD techniques are capable of producing true polycrystalline structures with high angle disorientations and grain sizes of the order of 100 nm and even less. Severe plastic deformation techniques, e.g., equal channel angular pressing (ECAP), multi axial forging (MAF), high pressure torsion (HPT), and accumulative roll bonding (ARB) are commonly used techniques for grain refinement. Among all the mentioned techniques above, MAF is one of the SPD techniques used to produce UFG materials. [1-5]

The advantage of MAF over other SPD techniques is that this method can be used for large specimens and can be incorporated for bulk production in industry as it is a small advancement of the conventional forging method which is easy to implement and is less costly in comparison to other SPD methods. The principle used in MAF is performing repetitions of free forging operations by changing the axis of applied load by 90^0 after each pass. The MAF technique provide less homogeneity compared to other SPD techniques, however low force level and open die forging leads to lower tool cost thus making this method more preferable over other methods. Also forging is one of the most common known methods of forming steels.

Steel under study is low carbon steel with carbon content of 0.08 %. This steel is widely used for making gears, shafts, bearings, moulds and some automobile components. Also this steel is widely used as structural steel because of its good strength to weight ratio. Till date processing this steel through common metal forming processes has found it so many uses in industry but to process it through multi axial forging to obtain grain refined low carbon steel with enhanced strength, high hardness, improved toughness and better wear characteristics will improve the service life of the component made of this steel thereby saving lot of money of replacement, also improving the property of high strength to weight ratio along with other enhanced properties can find this low carbon steel new applications which could help in replacing high priced steels and high cost heat treatment processes involved in obtaining the desired properties by altering the manufacturing route to obtain high quality end product of steel. [5-10].

The mechanical and dry sliding wear behavior of ultrafine-grained AISI 1024 steel processed using multi axial forging was checked by A.K Padap et.al. AISI 1024 steel was severely deformed by using warm 500^0 C multi axial forging (MAF) technique using up to nine forging passes in order obtain a composite ultrafine grained (UFG) microstructure consisting of fragmented cementite particles. V Soleymani et.al (2012) did the grain refinement of low carbon steel through multidirectional forging. The initial Coarse grains of average 38 µm size fragmented into very fine ferrite with grain sizes of about 1.2 µm. After MDF, the strength properties improved significantly, although uniform elongation and elongation decreased with increasing strain. Tareg S. Ben Naser et.al (2015) worked on the super plastic behavior of Al7075 alloy by Multiple-forging. They observed the decrease in tensile strength and better maximum elongation for the multiple forged aluminum samples in comparison to the base samples. T. Raghu et.al (2011) worked on the Isothermal and near Isothermal forging of titanium alloys. Isothermal and near isothermal forging are specialized metal-forming techniques used for producing critical aero engine components from advanced materials such as titanium alloys. Song-Jeng Huang et.al (2010) studied the tribological properties of low carbon steel with carbon percentage of 0.20% with different microstructure processed by heat treatment and severe plastic deformation. The ECAP method of severe plastic deformation was chosen for strain hardening of the initial material. It was been revealed that severe plastic deformation by equal channel angular pressing technique enhances efficiently the strength of the low-carbon steel and the decrease of the friction coefficient and its adhesive component. P.N. Rao et.al (2013) states that the multiple directional forging is the simplest method to achieve larger strains with minimum change from its original shape and allows processing of bulk products. They observed the increase in hardness from 54 HV to 91 HV after 3 cycles of MDF.[5, 6, 11--21].

II. EXPERIMENTAL

2.1 Multi-axial forging (MAF)

Multi-directional forging was applied for the first time in the first half of the 1990s for the formation of UFG structures in bulk billets. MAF is one of the SPD techniques used for grain refinement. The advantage of MAF over other SPD techniques is that this method can be used for large specimens and can be incorporated for bulk production in industry as it is a small advancement of the conventional forging method thus it is easy to implement and is less costly in comparison to other SPD methods. The principle used in MAF is performing repetitions of free forging operations by changing the axis of applied load by 90^0 after each pass.Low carbon steel having (wt %) of 0.08 C, 0.4 Mn, 0.1 Si, 0.002 P and 0.004 S and balance iron isused in this study. Samples were machined to cuboid shape of size 26.7 mm x 32.8 mm x 40 mm. The dimensional ratio of samples for MAF is 1.0:1.22:1.5. All samples were annealed at 1150^0C for 60 min to obtain uniform initialmicrostructure. Successive uniaxial compressions of e =-0.25 were applied to the longest side at each strain step.Assuming volume conservation and material isotropy, thisprocedure enables the initial dimensional ratio to be maintainedat the end of each pass. Samples were heated at 550^0Cfor 30 minutes, before they were alternately forgedwith loading direction changedthrough 90^0 after each pass. Graphite powder was used for lubrication duringforging. At large strains, use of graphite lubricationcauses relatively homogeneous deformation. The sampleswere quickly cooled in water after each pass of forging. Parameters which have significant effect on forming UFG structure, most important being the forming temperature lower forming temperature higher would be the strain required to produce UFG structure. Forging machine used was of 100 Ton power screw forging Birson, India make.

2.2 Micro-structural characterization

Optical microscope with digital camera was used to check the microstructures of original and MAFed samples. Microscope used for the study was of make Dewinter, India. The image analyzer technique equipped with Dewinter material plus 4.5 software was used to evaluate the grain size and to do phase analysis of the samples. The technique used to evaluate grain size was circle intercept technique.

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2.3 Mechanical behavior

Mechanical behavior of original samples and MAFed samples was checked for three parameters mainly i.e. hardness, tensile strength and toughness. Machine used to check the hardness of different samples was Rockwell hardness testing machine.Minor load of 10kgf and major load of 100kgf with the dwell time of 10 seconds were applied to check the hardness of samples. Carbide ball indenter of dia 1/16 inch was used to check the hardness. Four different readings at different locations were taken and result was finalized by taking mean of all the readings.Universal tensile testing machine used to carry out tensile tests was of make MTS, USA having capacity of 500 KN with resolution of 1 N. Samples for tensile testing was cut in cylindrical shape. The samples were tested on charpy testing machine of make FIE, India having least count of 2J.

2.4 Dry sliding wear test

In pin on disk apparatus once a pin with a tip, is positioned perpendicular to the other, usually a flat circular disk, the sliding path is a circle on the disk surface. The pin specimen is pressed against the disk at a specified load usually by means of an arm or lever and attached weights. Wear results are reported as volume loss in cubic millimeters for the pin and the disk separately. For the pin-on-disk wear test specimen of 20mm x 10mm x 10mm were cut using abrasion cutting machine and then the samples were grinded on surface grinder to obtain the flat surface. Once flat surface were obtained the samples were grinded on abrasive particle grit paper of various numbers (150, 220, 320, 400, 600, 800, 1000), once samples grinded on various grit papers then these samples were polished on velvet polishing wheel having alumina powder to achieve final finish and to obtain a surface which is free from any type of oxide layer or foreign particle to obtain accurate wear testing results. The pin obtained was weighed on electronic balance with least count of 0.001 gms. Then these samples were positioned on flat disk of the pin on disk apparatus calibrated at 600rpm and disk diameter of 55mm. Material of disk used in wear testing is EN-32 with hardness 65 HRC. Wear was done for various samples for different time intervals i.e. 15, 30, 45, 60 minutes for each sample for competitive study. Weight after each time interval was checked to calculate mass loss. Similar study of wear was done by varying load i.e. for 1kg, 2kg and 3kg for competitive study.

III. RESULTS AND DISCUSSION

Sample preparation using MDF was followed by characterization, mechanical testing and dry sliding wear test. In characterization optical microscopy was done and the microstructures thus obtained were analyzed using image analyzer to evaluate the grain size and to do phase analysis. In mechanical testing hardness of different samples were checked using Rockwell hardness testing machine, tensile strength evaluated using Universal tensile testing machine and toughness was evaluated using Charpy impact testing machine. Wear characteristics of various forged samples were evaluated by carrying dry sliding wear using Pin on disk apparatus. In this chapter results obtained from various tests are discussed and the results are analyzed.

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3.1 Optical emission spectrometry (OES)

The material procured from vendor was checked for its chemical composition using spark optical emission spectrometry. The chemical composition of low carbon steel under study is given in Table 1

Table 1: Chemical composition by wt% of low carbon steel

Element	Fe	C	Si	Mn	P	S	Cr
Percentage	99.1	0.07	0.151	0.439	0.0020	0.0048	0.0070

3.2 Optical microscopy

Microstructures obtained from computerized optical microscope for various samples are shown in figure 1(a, b, c, d).

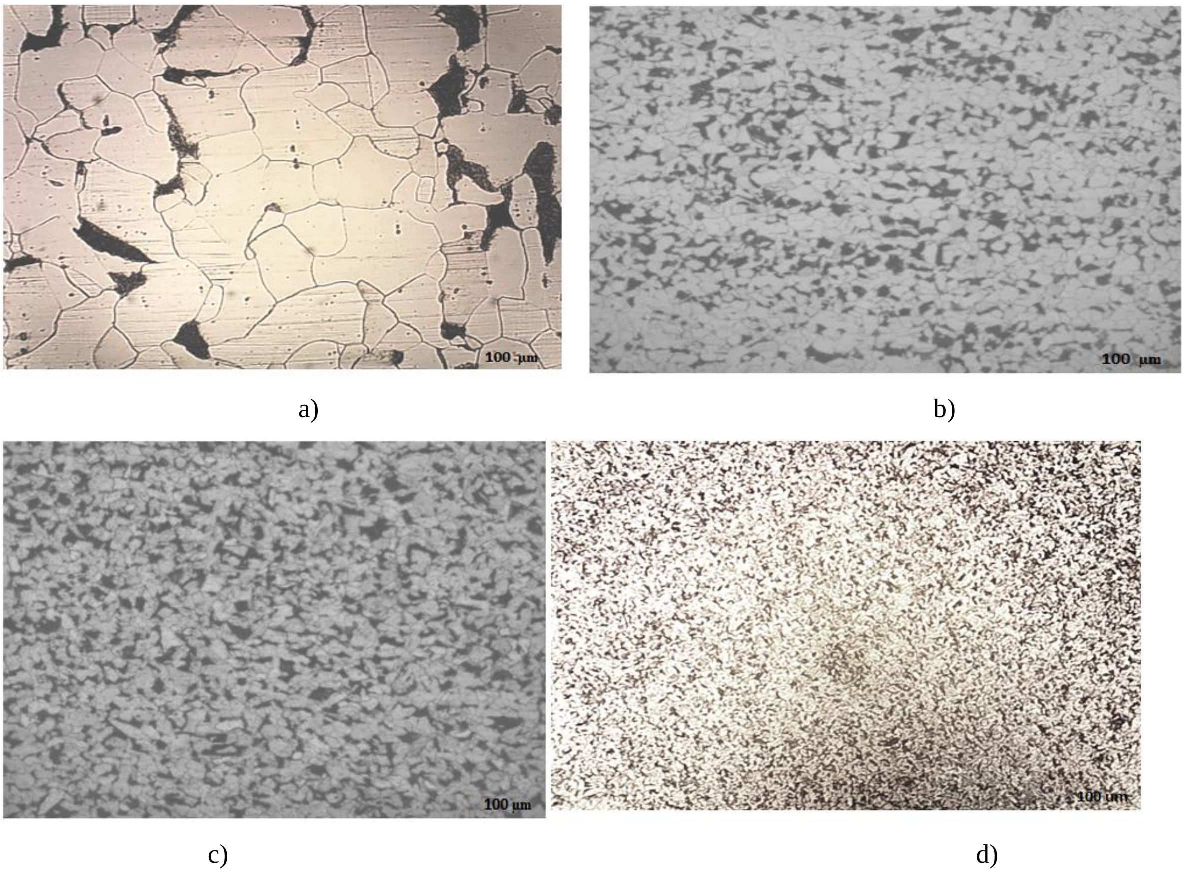

Figure 1: a)Microstructure of annealed low carbon steel at 100x, b) Microstructure of annealed low carbon steel at 100x, c) Microstructure of MAF sample (6 Passes) at 100x, d) Microstructure of MAF sample (9 Passes) at 100x.

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The microstructure of annealed low carbon steel and MAF samples subjected to per pass strain of 0.25 for different passes i.e. 3pass, 6 pass, 9 pass is shown in figure 1(a, b, c, d). Micro-structure shows the presence of pearlite colonies in ferrite matrix with increasing fragmentation of pearlite colonies with increase in number of passes. Average grain size of 80um of annealed sample is reduced to 40um after 3 forging passes. After 3 passes refined grains with fine substructures are observed in the deformed microstructure of ferrite grains and pearlite colonies distorted. After 6 & 9 passes increasingly finer and dense substructures are seen in ferrite grains. Increase in dislocation density along grain boundaries subjected to strain after every pass lead to the deformation of larger grains to smaller accompanied with the dynamic recovery. Along with ferrite phase, lamellar peralite phase with alternative plates of ferrite and cementite exist as shown in figure 2. With increase in number of strain, steps fragmentation and refining of pearlitic cementite is observed. Fragmentation of Pearlite is widespread after 9 strain passes. Fragmentation of Pearlite observed in steels is different in ECAP when compared with that of MAF steel. In ECAP Pearlitic cementite was plastically deformed rather than fractured as observed in MAF (Shin DH, 2004)). Low angle grain boundary (LAB) grains were deformed to grains with high angle grain boundary (HAB) with increasing strain steps as evident from microstructures shown above.

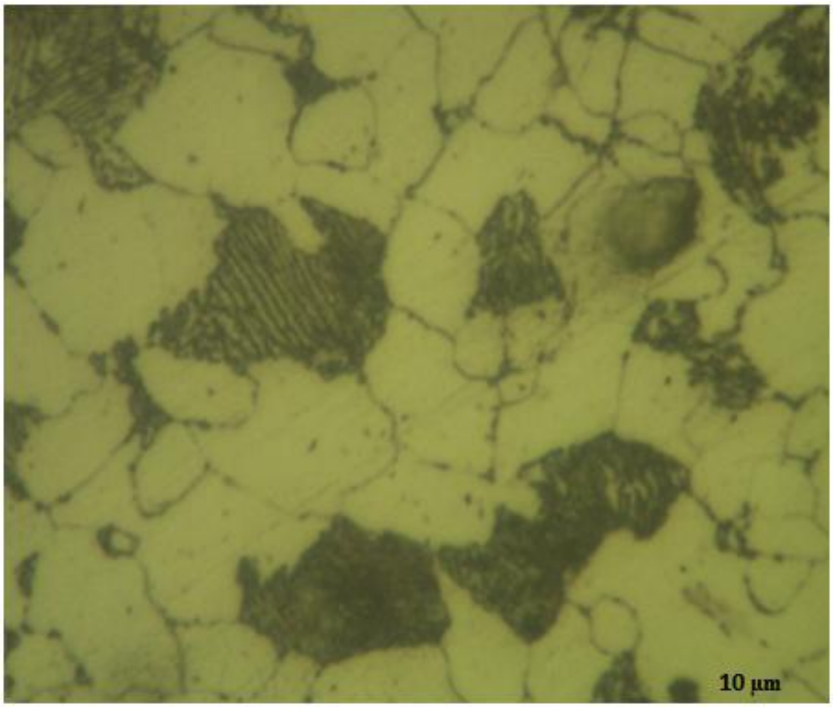

Figure 2: Lamellar Pearlite with alternative band of ferrite and cementite at 1000x

3.3 Grain Size and Phase analysis

Grain size is inversely proportional to strength of a material. Smaller the grain more would be the strength of a material according to the Hall-Petch equation. Grain Sizes of various low carbon steel samples under study are given in Table 2.

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Table 2 Grain size of steel samples

Description of sample	ASTM Grain size no	Size (µm)
Annealed	4	80
3 pass	6	40
6 pass	7	28.3
9 pass	9	11.9

The grain size of various samples were calculated using circle intercept method with image analyzer software from the image captured on inverted optical microscope with digital camera. As it is evident from the data mentioned in the table 2 the grain size of annealed low carbon steel sample was 80µm which was reduced to the final size of 11.9µm after 9 forging passes. Total reduction of 86% was obtained after 9 forging passes. On application of per pass strain of 0.2 during forging followed by quenching resulted in refinement of grains progressively with each pass. With each forging pass, the dislocations start piling up along the grain boundaries. When dislocation density is high enough to not to accommodate more dislocations along boundary, further increase in strain leads to grain refinement thus obtaining smaller grains with high angle grain boundary are obtained. Moreover with reduction in grain size, fragmentation of Pearlite was observed. Phase analysis provides a quantitative analysis of the different phases present in the micrograph of a sample. In low carbon steel obtained in annealed form and MAFed samples subjected to different passes was evaluated using image analyzer. Low carbon steel consists of basically two phases i.e. Ferrite matrix and Pearlite. The percentage of Pearlite present in the steel depends on the carbon content present in the alloy system under study. Percentage of ferrite and pearlite present in the annealed sample and forged samples subjected to different forging passes came out to be 88.76 % of ferrite and 11.24 % of pearlite.

3.4 Hardness

Hardness was obtained on Rockwell hardness testing machine and the results for various samples showing their hardness is shown in figure 3. In low carbon steel the hardness value has increased from 127 HV to 285 HV (nearly 130% increase in hardness).The enhancement in hardness is attributed to high dislocation density generated in the samples during warm multi-axial forging. Increase in hardness is commonly desired and observed feature of metals processed by SPD techniques. With increase in MDF strain, the dislocation density increases. Increase in strain also leads to formation of sub-grains and increase in disorientation from low angle grain boundaries to high angle grain boundaries which results increase in hardness. In the initial stages the increase in hardness can be explained by strain hardening and in later stages finer submicron size grains make dislocation movement difficult resulting in higher hardness. Hardness testing was performed on Rockwell hardness testing machine.

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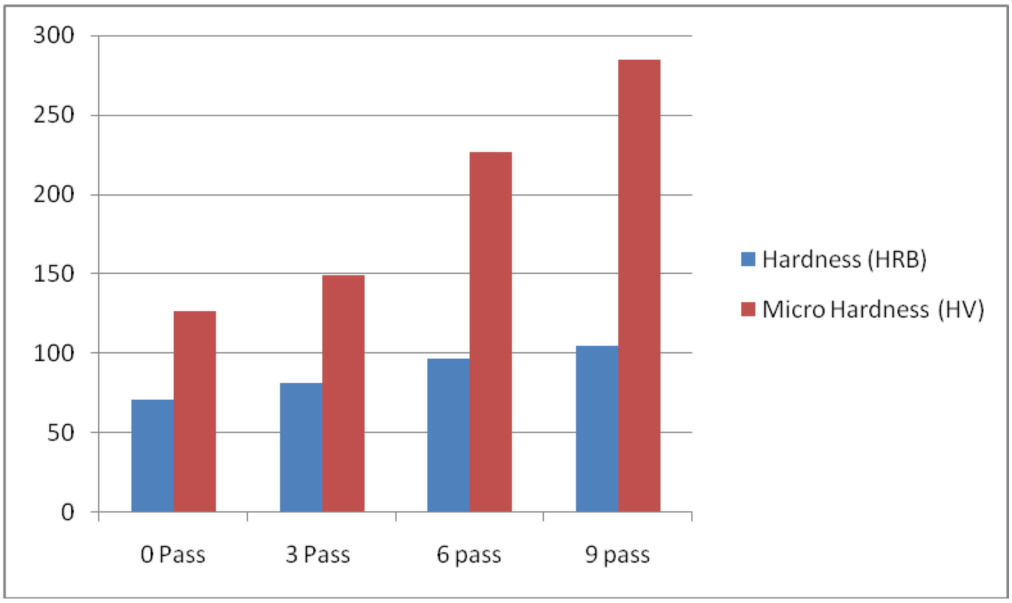

Figure 3: Hardness of forged low carbon steel samples

3.5 Tensile testing

Tensile test results for forged samples are given in figure 4.

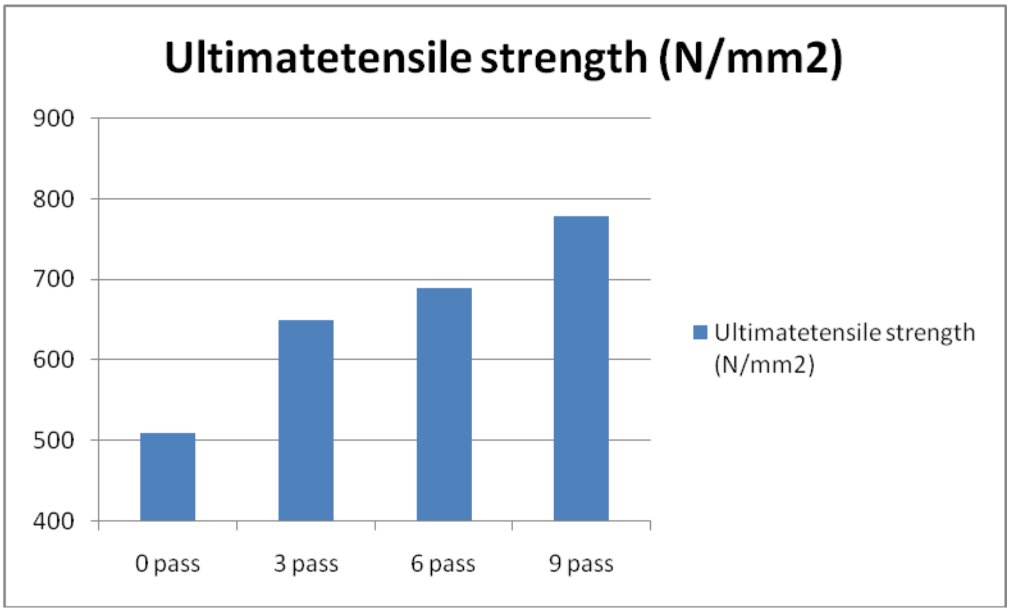

Figure 4: Tensile properties of forged low carbon steel

The properties show the improvement in Ultimate Tensile Strength (UTS) from 509.1 N/mm^2 for original sample to 777.8 N/mm^2 for 9 passes MAF sample (Increase of nearly 53%). Increase in strength is a commonly desired and observed feature of metals processed by SPD techniques. In the present work, with increase in

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number of strain steps, the dislocation density is expected to increase leading to formation of sub structures. These are clearly visible in the optical microstructures. Increase in strain leads to formation of sub-grains, which are characterized as low angle boundaries. With increase in number of strain steps (six and nine) the fraction of HAB increases. Thus, the increase in strength is expected since strength should increase with the decrease in grain size as per the Hall–Petch relationship. The presence of substructures and dislocations in the UFG materials suggests that residual work hardening have also contributed to the improvement in strength. Also, with increasing number of strain steps, the pearlitic cement cementite got fragmented, refined, and dispersed in ferritic matrix. These finer grains with HABs and finer submicron size cementite particles made dislocation movements difficult and resulting in higher strength values. This is reflected in the increased values of UTS.

3.6 Impact testing

Impact testing results for forged samples is given in figure 5.

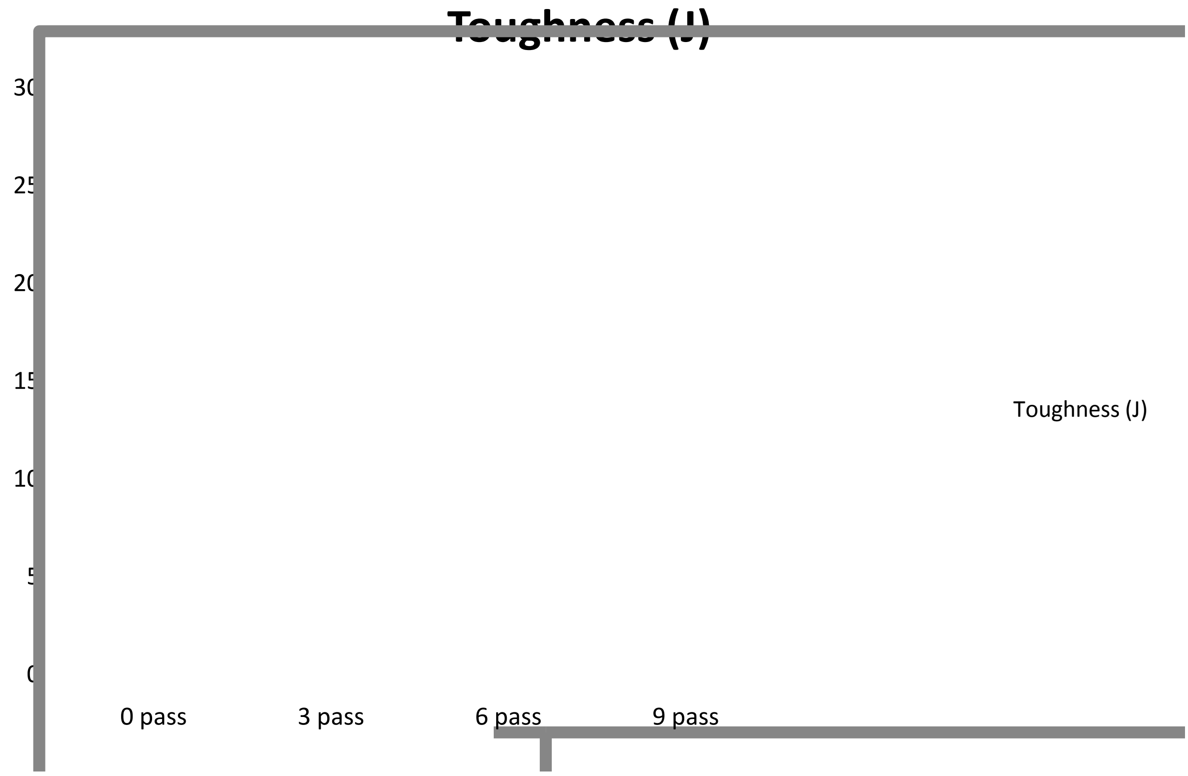

Figure 5: Impact testing results of forged low carbon steel samples

Impact testing is a measure of the amount of energy a material can absorb through impact and the ability of material to withstand sudden loads. It also is a measure of the materials ductility in failure. For part performance in body panels, fenders, bumpers, and other parts that may be impacted, it is desirable for the material to be able to absorb a high amount of energy when impacted so it is not easily broken. The data in figure 5 clearly shows the improvement in impact strength of the material. Low carbon steel is a ductile material and had low impact strength but as material was subjected to high strain deformation during MAF, there was improvement in impact strength. Impact strength showed significant improvement from 16J for original sample to 28J for 9 passes forged steel. Grain refinement, high dislocation density, increase in disorientation, increased tensile strength without much compromise in ductility and fragmentation of cementite at higher strain are all the possible reasons for improved impact strength.

3.7 Dry sliding wear test (Pin on disk apparatus)

Wear test was carried out on pin on disk apparatus. Samples prepared were grinded on silicon carbide paper of different grit sizes and then cleaned with methanol. Then samples were mounted on pin on disk apparatus and wear testing was performed by weighing samples after each interval. Graph for cumulative volume wear loss with respect to sliding distance of various steel samples for different loads is shown in fig 6(a, b, c). Mass loss was checked by weighing the samples after the desired time and then the cumulative wear loss corresponding to that was calculated by dividing the mass loss obtained with the density of steel. The test was conducted on circular disk of material EN32 having hardness 65 HRC and was conducted for different loads and different time intervals. The graph was plot for the samples subjected to different forging passes of cumulative wear volume loss vs. sliding distance for different loads. It is quite evident from the results obtained that the cumulative wear volume loss increases with the increase in load from load 9.8 N to 29.4 for the fixed sliding distance. Also from the data above we can observe that there is decrease in the cumulative wear volume loss from 0 forged pass samples to 9 forged pass sample hence improvement in wear characteristics with increasing strain steps. Wear rate also increases with increase in load. Improvement in the wear characteristics is though marginal with increase in forging passes but is evident as shown in graphs above. Adhesive wear of samples was observed. Initially the wear loss was less with small sliding distance but as sliding distance was increased wear loss increased prominently due to scratches initiated in metal surfaces and the asperities present between the two sliding surfaces promoting wear, but after some time with increasing sliding distance temperature was raised leading to formation of passive oxide layers which slows the wear rate with increasing sliding distance. Increased tensile strength, toughness and hardness are possible reasons for the improved wear characteristics. Also high dislocation density and piling of dislocations along grain boundary helped in improvement of wear results. Wear is function of ‘pull-off’ and pull-off work involved in generating the wear particles is a function of area under the stress strain curve of material. With increased ultimate tensile strength and increased toughness area under stress strain curve was increased hence higher pull-off work isrequired for wear, hence improved wear characteristics with increased forged steps. The Pin on disk apparatus used to carry out dry sliding wear test was of make Magnum engineers, India (Bangalore).

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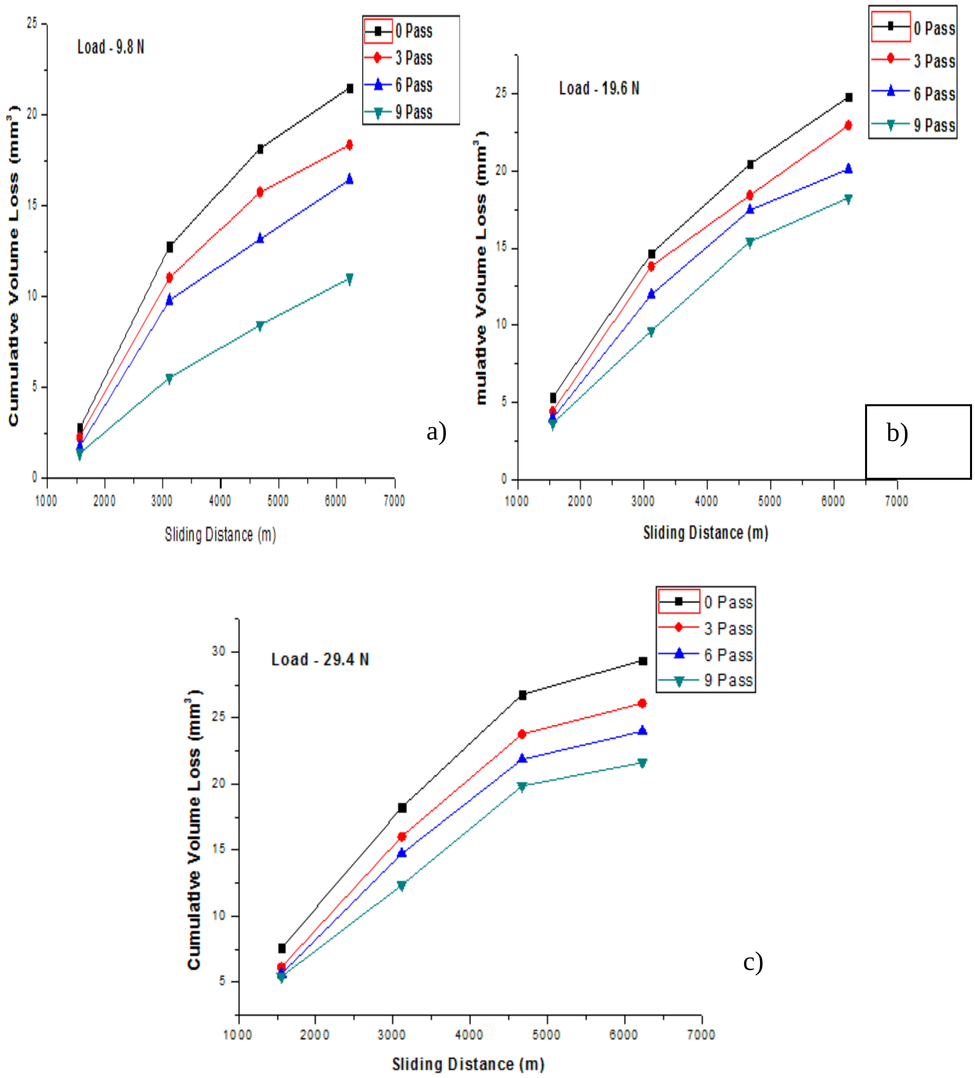

Figure 6: Cumulative wear volume loss vs. sliding distance for forged steel samples for different loads. a) 9.8N b) 19.6 N c) 29.4N.

IV. CONCLUSIONS

The following conclusions could be drawn from this study.

1. Refinement of grains was yielded as the result of multi-axial forging that strengthen the material and It can easily be visualized that there is increase in tensile strength, hardness and toughness was recorded due to the warm MAF.

2. The change in mechanical properties corresponding with the change in microstructure related very well with each other.

3. From the study of microstructure fragmentation of pearlite and refinement in grain size was observed with increase in number of strain steps.

4. Grain size reduction was obtained with each forging pass and total reduction of 80μm to 11.9μm was obtained from 0 forging pass to 9 forging passes.

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5. Phase analysis revealed the presence of 10% of pearlite in 90% of ferrite matrix where lamellar pearlite was observed with alternative bands of cementite and ferrite.

6. Increase in hardness from 127 HV to 285 HV was observed from 0 Passes to 9 forging passes.

7. The Ultimate tensile strength also showed improvement with increasing forging passes. Tensile strength increased from 509.1 N/mm^2 to 777.8 N/mm^2 for 0 forging pass to 9 forging passes.

8. Impact strength showed the improvement from 16J to 28 J from the start to final forging step. This result combined with tensile strength result lead to the improved wear characteristics.

9. In wear testing cumulative wear volume loss increased with increase in load, also wear rate increased with increasing load. Some signs of improvement were observed as the cumulative wear volume loss decreased for same load at same sliding distance decreased with increase in forging passes. Hence it can be concluded the better wear characteristics were obtained with increasing Multi-axial forged passes.

10. By alternating the experimental route i.e. changing the per pass strain, soaking temperature, soaking time and method of cooling after every forging pass may result in more grain refinement and better mechanical properties. Since low carbon steel is most commonly used steel and have got many critical applications also and is generally processed by forging or rolling, therefore extensive study in this topic and incorporating this method for bulk production could lead to enhanced life of steel thereby saving lot of money and time.

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REFERENCES

[1] Estrin. Y. and Vinogradov. A. ,*ActaMater.*, 61(3),2013, *782.*

[2] Chaudhari. G. P, Nath. S. K. and Padap. A. K, 2 April, 2010, Mechanical and dry sliding wear behavior of ultrafine-grained AISI 1024 steel processed using multiaxial forging, Journal of Materials Scinece, 45 (17), 2010. *483.*

[3] V Soleymani, B Eghbali, GrainRefinement in a Low Carbon Steel Through MultidirectionalForging, *Journal of iron and steel research international*, 19(10), 2012,74.

[4 R.Z.Valiev, R.K. Islamgaliev, I.V. Alexandrov, Bulk nanostructured materials from severe plastic deformation, *Progress in Materials Science*, 45, 2000, 103.

[5] Ashby, Michael F. & Jones, David R. H., *Engineering Materials 2. Published by Oxford: Pergamon Press, 1992.*

[6] AK Padap, GP Chaudhari, SK Nath, Mechanical and dry sliding wear behavior of ultrafine-grained AISI 1024 steel processed using multiaxial forging, Journal of materials science 45 (17), 4837-4845.

[7] Cantwell P.R.,Grain boundary complexions. *Journal of ActaMaterialia, Vol 62, 2014, 1–48.*

[8] Degarmo, E. Paul; Black, J T.; Kohser, Ronald A. *2003. Materials and Processes in Manufacturing. Published* [9] HussainaMaruff, Jayaganthana. R, Rao P. Nageswara, Singh. Dharmendra and Singh.Surendra, Comparative study of Microstructure and Mechanical properties of Al 6063 alloy

IJARSE
ISSN (O) 2319 - 8354
ISSN (P) 2319 - 8346

Processed by Multi axial forging at 77K and Cryorolling*The Authors. Published by Elsevier Ltd p. 2013, 29 – 133*

[10] Leng. Y 2008 Material Characterization Introduction to Microscopic and Spectroscopic Methods *John Wiley & Sons (Asia) Pte Ltd Hong Kong University of Science and Technology*

[11] *Kaushish, J. P. 2008*, Manufacturing Processes, *book of PHI Learning, pp. 469*

[12] Muszka Krzysztof, MajitaJanusz, Lukasz Bienias, 2006, Effect of grain refinement on mechanical properties of microalloyed steels, *Journal of Mettallurgy and Foundary Engineering Vol 32.*

[13] Noskova, L. G. Korshunov,and A. V. Korznikov, 2008, Microstructure and tribological properties of Al – Sn, Al – Sn – Pb, and Sn – Sb – Cu alloys subjected to severe plastic deformation *springer Science + Business Media, Inc Vol. 50, Nos. 11 – 12*

[14] Noskova.N.I, VildanovaN.F, Filippov. Yu.I, Churbaev.R.V, Pereturina. I.A,.Korshunov.L.G and Korznikov. A.V,2010, Preparation, Deformation, and Failure of Functional Al–Sn and Al–Sn–PbNanocrystalline Alloys *The Physics of Metals and Metallography,Inc © Pleiades Publishing* Vol. 102, No. 6, p. 646–651.

[15] Nakao.Y, Miura.H,,Nano-grain evolution in austenitic stainless steel during multi-directional forging. *Journal of Material Science and Engineering A, 528,2010, p 1310-1317.*

[16] PN Rao, D Singh, R Jayaganthan, Mechanical properties and microstructural evolution of Al 6061 alloy processed by multidirectional forging at liquid nitrogen temperature, *Materials & Design* 56, 2014, 97-104

[17] Shin Jong-Ho, JeongJaesuk, Lee Jong-Wook, Microstructural evolution and the variation of tensile behavior after aging heat treatment of precipitation hardened martensitic steel. *Journal of Material Characterization*, 99, 2014, pp. 230-237

[18] Singh. Dharmendra, Rao P. Nageswara, and Jayaganthan, R.,Microstructures and impact toughness behaviour of Al 5083 alloy processed by cryorolling and afterwards annealing*International Journal of Minerals, Metallurgy and Materials* Vol 20 (8), 2013, 759

[19] D Singh, PN Rao, R Jayaganthan, Effect of Deformation Temperature on Mechanical properties of Ultrafine grained Al-Mg alloys processed by rolling, *Materials and Design* 50, 2013, 646-655.

[20] QuekSiu Sin, ChooiZheng Hoe, Wu Zhaoxuan, 2015, The Inverse hall- petch relation innanocrystalline metals: A discrete dislocation dynamics analysis, *Journal of the Mechanics and Physics of Solids*, 88, 2016, 252.

[21] Wu. Y. D, 2015, Phase composition and solid solution strengthening effect inTiZrNbMoV high-entropy alloys, *Material and Design*, 83, 2015, 651–660.