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INVESTIGATION OF MAGNESIUM ALLOYS MACHINABILITY

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Abstract: *Magnesium is the lightest structural metal. Magnesium alloys have a hexagonal lattice structure, which affects the fundamental properties of these alloys. Plastic deformation of the hexagonal lattice is more complicated than in cubic latticed metals like aluminum, copper and steel. Magnesium alloy developments have traditionally been driven by industry requirements for lightweight materials to operate under increasingly demanding conditions. Magnesium alloys have always been attractive to designers due to their low density, only two thirds that of aluminium and its alloys [1]. The element and its alloys take a big part of modern industry needs. Especially nowadays magnesium alloys are used in automotive and mechanical (trains and wagons) manufacture, because of its lightness and other features. Magnesium and magnesium alloys are the easiest of all metals to machine, allowing machining operations at extremely high speed. All standard machining operations such as turning, drilling, milling, are commonly performed on magnesium parts.*

Keywords: Magnesium alloys, Lightweight metal, Machinability

1. INTRODUCTION

Magnesium is the lightest of all design metals. It's light in weight just like a plastic material and also tough like a metal. It's high specific toughness and rigidity, good machinability, castability and weldability with known methods are maked it attractive for industry. The use of magnesium, which is the latest metal of our age, is increasing in parallel with the advances in industry and technology. Due to its lightness, durability and long life, its usage is increasing in the industries. [2]

During the last years the application of magnesium and its alloys were grown many times in kinds of industry. This is due to numerous characteristics of the metal regarded to herein, which permit its use both as a structural element, and as a chemical addition to other metal alloys [3]. The metal is lighter than aluminum and has bigger tensile strength than steel. That is the reason for its necessary metallurgy using.

Magnesium and magnesium alloys are nonferrous metals with low density, good ductility, moderate strength and good corrosion resistance. When used an alloying agent, they can improve the mechanical, fabrication, and welding characteristics of aluminum. Some magnesium and magnesium alloys are used as lightweight materials in vehicles such as cars and trucks [4]. These magnesium alloys have a relatively low density and can help improve fuel efficiency.
Magnesium and its alloys has been used for a wide variety of applications, namely from the reason of their low density and high strength–to–weight ratio.
Low inertia, which results from its low density, is advantageous in rapidly moving parts. The

use of materials with low specific weight is an effective way of reducing the weight of structures. Magnesium alloys are used lightweight metallic materials as they offer a number of different interesting mechanical and thermal properties. [5-9]. Despite being the lightest structural metal, magnesium alloys exhibited poor machining at low temperatures due to their hexagonal closed-packed crystal structure, consequently required them to be processed at elevated temperature. Their highly affinity to oxygen lead them to an easy oxidation [10].

Magnesium with its good strength to weight ratio is one of the candidate materials to realise light weight construction, but it has to compete with various other materials [11]. So the different light metals have to compete not only with each other, but also with polymers and steels. Materials selection is thereby determined by economical issues as much as by materials and components characteristics or properties [12].

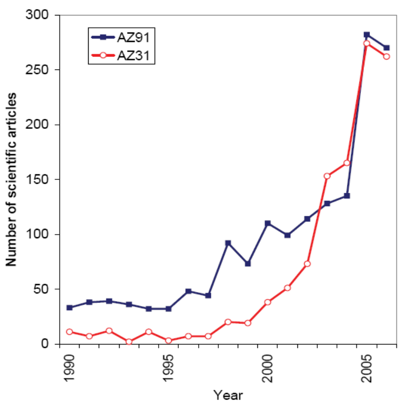

Figure 1. Number of scientific articles, values are from Cambridge Scientific Abstracts database, were termed AZ91 or AZ31 in the abstract [13]

The uses of magnesium alloys have been increasing recently so scientific studies are becoming increasingly important. Given in Figure 1, number of scientific articles which have terms AZ91 or AZ31 in the abstract.

However magnesium shows high potential to substitute conventional materials. Magnesium alloys should be used in applications where low mass and high specific properties are required. According to the combination of specific Young's modulus and high specific strength magnesium alloys show similar or even better values than aluminum and many commercial steels (fig.2) [14].

It also has considerably low melting temperature of 649 ^{0}C, slightly lower than that of aluminum. Magnesium alloy is one of the lightest materials and is attractive in many applications such as aircraft engines, airframes, helicopter components, cars, light trucks, automotive parts, computers and so much more [10]. Mg alloys, like other alloys with hexagonal closed-packed (HCP) crystal structures [16], are much more workable at elevated temperatures than at room temperature. The advantages of Mg, among other, tougher than plastic, better damping capacity as compared to cast iron and aluminum, electromagnetic interference (EMI) shielding than that of plastic, heat dissipation much higher than that of plastics, absorb vibration energy effectively and recyclability [17].

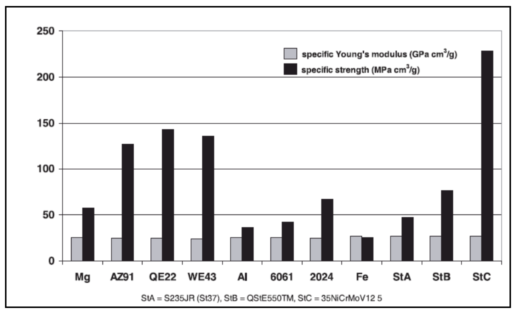

Figure 2. Comparison of specific Young's modulus and strength of different materials [14]

Table 1. Physical properties of Mg, Al, and Fe [15]

Property	Magnesium	Aluminium	Iron
Crystal structure	hcp	FCC	Bcc
Density at 20°C (g/cm3)	1,74	2,70	7,86
Coefficient of thermal expansion 20–100°C (×106/C)	25,2	23,6	11,7
Elastic modulus [Young's modulus of elasticity] (106 Mpa)	44,126	68,947	206,842
Tensile strength (Mpa)	240 for (AZ91)	320 for (A380)	350
Melting point (°C)	650	660	1536

2. METALLURGY OF MAGNESIUM ALLOYS

Magnesium (Mg), its atomic number is 12, is the lightest among the metals for structural application. Magnesium is the lightest of all the engineering metals, having a density of 1.74 g/cm^3. It is 35% lighter than aluminum (2.7 g/cm^3) and over four times lighter than steel (7.86 g/cm^3). The physical properties of Mg, Al and Fe are given in Table 1. Magnesium is the eighth most common element. It is produced through either the metallothermic reduction of magnesium oxide with silicon or the electrolysis of magnesium chloride melts from seawater. Each cubic meter of the sea water contains approximately 1.3 kg (0.3%) magnesium [15].

Magnesium alloys names are often given by two letters following by two numbers. Letters tells main alloying elements (A = aluminum Z = zinc, M = manganese, S = silicon). Numbers tells nominal compositions of main alloying elements respectively. Marking AZ91 mean magnesium alloy where is roughly 9 weight percent aluminum and 1 weight percent zinc. Shown in figure 3. Exact composition should be confirmed from the standards.

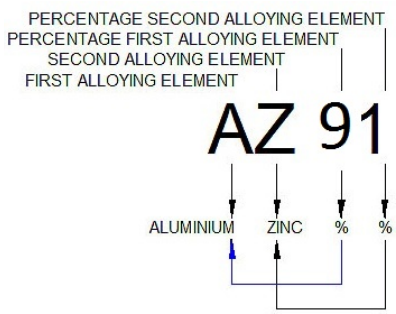

Figure 3. Marking magnesium alloys

Table 3. Some magnesium cast and wrought alloys typical composition (wt%)

Alloy	From*	Al	Zn	Mn	Si	RE	Zr	Th
AM60A	CD	6		>0.13				
AZ31B	WB+WS	3	1	0.3				
AS41A	CD	4		0.3	1			
AZ80A	WB	8	0.5	0.2				
AZ91B	CD	9	0.7	>0.13				
AZ91D**	CD	9	0.7	0.2				
EZ33A	CS		3			3	0.8	
HK31A	WS						0.7	3

*CS – sand casting; CP – permanent mold casting; CD – die casting; WS – sheet or plate; WB – bar, rod, shape, tube or wire
** High-purity alloys

In the last decade, the AZ series cast magnesium alloys, especially the AZ91 alloy, have been extensively studied and used for some structural components of automobiles, aircraft, and computers, because of high specific strength and good castability [16-19].
Commercial cast magnesium alloys for automotive applications are AZ and AM series alloys (AZ91D, AM50A, and AM60B). These alloys are excellent combination of mechanical properties, corrosion resistance, and die-castability. However, they have poor creep resistance above 125±C [20], which make them inadequate for major powertrain applications.

2.1. Magnesium – Aluminum

Aluminum is one of the most important alloying elements in magnesium. Several systems contain Al up to 10 mass %, e.g., AZ, AE, AM and AS. Figure 4 shows the Mg-Al system. Al is one of the few metals that dissolve easily in magnesium. Above the solubility limit $Mg_{17}Al_{12}$, a brittle intermetallic, precipitates out. The solubility limit of aluminum at the eutectic temperature is 11.5 at.% (12 mass %) and falls to about 1% at room temperature. Consequently, the $Mg_{17}Al_{12}$ plays a dominant role

Table 2. Convention for alloy elements designation

Letter	Alloying Elements
A	Aluminum
C	Copper
E	Rare earth metal
H	Thorium
K	Zirconium
L	Lithium
M	Manganese
Q	Silver
S	Silicon
Y	Yttrium
Z	Zinc

in determining the properties (Fig. 5). The commercial alloys based on Mg-Al involve further alloying additions of zinc, e.g., AZ91, AZ81 and AZ63 [21].

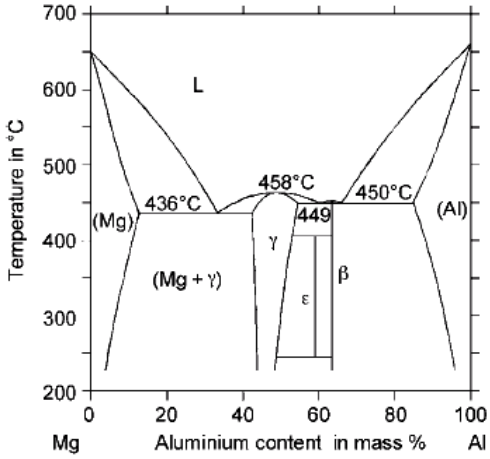

Figure 4. Phase diagram of Mg-Al binary alloy [21]

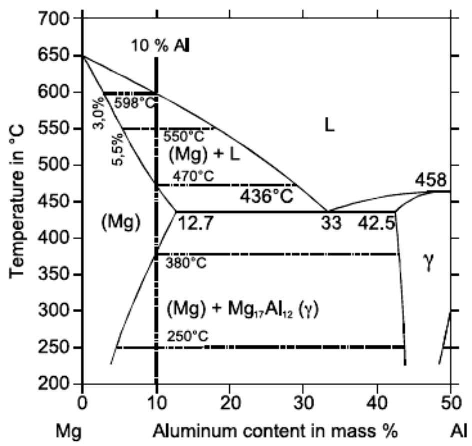

Figure 5. Magnesium – rich section of Mg-Al system [21]

Besides low density, magnesium based materials exhibit good specific mechanical properties, machinability, castability, weldability, thermal stability, damping and resistance to electromagnetic radiation [23]. However, as magnesium has low ductility, modulus of elasticity and limited strength and creep resistance at elevated temperature, it cannot be extensively applied in structural applications [22–24]. Therefore, magnesium is rarely used in its pure form. Instead, it is usually alloyed with other elements like aluminum, zinc, silver and zirconium to improve its properties like corrosion resistance and ductility [23,24–27]. Mechanical properties of magnesium are listed in Table 3. Its dynamic modulus of elasticity is 45 GPa and its static modulus of elasticity is 43 GPa.

3. MECHANICAL PROPERTIES AND APPLICATIONS

Magnesium-base products are available in a wide range of mechanical properties. As with metal manufactures in general, the tensile and other properties of the magnesium materials depend upon the composition, condition (whether cast or wrought), details of fabrication, heat treatment, and other factors. For the same composition, some mechanical properties vary considerably with the type of product [28]. Accordingly, it is important to define the kind of material as well as the alloy composition. Also, the direction in which the test specimen is taken in relation to the direction of fabrication and the thickness of the product are factors which influence strength and other properties.

In engineering design, the more important mechanical properties which ordinarily may come under consideration may include the following:

- Tensile yield and ultimate strength,
- Elongation,
- Shear strength,
- Compressive yield strength,
- Hardness,
- Impact resistance, and
- Endurance limit.

While magnesium sheet is considered a growth product for the 21st century - with its light-weight and high-strength qualities - the uptake of magnesium sheet has been hindered by expensive and difficult conventional production processes. Magnesium sheet has a variety of applications where light weight and quality finish is at a premium like automotive industry and personal electronics (cameras, MD players) [29]. The latest method to process magnesium alloy is Thixomolding. It is based on material flow in a semi solid state to achieve thin wall, high density, and complex shaped components. The material is kept at room temperature and is heated in a controlled environment before injection into a mold. Thixomolded components can be found in the automotive, electronics, power tool, computer and recreational industries. Parts include television housings, PDA covers, eyeglass

Table 3. Mechanical properties of magnesium at 20 ^{0}C [28] (* in 50mm ** with 500kg load, 10mm diameter ball)

	Tensile Strength, MPa	Tensile yield Strength (0,2%), MPa	Compressing yield Strength (0,2%), MPa	Elongation *%	Brinell hardness **
Sand cast, thickness 13mm	90	21	21	2-6	30
Extrusion, thickness 13mm	165-205	69-105	43-55	5-8	35
Hard rolled sheet	180-220	115-140	105-115	2-10	45-47
Annealed	160-195	90-105	69-83	3-15	40-41

frames, steering wheels and hand drill components[30].

Today high-grade car wheels of magnesium alloy we called 'mag wheels'. Due to low weight, good mechanical and electrical properties, magnesium is widely used for manufacturing of mobile phones, laptop computers, cameras, and other electronic components [36]. So, electronic devices of the metal are very important, too. Also the use of magnesium alloys in aerospace is increasing, mostly driven by the increasing importance of fuel economy and the need to reduce weight.

Advantages of magnesium are something necessary for the modern industry and metallurgy and they become from special magnesium characteristics. For example the automotive industry has crossed the doorstep from using magnesium in a protected environment, predominantly interior applications to an unprotected environment. [29]. Today you can see growing popularity of magnesium die casting, particularly in the automotive field.

Many of interior magnesium components include instrument panel, seat frames, steering wheel and others.The most popular world production involves roof panels, hood, rear deck lid, wheels, oil pan, starter/alternator and so on. One really needed magnesium area is automotive industry and technologies [31].

Fuel saving advantages of magnesium used in vehicles gives it a large popularity. The data indicate that the overall weight savings could be of around 10%. In turn, this weight saving would lead to a fuel saving of the order of 20-30% without drastic changes in design. Passenger car produces on average around 150 g/km spend gasses, but by magnesium technology that uses up energy is around 100-120 g/km. Considering the large number of vehicles around, we can say that weight saving could help to keep cleaner the atmosphere and to hold the global warming better. That would be done because of weight saving lead to a significant reduction of carbon dioxide released to the air [30-33].

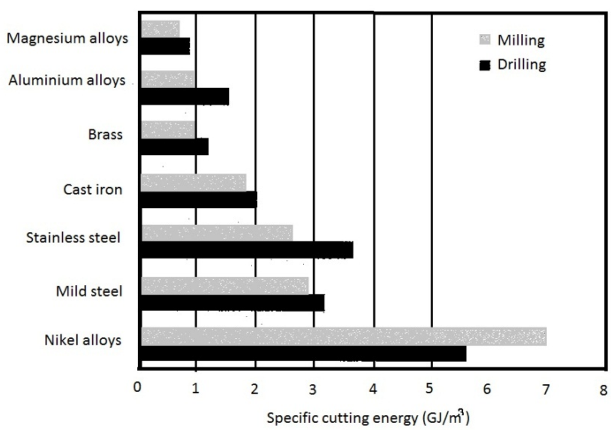

Figure 6. Values of specific power consumption (net), E_{sp}, for a variety of metals as determine for drilling and milling [34]

4. MACHINABILITY

Magnesium has very good machining abilities like sawing, punching, drilling, milling, turning compared to other metals. The specific cutting power is low and the surface is excellent and the chips are short. Magnesium and magnesium alloys are the easiest of all metals to machine, allowing machining operations at extremely high speed. Magnesium is the fastest machining metal and it has a high thermal conductivity. Advantages of it are, long tool life, the tool stays sharp for long time, low power consumption, about 55% lower than for aluminum alloys, reduction of machining time because of the high speeds, short chips an excellent surface.The cutting energy for machining of magnesium is lower than for other materials as illustrated by figure 6. The lower power requirements for machining magnesium alloys permit the use of deeper cuts and higher feed rates, and thus permit fast and efficient machining, as compared to other metals. Magnesium machining is normally done without any coolant. If when necessary to use coolant, a light mineral oil will suffice. Never use water based coolant because of the risk of any reaction with the chips during storage. High-speed tools or carbide tipped tools are preferred for the machining of magnesium. It is important to keep the cutting tool sharp to avoid from much heat [35]. The experiences with diamond tools are excellent but the costs are relatively high. It is necessary to store machined products under dry conditions and when there is a chance of condensation, extra protection is needed. Machines should be kept clean and the turnings should be stored in steel bins [37]. *Turning*, a typical lathe tool has a large relief angle (10^0 to 15^0). A larger back rake often causes feeding of the tool into the work. In some plants, 0^0 back rake is used to break chips and prevent curling. This practice is seldom recommended, as it increases roughness of the machined surface and increases power consumption. The side rake may vary from 0^0 to about 10^0. *Drilling* Magnesium alloys can be easily drilled with twist drills made of any high-speed steel. *Milling* cutter for magnesium should have fewer teeth than conventional cutters used for steel or other metals - preferably only one-half to one-third as many. The larger chip space and the heavier cut resulting from the smaller number of teeth reduce frictional heat and increase chip clearance. This leads to higher speeds, decreased distortion, lower power consumption, and smoother finish. Tapping are adequate if production quantities are small and if high-quality tapping is not required. When a large number of parts or close tolerances are involved, standard taps must be modified, or taps designed especially for magnesium must be used. *Sawing* Magnesium can be cut with hand or power saws. Because only low cutting pressure is required, large cuts can be taken. Hence, the saws must have large chip spaces for a free cutting action. Too small a chip space rapidly loads the teeth and causes the saw to ride over the work. *Grinding* is seldom necessary to grind magnesium, because machining produces good finishes. Surface roughness measurements of 0.075 to 0.125 µm have been produced on magnesium machined with diamond-tip tools. *Counterboring* magnesium should have a narrow margin of approximately 0.38 mm with adequate relief and cleaning angles, allow adequate chip space and eliminate rubbing. *Die threading* for magnesium should have approximately the same cutting angles as taps. A cutting edge relief of 0.10 mm is generally recommended, although there are applications, which that require extremely good surface finishes and high accuracy.

5. CONCLUSION AND SUMMARY

Use a lower cutting speed when compared to cutting aluminum. The workpiece temperature goes up with an increase in cutting speed and also smaller undeformed chip thickness. In other words, the slower the machining speed and the larger the chips, the lower the workpiece temperature will be. Due to this reason, some companies have modified woodworking tools for machining magnesium so as to achieve larger chips and lower fire hazard. The cutting tools used should have relief and clearance angles that are sufficiently large to prevent unnecessary cutting tool-workpiece friction, thus lowering the heat generated during the cutting process. Experiments were carried out using thermocouples mounted into the workpiece to monitor the workpiece temperature during machine. Despite the fire hazards, as competition from overseas low-cost production bases intensifies, and magnesium becomes increasingly used in electronics products, most machining job shops could very well find machining of magnesium a niche worth pursuing.

REFERENCES

[1] L. Duffy, "Magnesium Alloys", *Magnesium Alloys Magnesium Alloys Materials World*, Vol 4. No.3,pp. 127-30, 1996.

[2] A. Şık, "*Sürtünme karıştırma kaynağı ile birleştirilen magnezyum levhaların mekanik özelliklerinin incelenmesi*", *SAÜFBE*, Vol 14., No 2., 134-140, 2010.

[3] M. Mabuchi, T. Asahina, H. Iwasaki, and K. Higashi, "Muter. Sd. Technol", vol. 13, pp. 825-32, 1997

[4] M. Mabuchi, M. Nakamura, K. Ameyama, H. Iwasaki, and K. Higashi, "Mater. Sci. Forum", vols. 304-306, pp. 67-72, 1999.

[5] M. Avedesian, H. Baker, "*ASM Specialty Handbook- Magnesium and Magnesium Alloys*", ASM International,
USA, 3-84, 1999.

[6] J.R Davis, "Metals Handbook, Desk. Edition, Second Edition", *ASM International, The Materials Information Society,* USA, 560- 564, 1998.

[7] L. Ptáćek, "Magnesium alloys- present state of development and exploitation", *Proceedings of conference METAL 2001,* Ostrava - Hradec n. Moravicí, 1-12, 2001.

[8] K.A. Dahle, Z.C. Lee, M.D. Nave, P.L. Schaffer, D.H. Johnson, "*Development of the as-cast microstructure in magnesium-aluminium alloys*", Journal of Light Metals 1 , 61-73, 2001.

[9] L. Čížek a,, M. Greger , L.A. Dobrzański , I. Juřička , R. Kocich , L. Pawlica , T. Tański, "Mechanical properties of magnesium alloy AZ91 at elevated temperatures", *Journal of Achievements in Materials and Manufacturing Engineering*, Volume 18, Issue 1-2, September–October, 2006.

[10] H. Mohd Ruzi, M. Norhamidi, S. Abu Bakar, R. J. Khairur, M.N. Nor Hafiez, A. Sufizar, I.I Mohd Halim, Murtadhahadi, "*A Review of Workability of Wrought Magnesıum Alloys*, Advanced Manufacturing", Research Group'09 Seminar 3, 2009 .

[11] H. WESTENGEN, "Magnesium alloys for structural applications; recent advances", Colloque C7 suppliment au Journal de Physique 111, Volume 3, 1993.

[12] D. Eliezer, E. Aghion and F. H. (Sam) Froes, "*Advanced Performance Materials,"* Magnesium Science, Technology and Applications*,* Vol. 5, No. 3, pp. 201-212. 1998.

[13]http://en.wikipedia.org/wiki/File:Scientific_articles_AZ91_AZ31.png 08.03.2012.

[14]. C. Blawert, N. Hort and K.U. Kainer "*Automotive Applications of Magnesium And Its Alloys*", Trans. Indian Inst. Met. Vol.57, No. 4, pp. 397-408, August 2004.

[15] M. K. Kulekci, "*Magnesium and its alloys applications in automotive industry*", Int J Adv Manuf Technol 39:851–865, 2008.

[16] P. Cavaliere and P. P. De Marco, "*Materials Characterization 58*", The Japan Institute of Metals, 226–232, 2007.

[17] B. L. Mordike, T. Ebert, "*Magnesium – applications – potential*", Journal of Material Science Engineering A 302, pp. 37-45, 2001

[18] R.W. Cahn, C.X. Shi and J. Ke, "*Structure and Properties of Nonferrous Alloys*" Beijing, Science Press, Beijing, 1999.

[19] H. Watanabe, H. Tsutsui*, T. Mukai, K. Ishikawa, Y. Okanda, M. Kohzu, K. Higashi, "*Grain Size Control of Commercial Wrought Mg-Al-Zn Alloys Utilizing Dynamic Recrystallization*" Materials Transactions, The Japan Institute of Metals Vol.42 No.7 pp.1200-1205, 2001

[20] C. Suman, "SAE Technical Paper No.910416", Warrendale, PA, Society of Automotive Engineers, 1991.

[21] E. Horst, L. Mordike, B. Friedrich, "*Magnesium* technology: metallurgy, design data, applications" Springer Science & Business, 84-86, 2002.

[22] F. Moll, K.U. Kainer, in: K.U. Kainer (Ed.), "*Magnesium Alloys and Technology*", Wiley-VCH, Weinheim, pp. 197–217, 2003.

[23] M. Paramsothy, Q. B. Nguyen, K. S. Tun, J. Chan, R. Kwok, J. V. M. Kuma, M. Gupta, "*The ability of cast composite technology to enhance ductility of wrought magnesium and alloys*",Archive International Journal of Materials Research - Issue 2011/01

[24] A. Martin and J. Llorca, "*Mechanical behaviour and failure mechanisms of a binary Mg-6%Zn alloy reinforced with SiC particulates,*" Mater. Sci. Eng. A, 201, 77-87, 1995.

[25] W. Westengen, "*Magnesium: Alloying, in: K.H.J. Buschow, R.W. Cahn, M.C. Flemings, B. Ilschner, E.J. Kramer, S. Mahajan, P. Veyssiere",* Encyclopedia of Materials: Science and Technology, Elsevier, pp. 4739–4743, 2008.

[26] S.F. Hassan, K.F. Ho, M. Gupta, "*Increasing elastic modulus, strength and CTE of AZ91 by reinforcing pure magnesium with elemental*

copper", Mater Lett, 58, pp. 2143–2146, 2004

[27] K. Hirai, H. Somekawa, Y. Takigawa, K. Higashi, "Mater. Sci. Eng. A 403", 276–280, 2005.

[28]http://www.magnesium.com/w3/databank/index.php?mgw=153 08.03.2012

[29] M. Mabuchi, K. Ameyama, H. Iwasaki, and K. Higashi: "*Acta Mater*", vol. 47 (7), pp. 2047-57, 1999.

[30] H. Watanabe, T. Mukai, K.Higashi,"*Microstructural factors affecting superplastic properties in magnesium-based composites*" Metallurgical and Materials Transactions A Volume 32, Number 4, 923-929, 2007

[31] Y. N. Wang and J. C. Huang, "*Transition of dominant diffusion process during superplastic deformation in AZ61 magnesium alloys*", Metallurgical and Materials Transactions A Volume 35, Number 2, 555-562, 2007

[32] H. Watanabe, H. Tsutsui, T. Mukai, K. Ishikawa, Y. Okanda, M. Kohzu, K. Higashi *,"Superplastic Behavior in Commercial Wrought Magnesium Alloys"* Magnesium Alloys 2000, 350-3, 171-176 ,2000

[33] J.K. Solberg, J. Torklep, O. Bauger, and H. Gjcstland: Mater. Sei. Eng. A, 1991, vol. 134A, pp. 201-07

[34] W.F., Smith, "*Society of Manufacturing Engineers, forces at the cutting tool, tooling and manufacturing engineers handbook*" McGraw-Hill, vol. , machining, pp 1-19, 2004.

[35] W.F., Smith, "*Structure and properties of engineering alloys, second edition*", McGraw-Hill, ISBN 0-70-112829-8, 1993.

[36] I.J., Polmear, "*Light alloys: metallurgy of the light metals*", Third edition, Arnold, London, ISBN 0-340-63207, 1995.

[37] K.U. Kainer, "*Magnesium alloys and technology*", Dmg, Wiley-Vch, ISBN 3-527-30256-5, 2003.

[38] N. Tomac, K. Tønnesen, F. O. Rasch, "*Safe Machining of Magnesium*", Advanced manufacturing systems and technology: 4. Dec. 1997.

[39] A. Spicer, J. Kosi, C. Bullups and J. Pajek, "*Machining Magnesium With Water Base Coolants*", *SAE Paper* 910415, 1991.

[40] M. Videm, R.S. Hansen, N. Tomac and K. Tønnesen, "*Metallurgical Considerations for Machining Magnesium Alloys*", SAE Technical Paper 940409, 1994

[41] Machining Magnesium, Magnesium electron datasheet 254, 2011.