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Automobile Weight Optimization Using Magnesium Alloy AZ31B

Mutua James , J. M. Kihiu, G. O. Rading

Abstract—Magnesium-alluminium-zinc alloy (Mg alloy AZ31) is among the five general classes of wrought alloys that are strengthened by annealing. This paper will highlight the possibilities of manipulating the mechanical properties of Mg alloy AZ31B through rolling and annealing and present the material as a potential candidate for both structural and sub-structural application in passenger cars and light-trucks. Further, an overview of recent developments in efforts towards light weighting of automobile in relation to fuel consumption efficiency and pollutant gas will be presented. The findings of this research will assist automobile design engineers in optimizing the weight of automobile through replacement of steel and some aluminium components with magnesium alloy AZ31B of equivalent strength and stiffness.

Keywords—Annealing, light weighting, structural application, wrought alloys

I. INTRODUCTION

HYpothetically, magnesium and its alloys have an array of uses stretching from general, (a good alloying element in alluminium, desulfurization of iron and steel), non-structural uses, (as an anode to protect steel from corrosion, added to grey cast iron to produce nodular iron) to structural applications, (aircraft parts, magnesium wheels, electronic housing for aircraft and missiles, rapidly moving parts) [1]. The structural applications of magnesium and its alloy is dependent on certain properties such as low density, high damping capacity, excellent machinability at elevated temperature and high corrosion resistance. Presently, not all the said uses are in effect due to meager information on the full potential of magnesium and its alloys as a potential candidate for structural applications.

The potential of magnesium alloy AZ31B as a weight reduction material is clear when looking at its specific mass (1.78 g/cm^3), which is less compared to that of aluminium (2.7 g/cm^3) and also less than half of that of iron (7.80 g/cm^3). Apart from the direct weight reduction by material substitution, however, there are additional possibilities for light-weighting with magnesium. Magnesium specific fabrication techniques, such as thixomolding, hollow extrusions or thin-walled intricate forming, enable new design solutions [2]. Furthermore, the reduction of the total vehicle weight also offers the potential for indirect weight savings, such as a smaller engine or fuel tank.

Mutua James, Department of Mechanical Engineering, JKUAT (phone: +2540720408251; fax: (067) 52164; e-mail: mutuajay@eng. jkuat.ac.ke).

J. M. Kihiu, Department of Mechanical Engineering, JKUAT (e-mail: kihiusan@yahoo.com).

G. O. Randing, Department of Mechanical Engineering, UoN.

II. OVERVIEW

Many mechanical and physical properties of metals depend on the grain size. The best known effect is that described by Hall and Petch in the early 1950s, under which the yield stress of polycrystalline materials is inversely proportional to the square root of average grain diameter [3]. Refer to equation (1).

$$\sigma_y \ \alpha \frac{1}{\sqrt{\text{grain diameter}}} \tag{1}$$

The greatest effect is observed in the case of yield strength, which increases 3 - 5 times, whereas ultimate tensile strength increases 2 - 3 times [4]. Microstructure of magnesium alloy AZ31B may be varied by grain size refinement and microstructure texture control [5]. With grain size taking a greater influence on microstructure, it may be varied in a variety of ways which include but is not limited to; Use of nucleant, superheating, severe plastic deformation, equal channel angular extrusion, conventional rolling, accumulated bond rolling and annealing.

Grain refinement is the key to achieving better mechanical properties. From the various methods of grain refinement listed above, it is suggested that severe plastic deformation process is the best way to give fine or Ultra- fine grain structures [6], [7]. However, the most practical technique is rolling combined with suitable heat treatment which can be scaled for large bulk sheet or plate sample fabrication [8].

III. METHODOLY

The research work involved investigation of the effects of microstructure manipulation on mechanical properties of wrought Magnesium alloy AZ31B. The microstructure of this alloy as a function of its composition and thermal processing was varied with the aim of obtaining optimum combinations of mechanical properties. The emphasis was on the specific strength and rigidity of the material, the two primary mechanical properties mainly considered in the design of automobile structural applications. The research was carried out in two stages; literature review and experimental work. The literature available and relevant to this work was critically reviewed. This assisted in duly understanding the existing approaches used by researchers to handle weight related problems in automobiles. The experimental work involved variation of the alloys' microstructure through grain size refinement and microstructure texture alteration. Grain size refinement methods including annealing, and conventional rolling were adopted.

Tensile and hardness tests were carried out on specially prepared specimens from the microstructure optimized alloy. This helped in determining the specific strength and rigidity.

IV. RESULTS AND DISCUSSION

The experiments undertaken were rolling and annealing of magnesium alloy AZ31B strips to predetermined state, tensile testing of specially prepared specimen, hardness testing, and microstructure analysis. Cold rolling did not yield satisfactory results because right from the first pass the strips had side cracks and could not be used in tensile testing.

A. Warm rolling

From the experiments carried out, the results for each test were tabulated. Good thickness reduction with each successive pass was attained with a total percentage reduction of 50% or four passes. The reduction in each pass was distributed in a descending order with the lowest percentage reduction taking place in the last pass. This permitted better control of flatness, gage, and surface finish. The final thicknesses of the rolled strips were as shown in Table I.

TABLE I: Thickness after each pass

Sample No.	No. of passes	% Reduction in each pass	Total % reduction	Final thickness (mm)
1	-	-	-	3.0
2	1	20	20	2.7
3	2	20, 16	36	2.4
4	3	20, 16, 10	46	1.8
5	4	20, 16, 10, 4	50	1.5

B. Effects of rolling and annealing on mechanical properties of AZ31B

Tensile testing was carried out with view of checking the following mechanical properties; 0.2% yield stress (proof stress), ultimate tensile strength, stiffness and elongation. Five tests were carried out to get the average values for each property. The above properties were tabulated in table form for ease of comparison as shown in Table II.

TABLE II: Variation in mechanical properties

No.	Preparation	Youngs Modulus (Mpa)	0.2% Yield Point($YP_{0.2}$) (Mpa)	%Elongation (A)	Ultimate tensile strength σ_{uts} (Mpa)
1	As from manufacturer(AFM) along	44.74	134.52	5.26	260.68
2	AFM-Annealed at 350^0C for 7200s	44.62	142.12	12.06	271.54
3	Rolled at 423K 1 pass 20% reduction	42.06	209.48	4.60	282.54
4	Rolled at 423K 2 pass 36% reduction	44.64	227.40	6.44	300.10
5	Rolled at 423K 3 pass 46% reduction	44.90	240.52	8.08	319.92
6	Rolled 1 pass Annealed at 350^0C for 7200s	44.98	229.32	15.04	302.94
7	Rolled 2 pass Annealed at 350^0C for 7200s	44.96	243.08	15.68	323.26
8	Rolled 3 pass Annealed at 350^0C for 7200s	44.98	258.78	17.96	349.08

With the help of Optika Vision Pro camera, the microstructure characteristics for the rolled-annealed samples were recorded as shown in Fig. 1. For the 1 pass rolled-annealed specimen, the grains underwent some refinement maintaining their "necklace" structure. For the 2 pass rolled-annealed specimen, twinning disappeared and equiaxed grain structure was attained. Dynamic recrystallization also took place and the density of dislocations decreased near the grain boundaries forming low-angle boundaries. Fig. 1(a), (b) and (c) shows the microstructure of 1 pass-annealed, 2 pass-annealed and 3 pass-annealed specimens respectively. The grains were further refined with increase in the number of rolling passes with those in the 3^{rd} being finest. Annealing was done at 350^0C for 7200s as recommended from the ASTM standards [9]. This aided in the grain refining process. To determine the grain

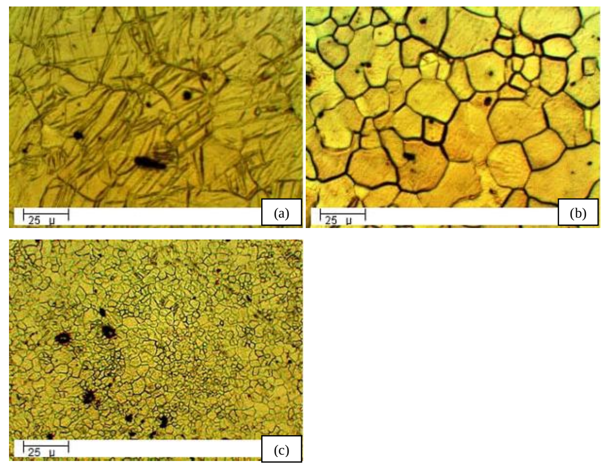

Fig. 1: Microstructure of rolled-annealed samples;(a) 20%, (b) 36% and (c) 46% reduction

size in the recorded micrographs, Microstructure characterizer software, (MiC3.0) was used. The grain size variation and changes in ultimate tensile strength corresponding to the percentage reductions and annealing conditions aforementioned were recorded as shown in Table III.

TABLE III: Grain size and ultimate tensile strength variation

No.	Preparation	Average grain size diameter(μm)	Average ultimate tensile strength $\bar{\sigma}_{uts}$ (Mpa)
1	As from manufacturer(AFM) along	10	260.68
2	AFM-Annealed at 350^0C for 7200s	9.5	271.54
3	Rolled at 423K 1 pass 20% reduction	9.0	282.54
4	Rolled at 423K 2 pass 36% reduction	7.5	300.10
5	Rolled at 423K 3 pass 46% reduction	5.0	319.92
6	Rolled 1 pass Annealed at 350^0C for 7200s	8.2	302.94
7	Rolled 2 pass Annealed at 350^0C for 7200s	6.7	323.26
8	Rolled 3 pass Annealed at 350^0C for 7200s	4.5	349.08

The optimum attainable ultimate tensile strength was 349 Mpa. This was achieved after 46% reduction followed by annealing at 350^0C for 7200s. From this optimum value of σ_{uts}, the optimum specific strength of the material under such conditions was calculated, refer to equation (2).

$$\text{Specific strength} = \frac{\text{Ultimate tensile strength}}{\text{Density of the material}} \qquad (2)$$

From the experiment;
Optimum ultimate tensile strength = 349 Mpa,

Density of the material = 1780 kg/m^3
Therefore,

$$\text{Specific strength} = \frac{390 \text{ Mpa}}{1780 \text{ kg/m}^3} = 196 \text{ MNm/kg}$$

The resultant specific strength for magnesium alloy AZ31 after rolling and annealing is 180% more superior than that of steel. For steel that is commonly used in structural and sub-structural automobile construction, the specific strength is approximately 70 MNm/kg [10]. Moreover, the specific rigidity of Mg alloy AZ31B is approximately 26 Mpa/kg, a unit higher than that of steel.

C. Recent developments towards light weighting of automobile and its impact to fuel consumption efficiency and pollutant gas emission

The average weight of a new car ranges between 1200 kg and 1400 kg while that of a light truck is approximately 2200 kg. Both cars and light trucks were at their lightest weight in 1987 [11]. This was facilitated by the use of aluminium intensive vehicles. However, the use of aluminium intensive vehicle was deemed unsatisfactory because of the increased roll-over and crash accidents attached to the lightweight. Since then, the weight has been generally increasing due to increased research and development. With this trend in mind, weight reduction took the center stage in order to curb the increase of accidents. The changes in the material composition are based on the following assumptions:

- replacement of 5% of conventional ferrous metals with high strength steel (the declining use of ferrous metals results from the application of less HSS to achieve the same resistance performances)
- replacement of 12% of ferrous materials with aluminium
- intensive replacement of 30% of ferrous materials with aluminium
- intensive substitution of 30% of ferrous materials with magnesium.

The move towards light weighting has been instigated by the increasing fuel costs and automobile emissions. This in turn is geared towards curbing the ever fluctuating automotive fuel economy and the climatic changes. Weight reduction is the most cost effective means to reduce fuel consumption and green house gases from the transportation sector. Generally, it has been estimated that for every 10% of weight eliminated from a vehicles total weight, fuel economy improves by 7%. This also means that for every kilogram of weight reduced in a vehicle, there is a reduction of about 20 kg in carbon dioxide emission [12]. Based on vehicle simulations, it is assumed that fuel consumption reduces by 0.4 L/100 km for cars, and 0.5 L/100 km for light trucks for every 100 kg weight reduction. In other words, for every 10% weight reduction, fuel economy increases by 6% for cars, and 8% for light trucks [13].

V. Conclusion

Based on the findings of this research, manipulation of mechanical properties of magnesium alloy AZ31 is quite possible through Rolling and annealing. Considering the resultant optimum specific strength and stiffness of the material after a combination of warm rolling and annealing, magnesium is a suitable candidate for structural and sub-structural construction of automobiles. Weight optimization in automobile can be fully achieved by effecting intensive substitution of ferrous and alluminium materials with magnesium alloy AZ31B of equivalent strength and stiffness.

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