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Investigating Resulting Residual Stresses during Mechanical Forming Process

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Abstract. Most manufacturing processes such as machining, welding, heat treatment, laser forming, laser cladding and, laser metal deposition, etc. are subjected to a form of heat or energy to change the geometrical shape thus changing the inherent engineering and structural properties of the material. These changes often cause the development of locked up stresses referred to as residual stresses as a result of these activities. This study reports on the residual stresses developed due to the mechanical forming process to maintain a suitable structural integrity for the formed components. The result of the analysis through the X-ray diffraction confirmed that residual stresses were induced in the manufactured parts and further revealed that residual stresses were compressive in nature as found in the parent material but with values less than the parent material.

1. Introduction

The manufacturing industry is observed to be evolving in this modern world of technological advancement. Several manufacturing processes are being employed in the fabrication of different engineering components thereby solving some of the basic societal problems. Among the manufacturing processes commonly employed are machining, welding, grinding, forging, casting, moulding and forming etc. [1], [2]. Fabrication of components through the traditional mechanical forming process is still very relevant even in this millennium. It may be augured that this may be limited within the small and medium scale manufacturers but this group are closer and more accessible to the general populace.

Mechanical forming is one of the conventional methods of metal-forming techniques employed in sheet metal forming process. The mechanical forming process causes permanent bending in sheet metal through the process of plastic deformation. Such permanent deformation may occur by slip, twinning or the combination of both methods during deformation. Mechanically forming a sheet into a shape may be a function of the material property of the sheet and the tooling system comprising of the punch and the die. Metal forming can be classified into different categories under mechanical working process, such as forging, extrusion, rolling, drawing, stretched forming, and other sheet forming

processes, casting, powder metallurgy and fiber metal forming, electroforming, rubber, stretched and super-plastic forming [3].
The principle of sheet forming operation involves the application of force to the sheet metal to modify the material geometry; this makes the process of metal forming unique because there is no material removal. The applied force stresses the metal beyond its yield strength, causing the material to plastically deform, but not to fail. By doing so, the sheet can be bent or stretched into a variety of complex shapes. Fig. 1 shows the schematic diagram of stretched forming process. A schematic of a mechanical forming process is shown in Fig. 1.

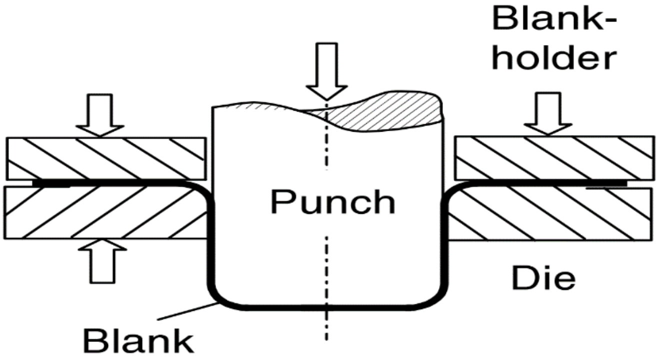


Figure 1: Schematic of Stretched Forming [4]

One of the most widely used press fabrication operation is bending and forming of metallic components. The mechanical forming process employs a punch rammed into a clamped plate positioned across a die. The force is applied to the punch above the plate to be deformed; the type of shape will depend on the punch and the die. The application of force consequently generates internal stresses and displacement thereby causing distortion within the structure of the material subjected to the load. Hence, the geometrical shape of the formed component depends on the load applied to the punch [2].
Over the decades, there had been increasing interest in the preparation and processing of new materials with unique properties and functions. The poor properties of materials such as ceramics and magnesium alloys have presented not only challenges but also great opportunities for metal forming researchers to develop new materials [2]. With this initiative, the real forming techniques such as mechanical forming may be further researched to get a more scientific understanding of the process for better positioning in meeting today's need. The mechanical bending process is by the material properties, and the response during the forming is influenced by its mechanical properties, which include the elongation, the yield point, anisotropy, grain sizes, residual stresses, and spring back.
Virtually all manufacturing processes, such as casting, welding, machining, moulding, and heat treatment, plastic deformation during bending, rolling or forging introduce residual stresses into the manufactured samples [4]. Investigations conducted by researchers on the subject of residual stresses in engineering components found that the most common causes of residual stresses are material plastic deformation, steep thermal gradients and phase transformations, nuclear radiation, as well as the exposure to electromagnetic fields [4]-[6]. On the other hand, a perspective of a researcher was that residual stresses arise as a result of misfits between different regions of the material, component or assembly [7]. Further studies on the subject confirmed that macro residual stresses could arise in engineering samples through the interaction between the misfit of parts within an assembly, and through the generation of chemical, thermal, and plastically induced misfits between different regions within one part [6].
Among other factors known to cause residual stresses can be the development of deformation gradients in various sections of the material. By developing thermal gradients, volumetric changes can

arise during the solidification or from solid-state transformations, as well as from differences in the coefficient of thermal expansion in samples made from different materials [4].
Residual stresses are often present in sheet metal parts after the process because of the non-uniform deformation of the sheet during forming. They are also referred to as the locked-in stresses and can be defined as those stresses existing within a material in the absence of any external loading or thermal gradients. Virtually all-manufacturing processes, such as casting, welding, machining, moulding, and heat treatment, plastic deformation during bending, rolling or forging induces residual stresses into the manufactured components [8]. This has necessitated the study into the residual stresses developed in sheets during mechanical forming processes, through this; the structural integrity of the formed component can be evaluated.
During past years, many different methods for measuring the residual stresses in different types of samples have been developed. Residual stress measurements may be classified as destructive, semi destructive, or non-destructive according to research and investigation into the subject [9] on residual stress measurement techniques. This is further illustrated with Figure 2, showing the various methods.

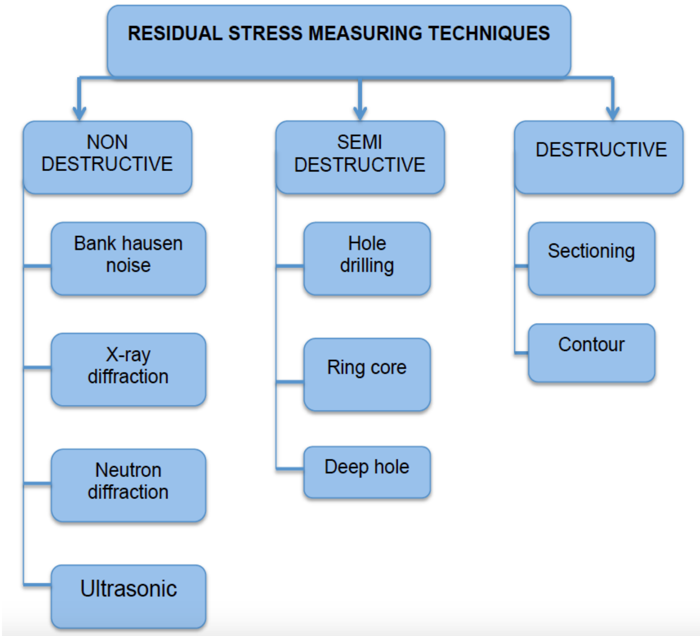


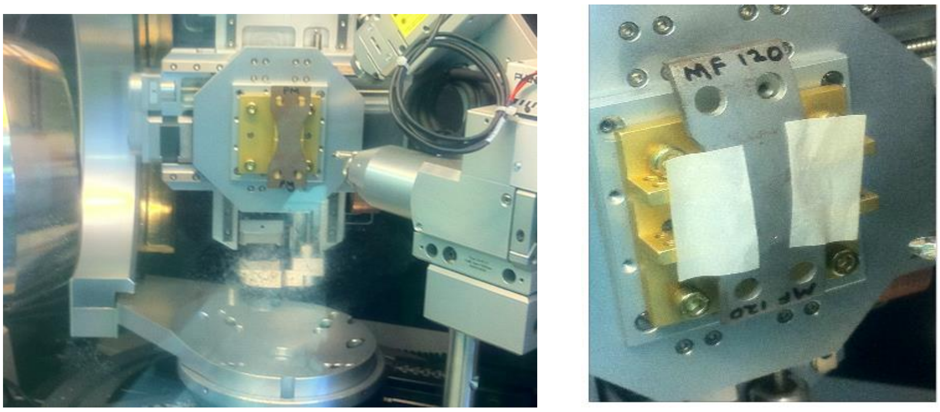
Figure 2: Summary of the Residual stress measurement

The destructive (sectioning technique and contouring) and semi destructive techniques (Hole drilling, Ring core and deep-hole), also referred to as mechanical method, are dependent on inferring the original stress from the displacement incurred by completely or partially relieving the stress when removing some material. These methods rely on the measurement of deformations due to the release of residual stresses upon removal of material from the specimen. Non-destructive techniques on the other hand, usually measure some parameters (strain) that are related to stress and these techniques include the x-ray or neutron diffraction, synchrotron, ultrasonic methods and magnetic methods. These techniques are being increasingly used because of their non-destructive nature.
The engineering properties of materials and structural samples notably fatigue life, distortion, dimensional stability, corrosion resistance, and brittle fracture can all be considerably influenced by residual stresses. Such effects usually bring about additional cost in repairs and restoration of the parts, equipment, and structures. Consequently, residual stress analysis is a compulsory stage in the design of parts and structural elements and in the estimation of their reliability under real service conditions [4], [9]-[11].

Another investigation of a researcher found that residual stress magnitudes, which do not exceed 80% of the original yield strength of a material contain minimal error [12]. However, if this percentage is exceeded, then the residual stress magnitude should be taken at the 80% yield value. It was also reported that residual stresses cannot be precisely determined and about 10-15% error can be expected when using the hole drilling method [10]. A study under similar experimental conditions further found [11] that an error of about 20% should be allowed when stainless steel plate is used compared to the results of a similar study that reported an error of about 10-15% for a hole drilling method [10].
Similarly, a detailed knowledge of the residual stress distribution remains difficult to gather despite the large number of publications on the investigation of residual stress measurements [11]-[13]. The following methods have been successfully used for residual stress measurements; layer removal, hole drilling, X-ray diffraction, neutron diffraction, synchrotron diffraction, ultrasonic and magnetic method. The most frequently applied among these techniques for metallic samples are the layer removal, the hole drilling technique and the x-ray diffraction method. More closely, X-ray diffraction utilizes the fact that when a metal is under stress, applied or residual, the resulting elastic strains cause the atomic planes in the metallic crystal structure to change their spacing. X-ray diffraction can directly measure this inter-planar atomic spacing; from this quantity, the total stress on the metal can then be obtained [14].

2. Experimental Methodology

The residual stress measurements were conducted at the South African Nuclear Energy Corporation (NECSA) facility and an X-ray diffractometer - Bruker D8 Discovery/Advance was used. The experimental set-up for the residual stress measurement of both parent material and mechanical formed are shown in Fig. 3. (a) and (b) respectively.



(a) (b)

Figure 3 (a) and (b): Residual Stress measurement setup for Parent and Mechanical Formed in the diffractometer (Photo taken at NECSA during the experiment)

Three sets of parent material and mechanical formed samples each were investigated and average result was presented. The measurements were taken at the three points indicated in Figure. 4. Three points were considered as shown for the measurement.

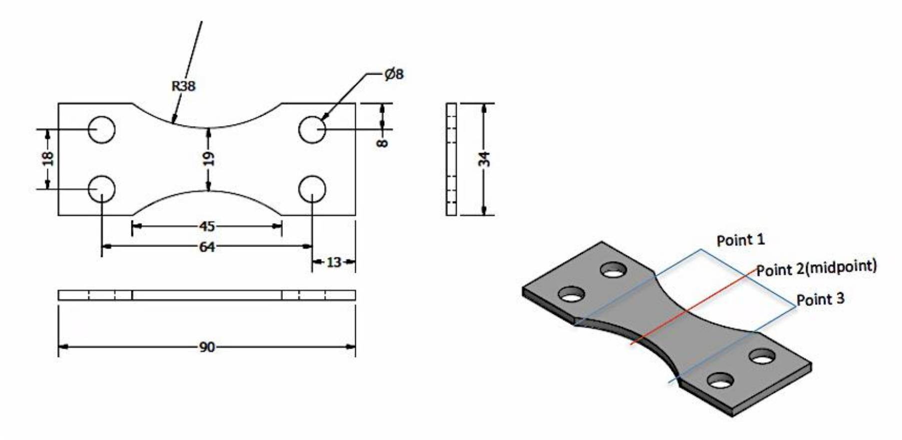


Figure 4: Test-piece isometric and residual stress measurement points

The diffractometer consists of the following samples:

- X-ray source and Graphite monochromator crystal for monochromatic beam on the primary side.
- Goniometer (Eulerian Cradle): Used for the accurate positioning of samples,
- Video microscope and laser for alignment.
- Area detector,
- GADDS software for control, data-acquisition and 2-D diffraction data processing.

The diffractometer is equipped with a standard Bragg-Brentano geometry with Cu tube and a detector. The 2θ scan range was set from 20 to 70^o at 10^o per step. The measurement for every azimuth angle ϕ has a set of tilt angle ψ between (0-70^o) in stepwise stages of 10^o each. The beam optics includes the graphite monochromator and a 0.8 mm diameter collimator mounted on the primary side.
The measurements were performed while set at an inclination mode to allow for higher sample tilt [4]. A laser video-alignment system was used for accurate sample positioning and the diffracted data were collected with a high star-area detector. The measurement parameters for the strain determination on the D8 GADDS diffractometer are presented in Table 1. The maximum measurement tilt angle considered in this study was 70^o in 2θ. For the purpose of sample shielding, the beam was held at high tilt angles. The peak evaluation method employed is the Pearson VII and the stress model is Biaxial + Shear stresses.

Table 1: Parameters settings on the D8 GADDS diffractometer

Parameters	**Value**
hkl reflection	220
2θ [^{o}]	99.67
Tilt angle ψ [^{o}]	0-70
Frame width, Δψ [^{o}]	7
Azimuth orientation ϕ [^{o}]	0, 45, 90, 180, 225, 270
Sample detector distance [cm]	15

3. Result and Discussion

Three sample sets of parent material and mechanical formed samples were investigated but only one set has been reported because of the compressive nature of both samples. The residual stresses in the two principal axes of transverse σ_{11} and σ_{22} *longitudinal* for PM and MF, were measured. This is a standard way to present residual stresses of processed materials most especially metals. One of the studies in this field [15] agrees with author's finding that residual stresses and strains in longitudinal direction are tensile and dominant and secondly that with increasing heat input, associated with higher line energy and/or multiple passes, the longitudinal residual strain/stress increases until a threshold is reached. This threshold is due to the material yielding in tension.

The measured frames were analysed using the BRUKER's LEPTOS v6 software. The program slices the diffraction rings into bins of desired width, integrates the slices, and fits the resultant peak. The analysis for strain was conducted using the freestanding 220 reflections. These were the highest reflections with better statistics that could be measured on the D8 GADDS instrument. The spotted patterns originate from the effect of the process to which the material was subjected. The residual stress tensor results measured at the three points (1, 2 and 3) for the parent material and the mechanically formed component are presented in Table 2 respectively.

Table 2: Stress tensor for the mechanically formed component and parent material

Measurement points	**Mechanical formed sample**		**Parent material**	
	σ_{11}	σ_{22}	σ_{11}	σ_{22}
1	-61.7 ± 41.6	--51.1 ± 41.6	-310.7±27.5	-399.5± 27.5
2	-53.9±41.2	11.8 ± 45.9	-299.8± 28.4	-319.6±28.5
3	-43.1 ± 55.9	-54.2 ± 63.6	-297.0±29.2	- 321.8±29.2
HV	116		94	

The stresses considered are in the two principal axes of transverse σ_{11} and longitudinal σ_{22} for the and mechanically formed component.

The parent material was found to be very compressive in nature considering the values of the measured tensors across the three points of measurement (-310.7±27.5, -299.8± 28.4 and -297.0±29.2). Similarly, tensor values of the mechanically formed components were also compressive in nature but observed to be more relaxed from the tensor values (-61.7±41.6, -53.9 ± 41.2 and -43.1±55.9) due to the mechanical forming process. The compressive nature of the stresses is attributed to strain hardening and cold working condition on the material. In addition, the micro Vickers hardness values confirm the exhibited evolved residual stresses of the mechanical formed samples. It was observed that the values of the micro Vickers hardness were enhanced in the formed sample in comparison to the parent material. The improvement in the hardness values is attributed to mechanical work and strain hardening. There are some proportionate relationships between the developed residual stresses and the increasing micro Vickers hardness in the formed samples.

Furthermore, the varying magnitude of the tensor across the three points of measurement can be explained by either of the following or all; the difference in the surface roughness, the effect of stress relaxation on their shape, influence of their grain size distribution, and the effect of machining during fabrication of the test sample.

4. Conclusion

The analysis of the residual stresses was conducted using the x-ray diffraction, and the study revealed the changes in the residual stresses as the samples were formed. The observed variations in the residual tensors from compressive in this study towards tensile in the mechanically formed parts confirm the findings from the literature [15]. Also, the difference in the magnitude in the tensile tensors at the three measurement points is attributed to the flow stress, mechanical and strain hardening. The changes in the micro Vickers hardness values confirm the developed residual stresses. It may be correct to establish that the residual stress can increase proportionately with the hardness value to a certain threshold that should be further determined.

5. Acknowledgement

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