Microstructural Development during Mechanical Forming of Steel Sheets

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Abstract — Metal forming is used synonymously with deformation, a process during which an object gets changed due to the applied force. These changes can either be reversible or irreversible depending on the type of material; size and geometry of the object and the magnitude of the applied force to the object. This paper reports the microstructural development after mechanical forming of steel sheet material by varying the applied loads. The microstructural evaluations showed that the applied loads employed caused an increase in the magnitude of the grain sizes in each loaded specimen. Furthermore, the increase in the grain size of the microstructure was observed to be directly proportional to the loads applied. In addition, the microhardness values of the cross sections investigated were found to increase with the applied loads. Hence, the grain size growth and the hardness were linearly dependent on the applied loads, and this implies that there is a correlation between the applied loads and the resulting microstructure of the material and the hardness of the material.

Keywords— **A**pplied load, Microhardness, Microstructural development and Mechanical forming.

I. INTRODUCTION

Metal forming is sometimes also referred to as metal deformation, a process during which the shape of a material gets changed due to the applied force. These changes can either be reversible or irreversible depending on the type of material, size and geometry of the object and the magnitude of the applied force to the object [1]. Metal deformations are achieved through the application of external forces to the workpiece, with the external forces being in equilibrium. With the application of load to the workpiece, internal stresses and displacements are generated causing shape distortions. If the loads are very low when the load is released, the workpiece has the tendency to return to its original shape. Consequently, it is then said that the applied loads were elastic and so were the stresses and strains, as such elastic strains are recoverable on release of the loads [1-3]. Metal forming process among other manufacturing processes such as casting, machining, joining, laser sintering, electron beam melting etc. are considered as manufacturing processes that uniquely changes the property of a material during the process of converting the stock or raw materials into finished or semi-finished products for different application purposes in both domestic and industrial sectors. The changes in the properties of a formed component or part result from the plastic deformation of the solid component. During this process, both mass and material cohesion are maintained. Metal forming applications have been successful in many industrial applications such as in automotive industry, aerospace, ship building and other construction applications [1-2]. The metal bending technique is a process that involves exerting a specific load on the upper die which presses into the clamped sheet of metal into the lower die creating a component with specific shape geometry. However, when the exerted load is removed and the component is taken out of the die, the component tends to change from the required geometry. This change of the component from the intended geometry is known as springback [5]. A typical schematic of mechanical forming process is shown in Figure 1.

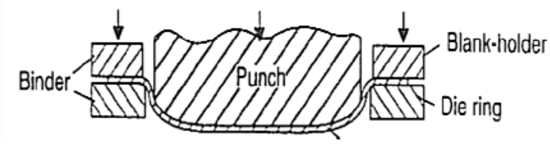

Figure 1: Schematic of Mechanical forming process [4]

Permanent bending of the sheet metal occurs with the commencement of plastic deformation. This may take place by slip, twinning, or a combination of both methods. The ability to form sheet metal to a desired shape depends on the material property of the workpiece and available tooling system. Brittle metals are known to be difficult to form without fracturing if no heat source is used, while ductile materials however are deformable by large amount before fracture occurs [1, 5]. Furthermore, they can also retain their molecular structure and strength. Ductility behavior occurs in low–strength steels whereas some high–strength steels are said to experience brittle behavior [6]. To effectively produce a bend in the finished part, the yield point of the material must be exceeded. If the bending force applied does not exceed the yield strength of the material, the beam returns to its original shape upon removal of the load as shown in Figure 2 (a). However, if the stress exceeds the material yield strength, the plate samples retains a permanent bend when the load is removed as shown in Figure 2 (b). When forming sheet metals, springback or elastic recovery will occur. Elastic recovery occurs until the residual stresses in the bend are in equilibrium with the stiffness of the material. The Young Modulus of elasticity of the material is a measure of the stiffness [7].

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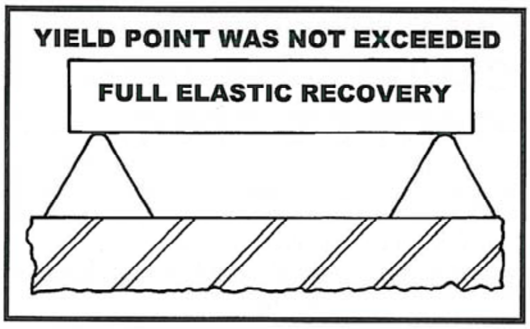
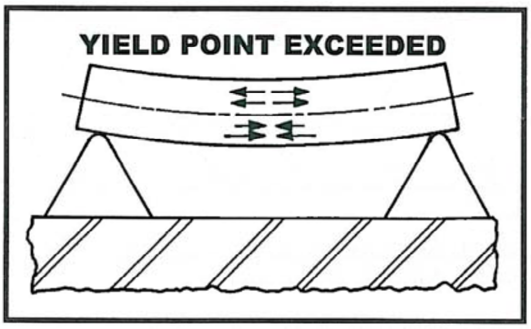


(a)



(b)

Figure 2: Schematic diagram showing (a) Elastic recovery (b) Permanent deformation [7]

Metals commonly used for manufacturing various products are composed of many individual randomly oriented crystals (grain). Metal structures that are not single crystals are called polycrystals. Rapidly cooling produces smaller grains while slow cooling produces larger grains. Each grain consists either as a single crystals for pure metals or polycrystalline aggregate for alloys. The behaviour of a single crystal or single grain is anisotropy but the ideal behaviour of a piece of polycrystalline metal is isotropic because the grains have random crystallographic orientation, thus its properties do not vary with the direction of testing. In practice, this situation rarely exists [8-9].

Grain size significantly influences the mechanical properties of formed metals. The influence is most commonly expressed in a series of constitutive equations that have the Hall-Petch form. Over the range of conventional grain sizes, the values of typical mechanical properties increase with the reciprocal root of the grain size. Large grain size is generally associated with low strength and ductility. Large grains particularly in sheet metals also result in a rough surface appearance after being stretched. The yield strength is the most sensitive property and can be related to the grain size by the Hall-Petch equation as illustrated by Equation (1) [9].

$$\sigma_y = \sigma_0 + K_y d^{-1/2} ----(1)$$

Where,
σ_y is the Yield Strength
K_y is the Hall-Petch slope indicating the extent to which dislocation are piled up barriers.
σ_0 is the Yield stress opposing the motion of dislocation.
d is the mean grain size.

Published literature in this field of study include the research work conducted by Liu *et al.*, [10] who investigated the deformation behavior of mild steel. The investigation entailed the heating of a rectangular plate to a temperature of 873K at a rate of 10K/s for a period of 1800s. After the completion of the rolling process, the specimen was cooled by water quenching. It was observed that in the warm deformed specimen, that the grain boundaries of the grains were cluttered, thus suggesting the presence of sub-grains boundaries. The grains that resulted due to the warm rolling were more or less equiaxed. The pearlite grains observed in the parent material were not noticed in the warm rolled specimen. The hardness results showed an increase in the microhardness of the material after warm deformation. The microstructure of the parent material consisted of pearlite and ferrite. Shin *et al.,* [11] conducted an experiment to investigate the effect of Equal Channel Angular (ECA) pressing on the microstructure and mechanical properties of low carbon steel. The experiment was conducted on a cylindrical sample at temperature of 623K. The sample was subjected to ECA pressing of four passes. The results of Shin et al., [11] investigation showed that there is a correlation between the microstructural evolution and the change in hardness of the low carbon sample. The microstructural results showed that the grain refinement was very noticeable after the first pass, while the hardness of the sample increased by a large amount after the first pass. Also, the change in the microstructure and hardness of the sample was less significant for further passes. Shin *et al.,* [11] concluded that alteration of ferrite during the ECA pressing influenced the hardness measurement of the low carbon steel. Similarly, Shabara *et al*., [12] also developed a numerical model to study the effect of material properties on forming loads, product geometry, springback and residual stress. They used computer aided design and manufacturing software to model the stretch bend process. The results from the numerical model developed for steel and aluminium showed that the springback magnitude relies significantly on the tensile force during the stretch bend process.

Steel is arguably considered the world's most "advanced" material. It is a very versatile material with a wide range of attractive properties which can be produced at a very competitive production cost. It has a diverse range of applications, and is second only to concrete in its annual production tonnage. Steel is not a new invention which leads to a common misperception that "everything is known about steel" amongst those outside its field. On the contrary, research within this field is probably the most challenging of all the material sciences. It is grounded on decades of research and much fundamental theory arises from the study of steel. Steel is generally defined as a ferrous alloy containing less than 2.0 wt. % C [13]. As such, mild steel plate is considered for this research investigation. It is important to gain an understanding on the impact of loading a material undergoes during mechanical forming. The process of mechanical forming of a metal sheet may alter the mechanical properties

ISBN: 978-988-19251-0-7
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

of the material. Similarly, the evolved microstructure of the mechanically formed component may be strongly influenced by the applied loads. In this investigation, the effect of varying applied loads on the microstructure, grain sizes and microhardness of mild steel plates were characterised and presented.

II. EXPERIMENTAL PROCEDURE

Six different experiments were performed; the samples were made from mild steel plate of 1 mm thickness. The specific loads applied on the sheet were 5kg, 10kg, 15kg, 20kg, 25kg and 30kg to deform the sheet to a curvature of 120 mm. These experiments were conducted at room temperature. The mechanical bending process was carried out on a 20 ton capacity mechanical press. It consists of an upper tool called the punch and a lower tool called the die, between which the sheet metal is located. Both the upper and the lower die were designated and fabricated from H13 tool steel specifically for the purpose of this research. The samples were carefully positioned and clamped in between the two ends of the lower die and held in place by the clamp before being stretched by impact of the force of the upper die on the clamped sample under the power of a hydraulic ram. The two clamping lower dies were made adjustable to allow the formed samples align with the lower die when the upper die is forcefully lowered into it. Clamping of the sheet was along the width of the workpiece so that stretching can occur over the length thereby promoting shrinkage across the width. Figure 3 shows the experimental set-up mechanical bending.

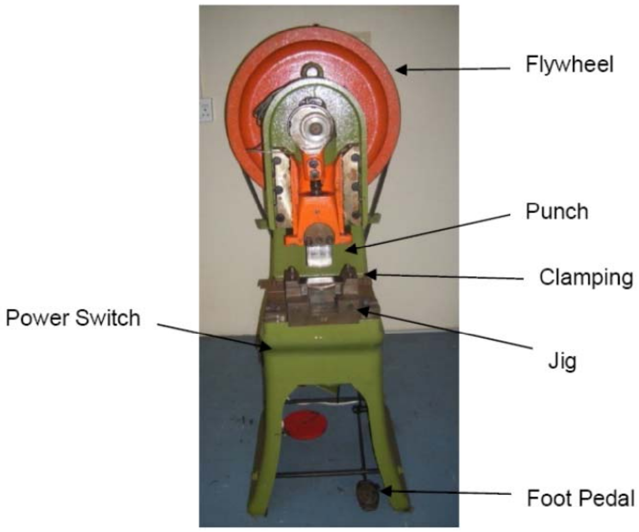


Figure 3: Experimental set-up for mechanical bending process

The microstructure of the cross-section of the as-received material and the deformed samples were observed under an optical microscope (Olympus PMG3). The individual grains were measured by using the measurement tools on the optical microscope, an average of five individual measured grain sizes were taken. The Vickers microhardness of the cross sections of both the as-received material and deformed samples were measured by using FM-ARS automatic indenter with a load of 300 g and a dwell time of 15 seconds. The indentations were taken at an interval of 2 mm, with all the indentations manually focused and read to ensure that all measurements were made on the specimen and not on the polyfast [material used to mount the specimen]. All the measurements were taken in the as-polished condition. The tensile samples were produced from the as-received material and tested in accordance with ASTM E-8 standard. A servo-hydraulic Instron 8801 tensile testing machine was used to conduct the tests. An extension rate of 5 mm/min and a gauge length of 50 mm were used.

III. RESULT AND DISCUSSION

3.1 Percentage Change in Radii due to applied loads

The radius of curvature of the punch is 120 mm but each formed mild steel plate attained a specific radius of curvature after the removal of the forming load. These attained curvatures were calculated using Equation (2); this is based on simple mathematics circle geometry. The percentage change in elastic recovery was calculated using the radius of curvature of the bending tool.

$$R = \frac{H}{2} + \frac{S^2}{8H} - - - - - - - (2)$$

Where;

R is the radius of curvature.
H is the perpendicular height from the midpoint of the curvature to the midpoint of measured length S.
S is the measured length between the two ends of the formed plate.

The formed steel plate showing the dimensions designations used in formula 2 is schematically illustrated with Figure 4.

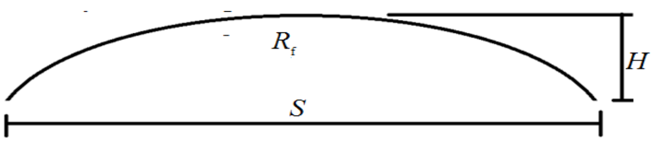


Figure 4: Schematic showing the parameters for calculating the radius of curvature

The measured radii of curvatures after unloading and the calculated percentage change in the radii are presented Table 1. The results showed that the radius of curvature of the mild steel plate after unloading decreases with an increase in the applied load. Thus, the results indicate that the percentage change in the elastic recovery of the plate decreases when the applied load is increased. The relationship between the percentage change in elastic recovery and the applied load is almost linear but inversely proportional. Hence, the results indicate that it is almost possible to predict the percentage change in the elastic recovery within the range of applied loads employed in this investigation.

Table 1: Results of measured curvature

Applied Loads (L) kgf	Curvature R (mm)	Percentage change in radii (%)
5	186.5	55.4
10	182	51.7
15	177	47.5
20	175	45.8
25	165	37.5
30	160.2	33.5

The work reported by Panthi *et al.*, [14] is in agreement with the results obtained in this research investigation. They found that there exists a linear but inverse relationship between applied load and the elastic recovery. This further established that the percentage change in the elastic recovery of the deformed samples decreases as the applied load increases thus, the linear influence of loads on the percentage change in the elastic recovery increases until a saturation point. The experimental results of the applied loads and the radii of curvatures presented in Table 1, shows that as the load increases, higher curvature is formed, this implies that more force is required to deform a plate to have smaller radius of curvature and similarly, the percentage change in the radius also follows the same pattern. The graph of the applied loads against the percentage change in the elastic recovery is presented in Figure 3.

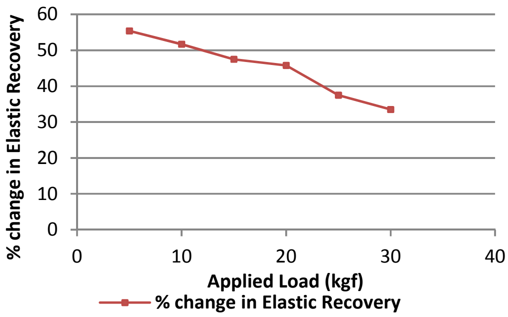


Figure 3: Plot of applied load against springback and curvature

The graph illustrates the progression that the percentage change in the elastic recovery decreases as the applied loads increases.

3.2 Microstructural Evolution

The evaluation of the microstructures of the as-received material and the deformed samples were carried out to establish the structural configuration of the grains, this gives a good baseline for comparison and also determine the effect of the process on the structure of the materials. As such, the samples were prepared and etched. It was found that the microstructure of the mild steel sheet consists of ferrite grains and pearlite evenly distributed in between the ferrite grains. The optical micrograph of the as-received material is shown in Figure 5 taken at 200x magnification.

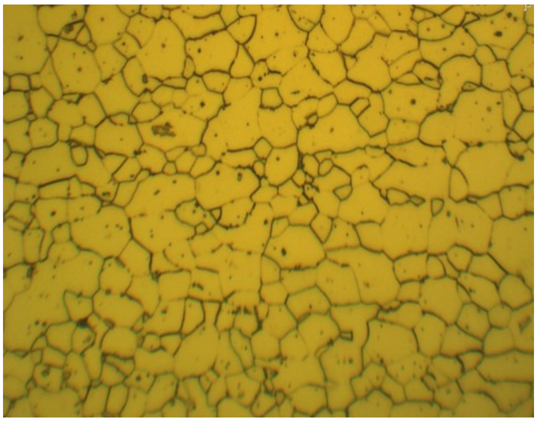


Figure 5: Micrograph of parent material.

Also, shown in Figure 6 is a typical micrograph of the measured grain sizes and presented in Table 2 are the five sets of measured grain sizes for the six deformed samples, the average grain sizes and the calculated percentage increases in the grain sizes were also presented. The percentage change in the grain size was determined with reference to the mean grain size of the as-received material and determined by measuring five large grains in each specimen.

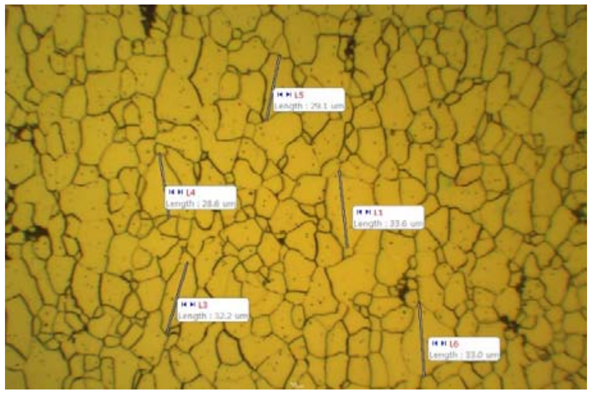


Figure 6: Typical micrograph of the measured grain sizes (10kgf load)

Table 2: Results of measured grain sizes

Load (kgf)	Summary of Measured Grain Sizes (µm)					mean (µm)	% change (µm)
	1	2	3	4	5		
5	31.7	25.1	26.9	32.9	30.7	29.5	11.1
10	29.1	28.6	32.2	33.6	33.0	31.3	18.0
15	32.9	35.4	39.5	32.3	32.8	34.6	30.4
20	38.3	34.6	35.0	34.2	42.5	36.9	39.2
25	35.0	46.5	39.4	36.2	38.5	39.1	47.5
30	48.5	37.4	39.9	45.5	43.2	42.9	61.8
PM	28.4	33.2	23.4	21.8	25.8	26.5	

It was observed that the effect of the loads on the formed samples brought about an incremental change in the grain sizes when compared to the as-received material. Similarly, the microstructural evaluation of the measured grains presented in Table 2 showed a direct relationship between the

ISBN: 978-988-19251-0-7
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

applied loads and mean grain sizes across the six samples investigated. This implies that an increase in the applied load increases the mean grain sizes of the deformed samples. Hence, the result of this investigation is in agreement with the findings of Kimura *et al*., [15] that reported that the forming loads alter the microstructure and may cause a formation of martensite in the microstructure of austenitic steels. Figure 7 also shows the progressive changes in the grain sizes with the increasing loads employed.

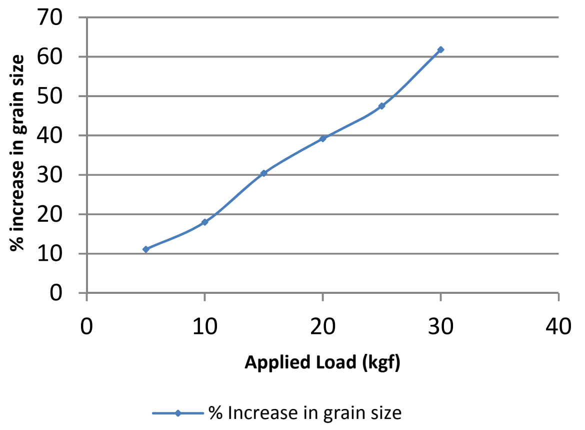


Figure 7: Plot of loads against percentage change in grain sizes

3.3 Vickers Microhardness

The results of the measurements of the indentations are presented in Table 3. Seven indentations were taken for each of the formed sample being investigated. These contain the average Vickers microhardness for each sample with the percentage increase in the hardness value when compared to the as-received material.

Table 3: Vickers microhardness measurement

Depth (mm)	Parent Material	Applied Load (Kgf)					
		5	10	15	20	25	30
2	33	33	34	35	36	37	39
4	33	33	34	35	37	38	39
6	32	33	35	36	37	38	40
8	32	34	35	36	37	38	40
10	32	34	35	36	37	38	40
12	33	34	34	36	37	38	40
14	33	34	34	37	38	38	42
Ave HV	32.6	33.6	34.4	35.9	37	37.9	40
% Increase	-	3.1	5.7	10.1	13.6	16.2	22.8

The variation of the Vickers microhardness profile across the cross sectional area with depth is also presented in Figure 8. The plot showed that all the hardness values increases at a point and some decreases slightly and increases again. This may be attributed to the effect of the load on the grain formation at different level or layers in the material. Hence, the applied load has a significant effect of the grain formation during the mechanical forming process which consequently also affected the grain sizes developed in the deformed samples.

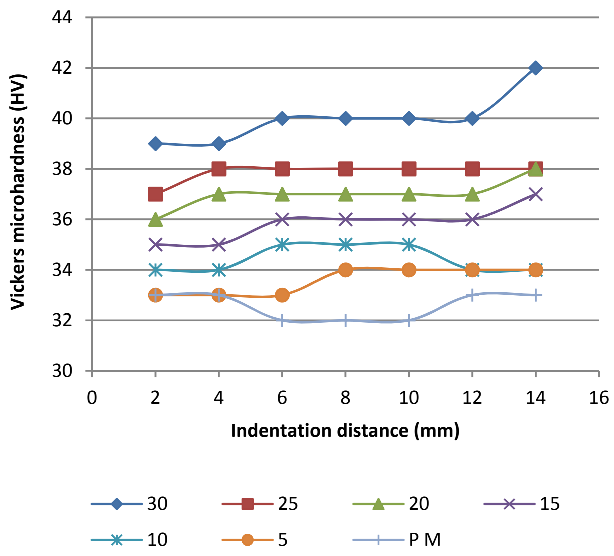


Figure 8: Plots of Vickers microhardness against distance

The applied load may also be attributed to cause the hardness across the cross sectional area of the plate investigated to increase and as such the percentage increase in the hardness due to the applied load is directly proportional to the increased load, this is shown in Figure 9.

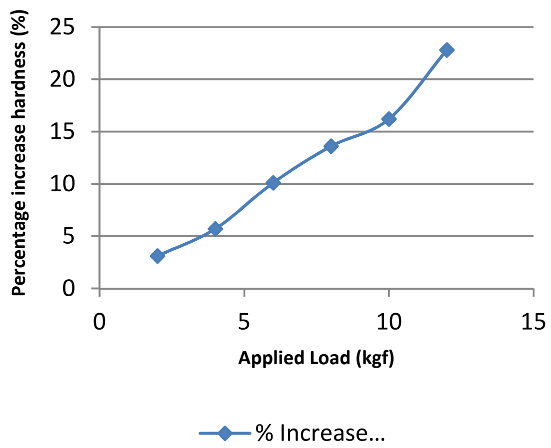


Figure 9: Graph of applied load against hardness

From Figure 9, it was found that percentage increase in the microhardness increases as the applied load increases; this is expected to have resulted from strain hardening that has occurred in each sample due to the applied loads.

IV. CONCLUSION

The microstructural evolution of mechanically formed samples under varying load conditions has been characterised and reported. The microstructure of the as-received material contained equiaxed grains. However, the grain sizes of the deformed mild steel plate showed elongated grains. The elongation of the grains was also observed to be directly proportional to the applied loads. Hence, the grains of the mild steel plates at large loads were more elongated than the grains in the plates deformed at smaller loads. Furthermore, it was observed that the Vickers microhardness of the material was enhanced after applying the loads. The increase in the Vickers microhardness of the material and forming load shows a linear relationship, this implies that the forming loads can significantly alter the microstructure of the steel material, consequently, elongating the grain size and improve the hardness of the material. Finally, the study showed that the grain size elongation and hardness obtained in the deformed samples were linearly dependent on the applied loads.

ACKNOWLEDGEMENT

The financial support of the University Of Johannesburg research fund is acknowledged.

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ISBN: 978-988-19251-0-7
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)