Experimental and Microstructural Investigation on the Mechanism and Phenomenological Modelling of Stress Relaxation Behaviour for Ductility Improvement in SS316L Stainless Steel and Pure Magnesium

by

Anand Varma

DEPARTMENT OF MATERIALS SCIENCE AND ENGINEERING

Submitted

In fulfilment of requirements of the degree of Doctor of Philosophy

INDIAN INSTITUTE OF TECHNOLOGY DELHI

JULY 2022

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CERTIFICATE

This is to certify that the thesis entitled "**Experimental and Microstructural Investigation on the Mechanism and Phenomenological Modelling of Stress Relaxation Behaviour for Ductility Improvement in SS316L Stainless Steel and Pure Magnesium**" being submitted by Mr. ANAND VARMA to the Indian Institute of Technology Delhi for the award of the degree of **DOCTOR OF PHILOSOPHY** 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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Acknowledgments

"Expressing gratitude is one of the simplest yet most special and powerful thing humans can do for each other." ***- Randy Pausch***

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Anand Varma

Abstract

Formability improvement has been in focus in view of commercial benefits, forming intricate shapes and improve in strength to weight ratio. Research in this area has spawned along many avenues, one of which is formability improvement through manufacturing optimisation.

Room temperature formability has been improved with the introduction of non – linear and time dependent slide motion. Use of non-conventional punch motion has been found to improve drawability over traditional V - shaped punch motion. These studies show that altering the strain path provides an effective way forward in improving formability of metals. Intermittent stopping of a typical tensile test results in stress drop and is referred to as stress relaxation. Such intermittent stops either during a tensile test or during sheet metal forming process, has shown improvement in ductility of the deforming samples.

Stress relaxation test is one of the transient tests and refers to the reduction of applied stress with time in a pre-stressed material. The stress drop behaviour has been extensively studied to evaluate various mechanical and metallurgical parameters related to thermally activated plastic deformation such as internal stress and activation volume. However, the contribution of stress relaxation to improvement in ductility has not been studied extensively.

The present work aims to understand the underlying mechanism of improvement in ductility due to stress relaxation. The work approaches the above statement by carrying out a) systematic uniaxial tensile stress relaxation and repeated stress relaxation tests in SS316 stainless steel and pure magnesium, b) microstructural characterization, and c) modelling the stress drop data obtained through stress relaxation tests.

The study also introduces a novel technique where a combination of macro indentation stress relaxation test and nanoindentation to understand the underlying mechanism. In addition, uniaxial stress relaxation test was carried out at micro scale in-situ in a scanning electron microscope to capture the microstructural changes during the test. With the data obtained through microstructural characterization, the novel technique and in-situ tests, the study propose and verify the underlying mechanism of improvement in ductility through stress relaxation.

Finally, post reviewing the existing models used to model the stress drop data, the study comes up with an advanced phenomenological model that not only overcomes the limitation of existing models but also is in line with the proposed mechanisms.

सार

व्यावसायिक लाभ, जटिल आकार बनाने और वजन अनुपात में ताकत में सुधार के मद्देनजर फॉर्मेबिलिटी सुधार पर ध्यान केंद्रित किया गया है। इस क्षेत्र में अनुसंधान ने कई रास्ते पैदा किए हैं, जिनमें से एक विनिर्माण अनुकूलन के माध्यम से निर्माण क्षमता में सुधार है।

सामान्य तापमान फॉर्मेबिलिटी को गैर-रेखीय एवं समय पराधीन स्लाइड मोशन के द्वारा सुधारा गया है। गैर-पारंपरिक पंच मोशन का उपयोग पारंपरिक वी-आकार की पंच मोशन पर कर्षणीयता में बेहतर पाया गया है। इन अध्ययनों से पता चलता है कि विकृति पथ को बदलना, धातुओं की फॉर्मेबिलिटी में सुधार करने का एक प्रभावी तरीका है। एक विशिष्ट तन्यता परीक्षण को आंतरायिक रोकने से प्रतिबल कम होता है और इसे स्ट्रेस रिलैक्सेशन के रूप में जाना जाता है। इस तरह के आंतरायिक कर, तन्यता परीक्षण के दौरान या शीट मेटल बनाने की प्रक्रिया के दौरान, विकृत नमूनों की लचीलापन में इज़ाफ़ा दिखाता है।

स्ट्रेस रिलैक्सेशन परीक्षण क्रमांतर परीक्षणों में से एक है और पूर्व-तनाव वाले पदार्थो में समय के साथ लागू प्रतिबल में कमी को संदर्भित करता है। आंतरिक प्रतिबल और सक्रियण मात्रा जैसे थर्मली सक्रिय प्लास्टिक विरूपण से संबंधित विभिन्न यांत्रिक और धातुकर्म मापदंडों का मूल्यांकन करने के लिए प्रतिबल पतन व्यवहार का बड़े पैमाने पर अध्ययन किया गया है। हालांकि, लचीलापन में सुधार के लिए स्ट्रेस रिलैक्सेशन के योगदान का व्यापक अध्ययन नहीं किया गया है।

अतः, स्ट्रेस रिलैक्सेशन से धातु के लचीलेपन मे इज़ाफ़ा कैसे होता है यह समझना इस शोध का लक्ष्य है| इस बात को देखते हुए, शोध को तीन भागो मे आगे बढ़ाया गया (१.) एकाक्षीय तन्यता स्ट्रेस रिलैक्सेशन परीक्षण एवं रिपेटेड स्ट्रेस रिलैक्सेशन परीक्षण शुद्ध मैग्नीशियम और स्टेनलेस स्टील ३१६ मे किये गए. (२.) मैक्रोस्ट्रक्चरल कैरेक्टराइजेशन (३.) प्रतिबल पतन के आंकड़ों का मॉडलिंग एवं अध्ययन|

आधारभूत तंत्र की खोज मे, इस शोध मे प्रथमतः , मैक्रो-इंडेंटेशन बेस्ड स्ट्रेस रिलैक्सेशन एवं नैनोइन्डेन्टेशन का उपयोग किया गया। इसके अलावा, स्कैनिंग इलेक्ट्रान माइक्रोस्कोप मे इन-सीटू टेस्ट की मदद से तन्यता परीक्षण के दौरान स्ट्रेस रिलैक्सेशन की वजह से आने वाले मैक्रोस्ट्रक्चरल बदलाव को वास्तविक काल मे देखा गया। इंडेंटेशन और इन-सीटू के परिक्षण से मिले आंकड़ों एवं जानकारी से स्ट्रेस रिलैक्सेशन के आधारभूत तंत्र को जानने मे तथा इसकी समझ में वृद्धि मिली है।

अंततः, इस शोध मे किये गए परीक्षणों से मिली जानकारी एवं आंकड़ों का बारीकी से अध्ययन करने के पश्यात एक नया घटना-क्रिया मॉडल/नमूना बनाया गया जो शोध मे किये गए परीक्षणों से मिली जानकारी एवं आंकड़ों को सटीक तरीके से समझाता है; और यह नया मॉडल/नमूना, मौजूदा मॉडलस /नमूनों की कमियों की भरपाई भी करता है।

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