

**MECHANICAL, WEAR AND CORROSION  
PROPERTIES OF A NOVEL Mg-10Dy-0.7La ALLOY**

*A THESIS*

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## CERTIFICATE

This is to certify that the thesis entitled “**MECHANICAL, WEAR AND CORROSION PROPERTIES OF A NOVEL Mg-10Dy-0.7La ALLOY**” is being submitted by **Mr. AMIT KUMAR PRASAD** to the Indian Institute of Technology Delhi for the award of the degree of **DOCTOR OF PHILOSOPHY**. This is a record of bonafide research work carried out by him under our supervision and guidance. The matter presented in this thesis has not been submitted, in part or in full to any other University or Institute for the award of any degree or diploma.

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## Abstract

Magnesium (Mg) alloys have attracted significant attention as a potential replacement material for aluminium alloys in the automobile industry due to their superior strength-to-weight ratio. However, poor corrosion resistance restricts their use in various engineering applications and thus, it needs to be significantly improved. Therefore, it is necessary to design Mg alloys with excellent mechanical, wear, and corrosion properties. The addition of rare-earth (RE) elements in Mg alloys results in weakening of the recrystallization texture, which improves formability, precipitation hardening and enhances its resistance to corrosion and tribological properties owing to the solid solution strengthening as well as increased melting temperatures of the second phase. Dysprosium (Dy) is one of the RE elements with many advantages as an alloying element with Mg, such as microstructure refinement, precipitation hardening, and minimal electrochemical potential difference.

Furthermore, the micro-alloying of La in Mg alloys significantly improves the mechanical and corrosion properties. Thus, Dy and La are potential alloying elements for developing novel Mg-RE alloys. Binary alloy Mg-10Dy and ternary alloy Mg-10Dy-0.7La were developed through casting. In the current dissertation, the effect of 0.7 wt.% La addition on mechanical, wear and corrosion behavior is investigated to evaluate the potential of these alloy systems.

Optimization of the microstructure and properties of the alloys were carried out through solution treatment and aging treatment. The potential of minor La addition in modifying the texture and recrystallization behavior of cold-rolled Mg-10Dy (wt.%) alloy was investigated. The samples were rolled and subsequently annealed at 350°C for varying time intervals. La addition was found to be significantly effective in enhancing the contraction and double twinning. This eventually resulted in faster recrystallization kinetics, finer grain size and weaker texture upon annealing in an Mg-Dy-La alloy

compared to Mg-Dy alloy. The Johnson-Mehl-Avrami-Kolmogorov (JMAK) model was employed to capture the evolution of recrystallization in both the alloys. A good agreement between model predictions and experimental results was obtained.

The effect of a small La addition on Mg-10Dy alloy has been studied using isothermal aging at 120°C. A combination of scanning transmission electron microscope (STEM) imaging and high-angle annular dark-field (HAADF) based electron tomography has been used to characterize the precipitates.  $\beta'_F$  and  $\beta'$  precipitates were identified, where  $\beta'_F$  precipitates form a bridge connecting two  $\beta'$  precipitates, thus forming a continuous network of precipitates. This network results in a significant increase in hardness.

Further, the effect of minor La addition on the wear behavior of as-cast Mg-RE alloy (Mg-10 wt.%Dy) was investigated in dry sliding conditions at different loads. The addition of RE elements to the Mg alloys effectively improves wear resistance at different loads. The experiments were performed using a ball-on-disc tribometer with a steel ball counterface as a function of normal load and constant sliding velocity. The wear surfaces were analyzed using a 3D profilometer and field emission scanning electron microscopy (FESEM) to investigate wear rate and wear mechanisms. It was observed that due to the formation of a stable oxide, surface layers and improved hardness of La containing alloy, the wear rate was significantly lower than the Mg-10Dy alloy at different applied normal loads. Abrasion, delamination, oxidation, and plastic deformation were established as the governing wear mechanisms.

The novel Mg alloy (Mg-10Dy-0.7La) was studied to have an excellent combination of corrosion and mechanical properties at room temperature (RT). In the automotive sector, RT and high-temperature corrosion investigation in chloride and cooling media are required for its wide applicability in automotive engine components. A combination of immersion test, potentiodynamic polarization and electrochemical impedance measurements was

utilized to evaluate the corrosion behavior under chloride and ethylene glycol (EG) media. The results suggest that Mg-10Dy-0.7La alloy has a considerably enhanced corrosion resistance as compared to AZ91 Mg alloy. This was attributed to higher activation energy and enhanced density of oxides ( $\text{Dy}_2\text{O}_3$ ,  $\text{La}_2\text{O}_3$ , MgO and  $\text{MgCO}_3$ ) in the former. In summary, the present study reports development of novel Mg-10Dy-.7La alloys with improved mechanical, wear, and corrosion properties for automotive applications.



## सार

मैग्नीशियम (Mg) मिश्र धातुओं ने अपने बेहतर ताकत-से-वजन अनुपात के कारण मोटरवाहन (ऑटोमोबाइल) उद्योग में एल्यूमिनियम मिश्र धातुओं के लिए एक संभावित प्रतिस्थापन पदार्थ के रूप में महत्वपूर्ण ध्यान आकर्षित किया है। हालांकि, खराब संक्षारण प्रतिरोध विभिन्न इंजीनियरिंग अनुप्रयोगों में उनके उपयोग को प्रतिबंधित करता है और इस प्रकार, इसमें काफी सुधार करने की आवश्यकता है। इसलिए, उत्कृष्ट यांत्रिक, घिसाव और संक्षारण गुणों के साथ मैग्नीशियम मिश्र धातुओं का रचना करना आवश्यक है। मैग्नीशियम मिश्र धातुओं में 'दुर्लभ मृदा धातुएँ' (RE) के जुड़ने से पुनः क्रिस्टलीकरण संव्युति कमजोर हो जाती है, जो ठोस विलयन को सुदृढ़ करने के साथ-साथ दूसरे प्रावस्था के पिघलने के तापमान में वृद्धि के कारण अभिरूपणीयता को बेहतर बनाता है, अवक्षेपण सख्त बनाना और संक्षारण गुणों और धातुश्रांतिकी गुणों के प्रतिरोध को बढ़ाता है। डिस्प्रेसियम (Dy) दुर्लभ मृदा धातुएँ में से एक है जिसमें मैग्नीशियम के साथ एक मिश्र धातु तत्व के रूप में कई फायदे हैं, जैसे कि सूक्ष्म संरचना शोधन, अवक्षेपण कठोरण, और न्यूनतम विद्युत रासायनिक विभवांतर।

इसके अलावा, मैग्नीशियम मिश्र धातुओं में लैंथनम की सूक्ष्म-मिश्र धातु यांत्रिक और संक्षारण गुणों में काफी सुधार करती है। इस प्रकार, डिस्प्रेसियम और लैंथनम (La) एक विलक्षण Mg-RE मिश्र धातु विकसित करने के लिए संभावित मिश्र धातु तत्व हैं। दोहरा मिश्र धातु Mg-10Dy और त्रिगुट मिश्र धातु Mg-10Dy-0.7La को ढलाई के माध्यम से विकसित किया गया था। वर्तमान शोध प्रबंध में, इन मिश्र धातु प्रणालियों की क्षमता का मूल्यांकन करने के लिए यांत्रिक, घिसाव और संक्षारण व्यवहार पर 0.7 wt.% La जोड़ के प्रभाव की जांच की गई है।

विलयन और काल दृढ़ीभवन प्रक्रिया के माध्यम से मिश्र धातुओं के सूक्ष्म संरचना और गुणों का इष्टतमीकरण किया गया। अतिस बेल्लिता Mg-10Dy (wt.%) मिश्र धातु की संव्यूति और पुनः क्रिस्टलीकरण व्यवहार को संशोधित करने में मामूली La संकलन की क्षमता की जांच की गई। नमूनों को बेल्लित किया गया और तत्पश्चात् अलग-अलग समय अंतराल के लिए 350 °C पर तापानुशीतित किया गया। La संकलन संकुचन और युग्मअ यमलन को बढ़ाने में काफी प्रभावी पाया गया। यह अन्ततोगत्वा Mg-Dy मिश्र धातु की तुलना में Mg-Dy-La मिश्र धातु में तापानुशीतल पर तेजी से पुनः क्रिस्टलीकरण बलगतिकी, सूक्ष्मतर रेणु आमाप और दुर्बल संव्यूति के परिणामस्वरूप हुआ। जॉनसन - मेहल - अवरामी - कोलमोगोरोव (जेएमएके) मॉडल को दोनों मिश्र धातुओं में पुनः क्रिस्टलीकरण के विकास को पकड़ने के लिए नियोजित किया गया था। मॉडल पूर्वानुमान और प्रयोगात्मक परिणामों के बीच एक अच्छा समझौता प्राप्त होता है।

120 °C पर समतापीय काल दृढ़ीभवन का उपयोग करके Mg-10Dy मिश्र धातु पर थोड़ा सा La संकलन के प्रभाव का अध्ययन किया गया है। अवक्षेपण की विशेषता को चिह्नित करने के लिए स्कैनिंग ट्रांसमिशन इलेक्ट्रॉन माइक्रोस्कोप (एसटीईएम) इमेजिंग और हाई-एंगल एनुलर डार्क-फील्ड (एचएएडीएफ) आधारित इलेक्ट्रॉन टोमोग्राफी के संयोजन का उपयोग किया गया है।  $\beta'_F$  और  $\beta'$  अवक्षेपों की पहचान की गई, जहां  $\beta'_F$  अवक्षेप दो अवक्षेपों को जोड़ने वाला एक पुल बनाते हैं  $\beta'$ , इस प्रकार अवक्षेपों का एक अविरल जालक्रमण बनाते हैं। इस जालक्रमण के परिणामस्वरूप कठोरता में उल्लेखनीय वृद्धि होती है।

इसके अतिरिक्त, विभिन्न भारों पर शुष्क स्खलन स्थितियों में ढलाई Mg-RE मिश्र धातु (Mg-10 wt. % Dy) के घिसाव के व्यवहार पर मामूली La संकलन के प्रभाव की जांच की गई। Mg मिश्र धातुओं में RE तत्वों को जोड़ने से विभिन्न भारों पर घिसाव के प्रतिरोध में प्रभावी रूप से सुधार होता है। सामान्य भार और

स्थायी स्खलन वेग के कार्य के रूप में इस्पात बॉल प्रतिरूप के साथ बॉल-ऑन-डिस्क ट्राइबोमीटर का उपयोग करके प्रयोग किए गए थे। घिसाव की दर और घिसाव के प्रक्रिया की जांच के लिए घिसाव की सतहों का विश्लेषण 3 डी प्रोफिलोमीटर और क्षेत्र उत्सर्जन स्कैनिंग इलेक्ट्रॉन माइक्रोस्कोपी (एफईएसईएम) का उपयोग करके किया गया था। यह देखा गया कि एक स्थिर ऑक्साइड, सतह परतों और La युक्त मिश्र धातु की बेहतर कठोरता के कारण, घिसाव की दर अलग-अलग लागू सामान्य भारों पर Mg-10Dy मिश्र धातु की तुलना में काफी कम थी। घर्षण, विपटलन, उपचयन, और सुघटय विरूपण को अधिनियंत्रक घिसाव के प्रक्रिया के रूप में स्थापित किया गया था।

नवीन Mg मिश्र धातु (Mg-10Dy-0.7La) का अध्ययन कमरे के तापमान (RT) पर संक्षारण और यांत्रिक गुणों के उत्कृष्ट संयोजन के लिए किया गया था। मोटरवाहन क्षेत्र में, क्लोराइड और शीतलन माध्यम में RT और उच्च तापमान संक्षारण जांच मोटरवाहन यंत्र घटकों में इसकी व्यापक प्रयोज्यता के लिए आवश्यक है। क्लोराइड और एथिलीन ग्लाइकॉल (ईजी) माध्यम के तहत संक्षारण व्यवहार का मूल्यांकन करने के लिए निमज्जी परीक्षण, पोटेंशियोडायनामिक ध्रुवीकरण और इलेक्ट्रोकेमिकल प्रतिबाधा माप के संयोजन का उपयोग किया गया था। परिणाम बताते हैं कि AZ91 Mg मिश्र धातु की तुलना में Mg-10Dy-0.7La मिश्र धातु में काफी वृद्धि हुई संक्षारण प्रतिरोध है। यह उच्च सक्रियण ऊर्जा और ऑक्साइड ( $Dy_2O_3$ ,  $La_2O_3$ , MgO और  $MgCO_3$ ) के बड़े हुए घनत्व पहला में के लिए जिम्मेदार ठहराया गया था।

संक्षेप में, वर्तमान अध्ययन मोटर वाहन अनुप्रयोगों के लिए बेहतर यांत्रिक, घिसाव और संक्षारण गुणों के साथ नवीन Mg-10Dy-.7La मिश्र धातुओं के विकास की प्रतिवेदन करता है।



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