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Repetitive Bending and Straightening of Sheet Metal: Effects on Microstructure and Mechanical Performance

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Abstract

This project investigates how the Repetitive Bending and Straightening (RBS) process affects the strength and internal structure of galvanised iron. The main goal was to compare the grain size and mechanical strength of the metal before and after undergoing three and five cycles of bending. To achieve this, grain size was measured using microscopy, and strength was evaluated using a tensile testing machine. The results showed that as the number of bending cycles increased, the internal grains grew larger, increasing from an original size of 4.22 µm to 7.68 µm after five cycles. Tensile testing revealed that the original sheet metal was the strongest, with an ultimate tensile strength (UTS) of 322.20 MPa and an average yield strength of 250 MPa compared to the processed sheet metal.

1. Introduction

The mechanical performance of metallic materials is intrinsically linked to their microstructure, particularly the grain size. According to the Hall-Petch relationship, grain refinement is a critical mechanism for enhancing both overall mechanical strength and yield strength, as a smaller grain size directly improves strength by providing grain boundaries that impede dislocation glide. Severe Plastic Deformation (SPD) is one of the methods to produce ultrafine-grained and nanostructured metals. The primary objective of SPD is to improve properties such as strength and hardness without altering the material's geometry [1].

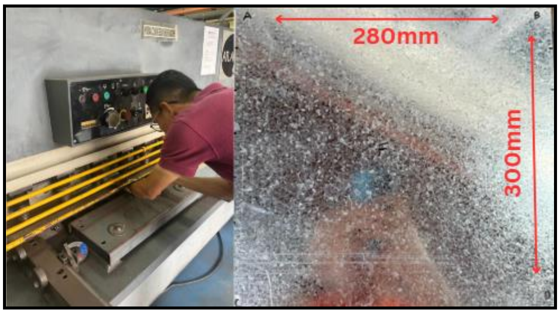
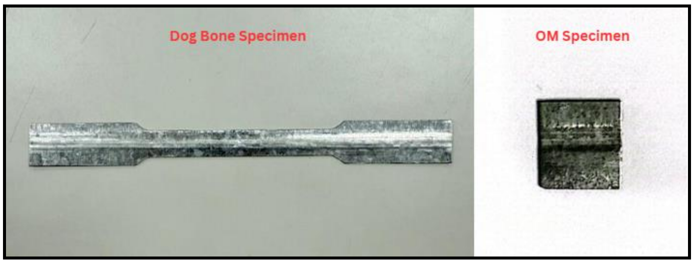
Although various SPD methods such as Equal Channel Angular Pressing (ECAP) [2], High Pressure Torsion (HPT) [3], and Accumulative Roll Bonding (ARB) [4] are well established, they are often associated with significant limitations; for example, ECAP requires complex machinery and precise alignment, restricting its use primarily to small-scale specimens.

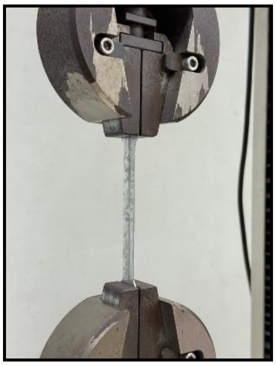
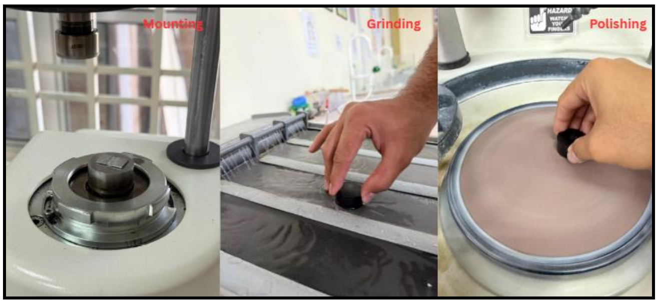
To address these challenges, this project focuses on the Repetitive Bending and Straightening (RBS) [5] method, a specific SPD technique designed for sheet metal. RBS subjects the material to cyclic bending and straightening, introducing intense plastic strain to facilitate grain refinement. Unlike ECAP, RBS is regarded as a geometrically simple, cost-effective, and scalable procedure. Consequently, this study utilizes the RBS technique to induce plastic deformation in sheet metal, aiming to enhance its mechanical properties while maintaining its original geometry and composition.

2. Methodology

The experimental methodology employed in this study investigated the effects of the RBS process on galvanised iron sheet metal with a nominal thickness of 1 mm. Samples with dimensions of 300 mm x 280 mm were prepared and subjected to 0, 3, and 5 RBS cycles to induce cumulative plastic strain. The deformation process utilised a bending machine to create a 45° angle at 70 mm intervals, followed by straightening using a slip bending machine. To evaluate mechanical performance, the processed sheets were machined into standard dog-bone specimens in accordance with ASTM E8/E8M guidelines and tested using a Shimadzu AG-1 Universal Testing Machine with a 10 kN load capacity. Subsequently, microstructural analysis was conducted by hot mounting samples in phenolic powder, followed by grinding with silicon carbide papers ranging from 240 to 600 grit and polishing with a silica suspension. The grain structure was revealed using a nitric acid (HNO_3) etchant, and the average grain size was subsequently quantified using optical microscopy and the linear intercept method, adhering to ASTM E112 standards. Table 1 represents the machine process flow of the study.

Table 1: *Machine Process Flow*

No	Process	Visual
1	Material Preparation Machine: Hydraulic Swing Beam Shears	
2	RBS Process Machines: Bending Machine & Slip Bending Machine	
3	Specimen Fabrication Machine: CNC Milling Machine	

4	Mechanical Testing Machine: Universal Testing Machine	
5	Microstructural Preparation and Analysis Machines: Hot mounting, Grinding and Polishing.	
6	Characterisation Machine: Optical Microscope	

2.1 Material and Specimen Preparation

The primary material utilised in this research was galvanised iron (GI) sheet metal with a nominal thickness of 1 mm, selected for its balance of ductility and structural applications. The preparation process commenced with the cutting of the raw GI sheets into rectangular blanks of 300 mm x 280 mm x 1 mm using a hydraulic swing beam shear machine to ensure dimensional precision and clean edges. These blanks were then subjected to the RBS process for a varying number of cycles: 0 (GI-0), 3 (GI-3), and 5 (GI-5), to induce plastic deformation. After the RBS process, the sheets were further machined into standardised tensile specimens. The Computer Numerical Control (CNC) milling machine was utilised to produce "dog-bone" shaped samples in accordance with ASTM E8/E8M standards.

2.2 RBS Process

The RBS process was conducted to introduce plastic strain into the galvanised iron sheets through cyclic deformation. Initially, the flat sheet metal was marked at 70 mm intervals to establish consistent bending points. The sheet was then fed into a manual bending machine to create a 45° V-shape bend at each marked position. Following the bending phase, the deformed sheet was passed through a slip bending machine for the straightening process to return it to its original geometry. This sequence of bending and subsequent straightening constitutes one complete RBS cycle. For this study, the procedure was repeated for three and five cycles respectively, allowing for the observation of cumulative deformation effects on the material's internal structure without significantly altering its external dimensions.

2.3 Testing Procedures

2.3.1 Mechanical Testing

To evaluate the mechanical performance of the galvanised iron after the RBS process, tensile tests were performed using a Shimadzu AG-1 Universal Testing Machine (UTM) with a 10 kN load capacity. The specimens, prepared according to ASTM E8/E8M standards, were subjected to a constant loading rate until fracture occurred. This procedure allowed for the precise measurement of key mechanical properties, including yield strength, ultimate tensile strength (UTS), and the percentage of elongation, providing a quantitative assessment of how the repetitive deformation affected the material's overall strength and ductility.

2.3.2 Microstructural Analysis

The microstructural evolution of the specimens was characterised through optical microscopy to observe changes in grain morphology. The process began with sample preparation, involving hot mounting in phenolic powder followed by sequential grinding with silicon carbide (SiC) abrasive papers (240, 320, 400 and 600 grit). After achieving a mirror-like finish through polishing with a silica suspension, the samples were etched using a nitric acid (HNO_3) solution to reveal the grain boundaries. The grain size was then quantified using the linear intercept method in accordance with ASTM E112 standards, capturing images at 1000x magnification to calculate the average grain diameter for each RBS cycle condition.

3. Results and Discussion

Figure 1 illustrates the stress-strain curves for the galvanised iron specimens subjected to varying RBS cycles. The graph depicts the mechanical behaviour of the 0 (G1-0), 3 (GI-3), and 5 (GI-5) RBS cycles. Figure 2 displays the microstructure used to obtain the ASTM grain size number (G). Additionally, Figure 3 displays the average grain diameter (μm) against the number of RBS cycles.

3.1 Tensile Tests

The results from the tensile tests are summarised in Table 2. It can be observed that the original specimen (GI-0) exhibits the highest UTS of 322.20 MPa and a yield strength of 250 MPa compared to the processed specimens.

Table 2: *Tensile Results*

Specimen	Ultimate Tensile Strength (MPa)	Yield Strength (MPa)
GI-0	322.20	250
GI-3	295.68	195
GI-5	290.90	180

Figure 1 represents the stress-strain curves for the 0, 3, and 5 RBS cycles. After three cycles (GI-3), the UTS decreased to 295.68 MPa and the yield strength was 195 MPa. After five cycles (GI-5), the UTS reached its lowest value at 290.90 MPa, and the yield strength decreased to 180 MPa. This declining trend in strength indicates that the RBS process on galvanised iron does not improve the mechanical strength of the material under these specific parameters. This suggests that the plastic strain introduced was insufficient to enhance the mechanical properties of the material.

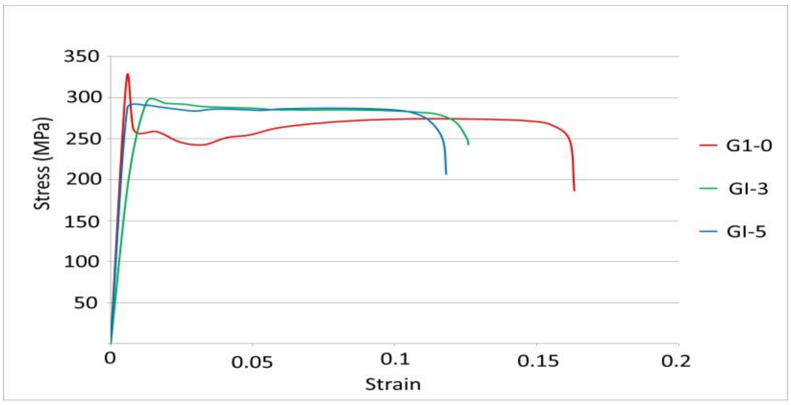


Figure 1: *Stress-strain curves for varying RBS cycles*

3.2 Optical Microscopy

The evolution of the grain structure was observed using optical microscopy. This analysis evaluated the microstructural effects on galvanised iron through the RBS process at 0, 3, and 5 cycles. The grain size analysis was conducted at 1000x magnification using the linear intercept method in accordance with ASTM E112 standards. Grain boundaries were highlighted to ensure accurate marking of intersections to determine the ASTM grain size number (G). To achieve high precision, linear interpolation was applied to the reference data to calculate the final average grain diameter for each sample. Figure 3 shows the interception marking lines on the microstructure used to obtain the ASTM grain size number (G). From the analysis, the results for the microstructural effects on galvanised iron through RBS cycles are presented in Table 3. The average grain diameters increased from 4.22 μm for the as-received sheet to 60.6 μm for three cycles and 7.68 μm for five cycles of RBS.

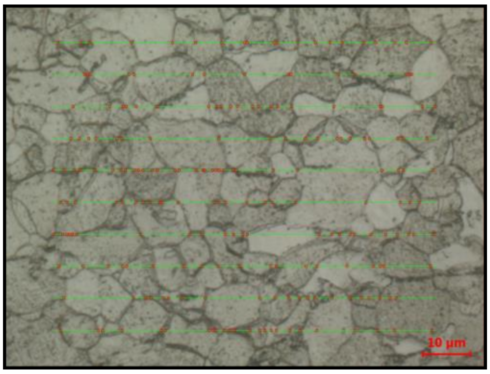


Figure 3: *Interception marking lines on the microstructure for grain size determination*

Table 3: *Analysis of grain size results*

RBS Cycle	Grain Size Number (G)	Average Diameter (μm)
GI-0	12.84	4.22
GI-3	11.79	6.06
GI-5	11.09	7.68

Figure 4 illustrates the average grain diameter (μm) against the number of RBS cycles. In this study, the grain size number (G) decreased with the increasing number of cycles, while the average grain diameter increased from 4.22 μm to 7.68 μm. The RBS process did not result in grain refinement; instead, the mechanical energy applied during the bending and straightening cycles facilitated grain growth. This indicates that grain coarsening, rather than refinement, occurred due to the RBS process.

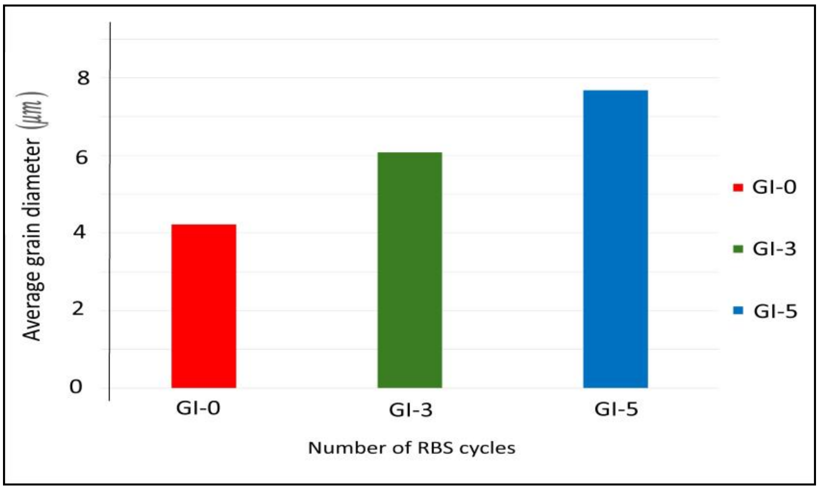


Figure 4: *Average grain diameter (μm) versus number of RBS cycles*

4. Conclusion

This research concludes that the RBS process significantly alters both the microstructural and mechanical properties of galvanised iron, though not in a manner that enhances material strength. The microstructural analysis revealed that an increasing number of RBS cycles leads to grain coarsening rather than refinement. The average grain diameter increased from 4.22 μm in the original specimen to 7.68 μm after five RBS cycles. Furthermore, mechanical testing showed that the original specimen (GI-0) possessed the highest UTS of 322.20 MPa and the highest yield strength of 250 MPa. As the number of cycles increased, the UTS steadily decreased, as demonstrated by the decreasing peaks in the stress–strain curves and the summarised tensile data. Finally, this study confirms that for 1 mm thick galvanised iron, the mechanical energy introduced during the RBS cycles does not improve the mechanical strength of the material under these specific parameters.

Acknowledgement

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:****Amirul Raimi Abdul Rahman, Mohd Nizam Katimon;* ***data collection:*** *Amirul Raimi Abdul Rahman;* ***analysis and interpretation of results:*** *Amirul Raimi Abdul Rahman, Mohd Nizam Katimon;* ***draft manuscript preparation:*** *Amirul Raimi Abdul Rahman, Mohd Nizam Katimon. All authors reviewed the results and approved the final version of the manuscript.*

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