Influence of Notch Constraint on Creep Damage Evolution and Rupture Life of Grade 91 Steel

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We hereby declare that We have checked this thesis and, in our opinion, this thesis is adequate in terms of scope and quality for the award of the degree of Master of Science.

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I hereby declare that the work in this thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at Universiti Malaysia Pahang or any other institutions.

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ABSTRAK

Untuk mencapai kecekapan maksimum, loji janakuasa arang batu perlu beroperasi pada suhu dan tekanan yang tinggi. Semasa operasi, komponen janakuasa terdedah kepada persekitaran rayapan yang boleh mendorong berlakunya kegagalan komponen yang tidak diingini. Ramalan kegagalan secara rayapan bagi keluli pada suhu tinggi memerlukan pengujian dibawah julat tegasan dan suhu tertentu yang biasanya mengambil masa yang lama serta memerlukan peralatan atau mesin yang boleh bertahan untuk tempoh masa tersebut. Justeru, usaha untuk membangunkan alternatif atau cara baharu bagi mengurangkan masa serta kos pengujian sedang giat dijalankan. Tambahan pula, komponen ini biasanya dibebani tegasan pada beberapa paksi disebabkan oleh ketidakseragaman permukaan dan bentuk komponen. Oleh itu, kajian ini akan memfokuskan kepada penyiasatan dan penilaian tingkahlaku kegagalan rayapan, kesan kekangan takuk kepada kerosakan dan tempoh masa sebelum kegagalan rayapan berlaku sepenuhnya, dan membangunkan model ramalan rayapan bagi keluli Gred 91. Ujian rapayan dijalankan ke atas spesimen tanpa takuk dan spesimen bertakuk yang mempunyai tahap ketajaman 2.28 dan 4.56. Ujian ini dilakukan pada suhu 600°C dengan julat tegasan 160-190 MPa untuk spesimen tanpa takuk dan 210 – 240 MPa untuk spesimen bertakuk. Selain itu, analisis unsur terhingga bersama model berasaskan terikan juga telah digunakan untuk membuat ramalan kegagalan rayapan dan evolusi kerosakan di bawah pengaruh tegasan. Oleh kerana data yang diperolehi daripada ujian rayapan adalah terhad, data rayapan tambahan telah diambil daripada kajian literatur untuk memformulasi model bahan dan model kerosakan berasaskan kemuluran Monkman-Grant. Semasa analisis ini, pengurangan kemuluran bahan yang disebabkan oleh takuk dianggar menggunakan model pertumbuhan rongga berdasarkan cadangan daripada Cock dan Ashby. Ubah bentuk lengkung rayapan yang diperolehi daripada ujian rayapan ke atas kedua-dua jenis spesimen menunjukkan berlakunya tiga peringkat rayapan iaitu peringkat utama, pertengahan dan akhir. Ubah bentuk peringkat pertengahan dilihat mendominasi berbanding peringkat-peringkat rayapan yang lain. Pada paras tegasan bersih yang sama, keputusan analisis menunjukkan tempoh masa sebelum kegagalan rayapan bagi spesimen bertakuk adalah lebih lama berbanding spesimen tidak bertakuk. Hal ini menunjukkan berlakunya kesan 'diperkuat melalui takuk'. Selain itu, keputusan analisis yang dijalankan menunjukkan tegasan 'von-Mises' mempengaruhi tempoh masa kegagalan rayapan. Pemeriksaan ke atas permukaan patah spesimen tanpa takuk pula mendedahkan, lesung mulur mendominasi. Untuk spesimen bertakuk pula, apabila tahap ketajaman bertambah, lesung mulur yang bersaiz lebih kecil berkumpul di kawasan berdekatan takuk. Ini menunjukkan berkurangnya ubah bentuk tidak anjal adalah sedikit dan rayapan berlaku pada kadar yang terhad. Tempoh masa keseluruhan rayapan yang diperolehi daripada analisis unsur terhingga didapati hampir sama dengan data yang diperolehi daripada ujian rayapan. Semua data tempoh masa rayapan ini berada pada paras tidak melebihi julat ± faktor 2. Selain itu, tegasan tiga paksi dan terikan rayapan didapati mempengaruhi lokasi berlakunya permulaan kerosakan. Lokasi ini adalah konsisten dengan kawasan berlakunya ubah bentuk tidak anjal terhad yang diperolehi semasa pemeriksaan permukaan patah. Usaha telah diambil untuk membangunkan model ramalan berasaskan tekanan berdasarkan peraturan kuasa Norton bagi meramalkan hayat rayapan. Perbandingan di antara ujian rayapan dengan analisis unsur terhingga dan peraturan kuasa Norton keputusan yang hampir sama. Secara kesimpulannya, kehadiran takuk memberi kesan kepada ubah bentuk rayapan dan tempoh masa kegagalan rayapan untuk keluli Gred 91. Model rayapan yang dicadangkan dalam kajian ini juga didapati memadai untuk meramal tempoh masa kegagalan rayapan di bawah pengaruh tahap ketajaman takuk yang berbeza.

ABSTRACT

Coal-fired power plants must operate at higher temperatures and pressures to achieve maximum efficiency. During operation, components are exposed to a creep environment that can lead to catastrophic failure. Predicting the creep rupture life of high-temperature steel components requires hours of robust long-term testing over a range of stresses and temperatures. Considerable effort has been made to develop alternative methods that reduce the time and cost of testing. In fact, components are usually under a multiaxial state of stress due to irregularities caused by curvatures, edges, and notches. The present work focused on evaluating the creep behaviour, the effect of notch constraint on creep damage and rupture life, and the development of a prediction model of Grade 91 steel. Creep tests were performed on smooth and notched specimens having the acuities of 2.28 and 4.56. The tests were conducted at 600 °C under different stress levels ranging from 160 MPa to 190 MPa for smooth specimens and from 210 MPa to 240 MPa for notched specimens. In addition, finite element analysis was performed in conjunction with the strain-based ductility exhaustion model to predict the creep rupture life and damage evolution under the influence of different stress states. Due to the limited data obtained from the experiment, additional data from the literature were used to formulate the constitutive material and damage model incorporating Monkman-Grant ductility. The reduction in ductility induced by the notch was estimated using the Cock and Ashby void growth model. The creep curve obtained from the creep tests shows all three stages, termed primary, secondary, and tertiary, for both specimens. The secondary stage appears to be dominant in all three stages. Analysis of creep life under the influence of net stress showed that the notched specimen had a longer creep life than the smooth specimen at the same stress level, indicating a "notch strengthening" effect. The von-Mises stress was found to control the rupture life. Fractographic examination exposed that ductile dimples predominated in the smooth specimen. For the notched specimen, as the notch acuity increased, the region adjacent to the notch showed shallow dimples, indicating less plasticity and limited creep deformation. Furthermore, the rupture time calculated by finite element analysis also showed good agreement with the experimental data for both short- and long-term creep regimes. All the rupture time data fall within the ± factor of 2. It was also found that the location of damage initiation is strongly influenced by the triaxiality and equivalent creep strain. This location was consistent with the lower plasticity region on the rupture surface of the crept sample during the fractography examination. In conclusion, the presence of a notch affects the creep deformation, damage, and rupture life of Grade 91 steel. The proposed model proves to be adequate for predicting the creep life at different notch acuities. An effort has been made to develop a stress-based prediction model based on Norton's power law to predict the creep rupture life under the influence of multiaxial-stress states. Comparison of the experimental results with the finite element analysis and Norton's power law shows a good agreement. In conclusion, the presence of a notch affects the creep deformation, damage, and rupture life of Grade 91 steel. The proposed model proves to be adequate for predicting the creep life at different notch acuities.

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