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A review of creep deformation and rupture mechanisms of low Cr-Mo alloy for the development of creep damage constitutive equations under lower stress

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Abstract— *This paper presents a review of creep deformation and rupture mechanisms of low Cr-Mo alloy for the development of its creep damage constitutive equations under lower stress level. The existing phenomenological type of creep damage constitutive equations, proposed and developed by Hayhurst, do suffer the deficiency of inaccuracy in predicting the creep strain under multi-axial situation. Furthermore, it was not developed specifically for low stress. The paper reports a critical review on the cavity nucleation and the cavity growth, the deformation mechanisms and the creep damage evolution characteristics of the low Cr-Mo alloy at the temperature ranging from 723K to 923K (450 ℃ ~650 ℃), particularly under low stress level (*$0.2\sim0.4\ \sigma_Y$*), to form the physical base for the development of creep damage constitutive equation. It covers the influence of the stress level, states of stress, and the failure criterion.*

Keywords: cavitation, creep damage, ductility, low Cr-Mo alloy, stress level, stress state

1 Introduction

Low Cr-Mo alloy steel is widely used for steam pipeworks in the power generation industry, particularly in fossil fuel plants and nuclear reactors at elevated temperatures of 723K-823K (450℃-550℃) and varying stress levels of 40MPa-200MPa. This steel is selected since it offers the necessary creep strength at optimal cost. A number of service experiments were reported at the temperature range of 723K-923K (450℃-650℃) and at varying stress levels of 30MPa-350MPa [1]. The lower stress level is associated with the expected long life of power generation installation.

Clearly evidences from the industry and institutions show that a new set of creep damage constitutive equations is required to be developed to depict the mechanical damage behavior and rupture lifetime [2-4].

The most popular Kachanov-Robatnov-Hayhurst (KRH) formulation was not developed for low stress and cannot depict the creep strain accurately under multi-axial state of stress due to its three-dimensional generation method used [4-6]; moreover, its disadvantages have been reported in detail by Xu and his fellows [4- 6]. In 2004, the European Creep Collaborative Committee (ECCC) [2] established a new project to develop a new set of constitutive equations for low alloy steel because the previous creep model cannot present accurate results for the high temperature industry. Likewise, the same requirement raised by ECCC was raised by the Nuclear Research Index (UK) [3] to ensure the inspection of operated components. In 2012, the simulation results presented in Hosseini *et al.*'s work from the Swiss Federal Laboratories (SFL) shows by using the five predicting creep damage constitutive models the lifetime for lower stress is overestimated; moreover, these creep models cannot depict the tertiary stage which is closely related with lifetime fracture [7]. Therefore, it is important to conduct a critical review on the creep deformation process and rupture mechanisms to firmly establish the foundation for the development of a set of creep damage constitutive equations. At this current stage, the authors believe that for low alloy Cr-Mo steel there is a lack of clarity of the damage processes at low, intermediate, high stress levels and stress states, and also there is a lack of understanding of the microstructure changes during creep services.

In this paper, a critical analysis of creep deformation and rupture under creep stress levels and states at varying constant temperature on the low Cr-Mo alloy, such as 2.25Cr-1Mo (T/P22) steel is reported. It shows that the different stress levels and the stress states have a significant influence on the creep evolution, creep rupture and rupture ductility. Also the physical base for constitutive modeling of creep deformation and damage is given.

2 Effect of stress level under uni-axial creep

The data of the specimens to analyze the creep deformation and rupture processes were extracted from published literatures and research institutions' (universities, companies and high temperature industries) laboratories [1, 8-11].

2.1 Effect of the stress level on creep lifetime

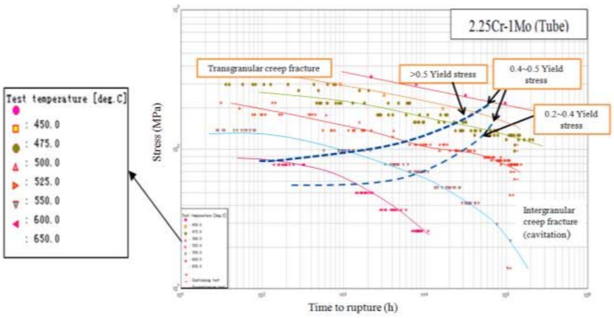

Fig. 1. Stress versus time to rupture at 450,475, 500,525, 550, 600 and 650°C for P22 steel Tubes, adapted from [1]

Figure.1 shows the long-term performance of the transition from higher stresses (> 0.5 σ_Y) to lower stresses (0.2~0.4 σ_Y) for 2.25Cr-1Mo steel depends on the creep rupture time. This figure reflects that at higher stress levels the damage mechanism differs from the low stress levels; this observation indicates that the former constitutive equation modeling based on the analysis of short-term data extrapolation from high stress to low stress is not reliable.

Based on the experimental data of the stress versus time to the rupture, the mechanical relationship could be assumed as:

$$T_f \propto \frac{1}{\sigma - \sigma_0} \tag{1}$$

Where T_f is fracture time, σ_0 is the initial elastic creep stress.

2.2 Effect of the stress level on strain at failure

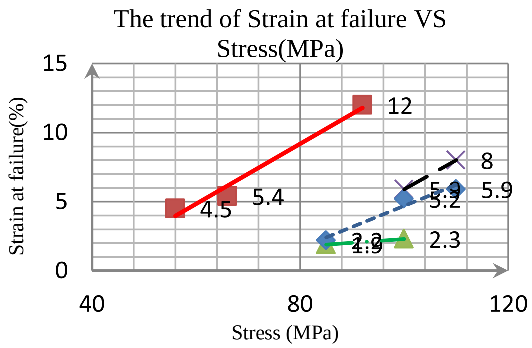

Fig. 2. Experimental data summarized from [11] at the temperature of 640°C (Dash line) and 620°C (Solid line), data collected from ERA report

Figure. 2. shows the strain at failure is increasing as the stress level increases.

Based on the experimental data of strain at failure versus stress, the mechanical relationship could be assumed as:

$$\varepsilon_f \propto A(\sigma - \sigma_0)^n \tag{2}$$

Where, ε_f is fracture strain and σ is external stress, σ_0 is the initial elastic creep stress.

2.3 Effect of the stress level on creep rate

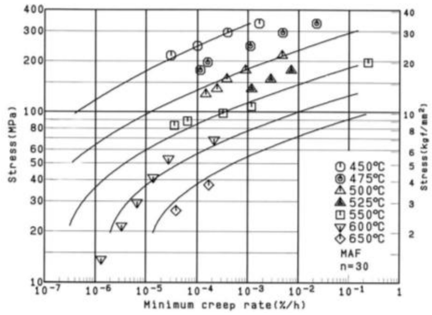

Fig. 3. Stress versus minimum creep rate for P22 steel tubes [10]

Figure. 3 shows the creep behavior of the alloy 2.25Cr-1Mo at 450℃-650℃ (minimum creep rate against stress). The above observation indicates that the stress level does influence the creep behavior of the alloy, having a larger effect on the minimum creep rate. A careful analysis was carried out with the creep data only to check the variation of the minimum creep rate with stress and verify the possibility of expressing the data according to this relation.

Based on the experimental data for stress versus minimum creep rate, the mechanistic relationship could be assumed as:

$$\dot{\varepsilon}_{min} \propto e^{\frac{\sigma - n}{m}} \tag{3}$$

Where, $\dot{\varepsilon}_m$ is minimum creep rate, σ is external stress, n, m are materials parameter.

2.4 Effect of the stress level on ductility

An investigation from experimental aspects shows that at different regime of rupture ductility varies with externally applied stresses [12, 13]. The various ductility regimes are associated with distinct rupture mechanisms which affect the accuracy in investigating the constitutive equation [12-14].

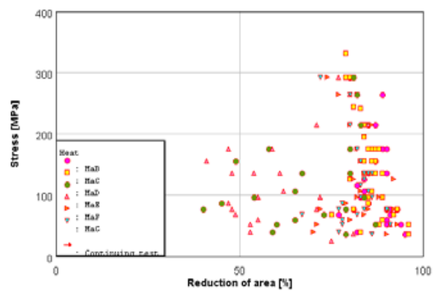

Fig. 4. The stress depends on reduction of area for 2.25Cr-1Mo steel (P22) [1]

Figure. 4 exhibited the ductile failure results of the sample under higher stresses; also, it exhibited low ductility results of the samples under lower stresses level.

ECCC proposed a general trend of elongation versus the log rupture time to depict the effect on ductility [14]. However, this analysis of the effect of the stress level on ductility has been carried out with the reduction of the specimen area, which is due to the effect on the estimate of the true stress based on elongation (likely to be inaccurate as regards the behavior of the region with ultimately failure; such as, necking behavior).

TABLE. I

The summerised ductility equation for dominate mechanism under low stress, intermediate stress and high stress has been slected from ECCC [2]

	Stress level	Dominate mechanism	Model Developer	Ductility Model
Multi-axial rupture ductility model	Under High stress level $> 0.5\sigma_Y$	Grain boundary cavity growth	Marlof [15]	$\frac{\bar{\varepsilon}_f}{\varepsilon_{fu}} = \frac{1}{3}\frac{\sigma_{vm}}{\sigma_m} = \frac{\left(\frac{3}{2}\frac{\sigma_1 - \sigma_m}{\sigma_{vm}}\right)}{\left(3\frac{\sigma_m}{\sigma_{vm}}\right)} = \frac{1}{2}\frac{(\sigma_1 - \sigma_m)}{\sigma_m}$ (4)
			Ewald [16]	$\frac{\bar{\varepsilon}_f}{\varepsilon_{fu}} = \frac{3}{2}\frac{\sigma_1 - \sigma_m}{\sigma_1}$ (5)
			Sheng [17]	$\frac{\bar{\varepsilon}_f}{\varepsilon_{fu}} = \frac{3}{2}\frac{(\sigma_1 - \sigma_m)}{\sigma_{vm}}\left(\frac{\sigma_{vm}}{\sigma_1}\right)^m$ (6)
	Between high and low stress $0.4\sigma_Y \sim 0.5\sigma_Y$	Diffusion controlled cavity growth	Hales [18]	$\frac{\bar{\varepsilon}_f}{\varepsilon_{fu}} = \frac{2}{3}\frac{\sigma_1}{S_1}\left(\frac{\sigma_{vm}}{\sigma_1}\right)^{m+1}$ (7)
	Under Low stress $0.2\sigma_Y \sim 0.4\sigma_Y$	Constrained cavity growth	Spindler [19]	$\frac{\bar{\varepsilon}_f}{\varepsilon_{fu}} = \exp\left[p\left(1 - \frac{\sigma_1}{\sigma_{vm}}\right) + q\left(\frac{1}{2} - \frac{3\sigma_m}{2\sigma_{vm}}\right)\right]$ (8)

2.5 Effect on the characteristic and mechanism under high stress range

At high stress ($0.4\sigma_Y$) the plasticity-controlled cavity growth mechanism is predominant, and there is an increasing rupture strain with the increasing creep strain rate [20, 21]. Under this stress level, the creep rupture occurs based on the wedge-type micro-crack which forms at a triple grain junction and the growth cracks will lead to local grain-boundary separation [20, 21]. Furthermore, failure occurs relatively quicker and is accompanied by elongation deformation at this stress level [20, 21]. The speed of the plastic strain increases rapidly after the external loading is applied. In this condition, the fracture is based on the transgranular cavities [20-22]. Further study shows the creep failure is associated with ductility because the reduction area of the specimens presented is around ¾ of the cross section under high strength condition [20-22].

2.6 Effect on the characteristic and mechanism under moderate stress range

Mohyla and Foldyna [23] report that at 873K (600℃) and at 110MPa ($0.4\text{-}0.5\sigma_Y$), the microstructure of the experimental specimens has seen the elliptical creep cavities, wedge type creep cavities and grain boundary cavities. These results indicate that the creep deformation and rupture behavior is a mixture under the stress level of ($0.4\text{-}0.5\sigma_Y$).

2.7 Effect on the characteristic and mechanism under low stress range

At low stress ($0.2\sim 0.4\sigma_Y$); Parker and Parsons claimed that the nucleation controlled constrained cavity growth is the predominant mechanism [20, 21]; and the fracture is due to the intergranular cavities behavior.

The experimental data which has been plotted as the typical creep curve (creep strain versus lifetime) for low Cr-Mo alloy shows the primary creep stage often occupied approximately 10% of the total specimens' lifetime; however, the tertiary creep stage takes the largest portion of about 80% of the total lifetime [20-22].

In 2004 Dobrazanski classified the creep evolution of low-alloy Cr-Mo steel as the development of cavities, the formation of microcracks and macrocracks which lead to eventual rupture [24, 25]. His research reflects that under low stress level, the 1Cr-0.5Mo steel and T/P23 steel start to nuclei at $0.4\sim 0.6T_R$; the report from EPRI shows similar result that T/P22 steel starts to nuclei at $0.25T_R$[4]; these results seem to contradict the earlier assumption about instant nucleation cited and then used by Dyson [26]. Consequently, this leads to the question of the need to examine the applicability of Dyson's creep damage constitutive equation under low stress.

3 Effect of multi-axial stress state

3.1 Effect of the stress state on notched bar (Tri-axial stress state)

Comparing with the specimens' lifetime under the tensile stress and notched bar (which provide the tri-axial stress state) condition, the life under the tri-axial stress state has been extended due to the reduction of von Mises stress occurred when hydrostatic stress is imposed on uni-axial tension [27].

Needham [28], by comparing smooth and notched specimens (under higher stresses), examined the effect of the stress state on the nucleation rate in two Cr-Mo steels. He found that it is the maximum principal stress, σ_1 which controls the nucleation; likewise, von-Mises equivalent rate is usually less important at high stresses. Currently, the experiment of the creep deformation performance on the notched bar of 2.25Cr-1Mo steel under higher stresses is been conducted [29], the results illustrate that the cavity size around the crack tip increases dramatically, but the cavity number only increases slightly [29].

3.2 Effect of the stress state on ductility

As has been reported by Longsdale and Flewitt [30] and Chuman et al. [31] the hydrostatic stress has great influence on the multi-axial stress; Also they [30, 31] have indicated that the domination multi-axial stress is hydrostatic stress which leads to final creep fracture under lower stresses [31], and the equivalent stress is dominant to evaluate the creep fracture under higher stresses [32]. Therefore, further work will focus on the experimental results which could show the dominate stress that could reflect the multi-axial state influence; If this has been carried out, a hypothesis will be made to derive uni-axial equations set to multi-axial equations set; this has been discussed in section III.

4 Creep rupture criterion

4.1 Summary of the existing creep rupture criterion

TABLE. II

Fuilure criterion been used for low alloy creep damage constitutive equaitons

Types of constitutive equation used for low Cr-Mo alloy	Originated from Year	Failure Criterion
Kachanov [33]	1958	Critical damage D=1
Kachanov Robatnov(KR) [34]	1969	Critical damage ω_c
Lemaitre [35]	1985	Critical damage D_c
Piques [36]	1989	f=porosity
Kachanov –Robatnov-Hayhurst (KRH) [37]	1995	Critical damage ω_c
Dyson and McLean [38]	2000	Critical strain at failure $\varepsilon_f = 5\%$
Qiang Xu's [4]	2000	Critical damage ω_c
Michel [39]	2004	limit load $\lVert\vec{P}_L(\sigma_0)\rVert$
Lmaitre and Desmorat [40]	2004	Critical damage D_c
Whittaker, Wilshire [41]	2012	Limited activity energy: Q_c^*

Table II summarized the different creep rupture criterion which has been applied in creep damage constitutive equations for low alloy; nevertheless, these creep rupture criteria do not necessarily have clear physical meanings associated with the creep rupture behavior and rupture mechanism [32].

The statistic creep rupture criterion do not have physical meanings and are not able to predict the accurate creep curve and creep deformation behavior [3-5]; therefore, a new consideration of the rupture criterion should be conducted.

4.2 Effect of the low stress level on the cavity nucleation rate and cavity growth rate

Longsdale and Flewitt reported that under lower stresses (55.6, 60.6 and 70.6 MPa, at 873K (600℃)) for 2.25Cr-1Mo steel, the cavity rate of accumulation increases monotonically with time and at a given time. It was greatest for the largest applied stress [30]; the density of the cavity observed on the grain surfaces increased continuously throughout the creep life; its cavity growth rate is slightly increased with the accumulation of time [30] From the experimental observations on the cavity nucleation and cavity growth, Needham [28] found that the functional relationship for cavity nucleation rate, cavity growth rate, and the rupture lifetime for 2.25Cr-1Mo steel and 1Cr-0.5Mo steel are inversely related to maximum principal stress,σ_0, by a power law, under lower stresses; the power law index number is presented in Table. III for these two Grades.

TABLE. III

Summary of stress index for power law behaviour under the low stress [28]

Under low stresses (0.2~0.4 yield stress) MPa			
depends on maximum principal stress	Cavity nucleation rate	cavity growth rate	rupture lifetime
power law stress index	5~7	3.5~4.5	4.8

4.3 Effect of the high stress level on the cavity nucleation rate and cavity growth rate

Kawashima and *et al.* reported that for 2.25Cr-1Mo steel the creep ruptures lifetime depends on the cavity nucleation rate and cavity growth size [42].

TABLE. IV

The cavity growth rate versus stress in low Cr-Mo alloy, under the high stress [42]

cavity growth rate(m/s)	stress (MPa)
3.16228E-14	117.5
5.62341E-14	127.5
7.49894E-14	145
1.77828E-13	160
3.16228E-13	170
1.77828E+12	190
3.16228E-12	225

Table. IV shows the growth rate increases with the increase of the applied stresses under higher stresses [30]. These results indicate that the cavity growth behavior is associated with the creep rupture behavior and mechanism.

TABLE. V

Summary of stress index for power law behaviour under the low stress [28]

Under intermediate and high stresses (>0.4 yield stress) MPa			
depends on maximum principal stress and equivalent stress	Cavity nucleation rate	cavity growth rate	rupture lifetime
power law stress index	3.5~5	3.5~5	3.5~5

As the cavity nucleation rate is strongly dependent upon the maximum principal stress (under low stress conditions), and dependent upon both of the maximum principal stress and the equivalent stress (under intermediate and high stresses), the rupture lifetime could be predicted from knowledge of the nucleation rate determined under a uniaxial tensile [28]. Therefore, further work will focus on the critical value of the void nucleation rate and the growth rate depending on the creep lives. If this has been carried out, a hypothesis of a new creep rupture criterion will be developed to conduct the physical–based creep rupture behavior and mechanism.

5 Multi-axial stress rupture criterion

The multi-axial stress rupture criterion of low Cr-Mo alloy has been determined from analyses of hollow cylindrical, notched bar and hollow cruciform specimens [27, 30, 42].

From the analyses of the previous experimental data, the results show the maximum principal stress, σ_1, Mises stress σ_{Mises} and hydrostatic σ_H are associated with creep damage process which leading to the rupture [31]. Moreover, the results indicate that the dominated stress system which leading to the intergranular fracture seems to be the hydrostatic stress, and the rupture behavior has a strong dependence on maximum principal stress σ_1; therefore, the equation of the multi-axial stress rupture criterion [30] could be expressed as:

$$\sigma_{eq} = \alpha\sigma_1 + \beta\sigma_{Mises} + \gamma\sigma_H \quad (9)$$

$$\gamma > \alpha > \beta$$

6 Result and discussion

Based on the review of experimental data and the microstructure observation under varying stress ranges and stress states, the new set of creep damage constitutive equation to be developed should satisfy the following requirements which should be able to:

1) represent the transition between lower-shelf intergranular rupture and upper-shelf ductile-transgruanlar rupture as a function of temperature, strain rate, stress and material pedigree;
2) express the mechanistic relationship between applied stress versus time to rupture:

$$T_f \propto \frac{1}{\sigma - \sigma_0} \quad (1)$$

3) reflect the mechanistic relationship between the strain at failure versus stress:

$$\varepsilon_f \propto A(\sigma - \sigma_0)^n \quad (2)$$

4) show the mechanistic relationship between between minimum stress rate and applied stress:

$$\dot{\varepsilon}_{\min} \propto e^{\frac{\sigma - n}{m}} \quad (3)$$

5) depict the dominated constrained cavity growth deformation mechanism under low stress level, $0.2\sigma_Y \sim 0.4\sigma_Y$;
6) depict the dominated plastic hole growth deformation mechanism under high stress, $> 0.5\sigma_Y$;
7) depict the diffusion deformation mechanism stress in between $0.4\sigma_Y$ and $0.5\sigma_Y$;
8) show the effect of the stress states on creep ductility, under multi-axial conditions;
9) show, under lower stresses, the rupture criterion is amalgamated with the cavity density;
10) show, under higher stresses, the rupture criterion is amalgamated with the cavity size;
11) express the multi-axial stress rupture criterion:

$$\sigma_{eq} = \alpha\sigma_1 + \beta\sigma_{Mises} + \gamma\sigma_H \quad (9)$$

$$\gamma > \alpha > \beta$$

7 Conclusion

This paper provides a critical analysis of the obtained experimental observation on the creep deformation and the creep damage evolution mechanisms. The requirements of the creep damage constitutive equation in terms of lifetime and strain at failure under a range of stress states and stress levels have been investigated. Further work will focus on the development of the creep damage constitutive equations for low Cr-Mo alloy which could be used in engineering design, or with the finite element continuum damage mechanics methods.

8 References

[1] NIMS, creep data sheet. *National Institute for Materials Sciences*. No. 3B, 1986. [online] available: http://smds.nims.go.jp/cgi-bin/MSDS/factOpen/directv8_en.cgi?key=52 (Accessed on 20/3/2013)

[2] S.R. Holdsworth, G. Merckling, 'Developments in the Assessment of Creep-Rupture Properties' [online].ECCC (2012).http://www.ommi.co.uk/etd/eccc/advancedcreep/SRHGMpap1.pdf (Accessed on 25/3/2012)

[3] Nuclear Research (2010), Nuclear Research Index Section A, Structural Integrity, http://www.hse.gov.uk/nuclear/nri-topics/2012/section-a.pdf. (Accessed on 25/3/2012)

[4] Q. Xu. (2000) Development of constitutive equations for creep damage behaviour under multi-axial states of stress. *Advances in Mechanical Behaviour, Plasticity and Damage*. pp. 1375-1382

[5] Q. Xu., M. Wright. And Q.H. Xu. (2011) The development and validation of multi-axial creep damage constitutive equations for P91. *ICAC 11: The 17th international conference on automation and computing*. Huddersfield, UK. September 10. 2011

[6] Q.H. Xu., Q. Xu., Y.X. Pang, and M. Short (2012). Current state of developing creep damage constitutive equation for 0.5Cr0.5Mo0.25V ferritic steel, The 2nd International Conference on Machinery, *Materials Science and Engineering Applications (MMSE 2012)* 16th-17th, June 2012. Wuhan, China.

[7] E. Hosseini., S.R. Holdsworth and E. Mazza. (2012). Creep constitutive model considerations for high-temperature finite element numerical simulations. *The Journal of Strain Analysis for Engineering Design*. *47*. pp. 341-349

[8] NRIM creep data sheet. *National Research Institute for Metals*. No 11B, 1997

[9] NIMS creep data sheet. *National Institute for Materials Sciences*. No. 36B, 2003

[10] NIMS, creep data sheet. *National Institute for Materials Sciences*. No. 3B, 1986

[11] R.J. Hayhurst, R. Mustata, and D.R. Hayhurst, (2005) Creep constitutive equations for parent, Type IV, R-HAZ, CG-HAZ and weld material in the range 565–640 °C for Cr–Mo–V weldments. *International Journal of Pressure Vessels and Piping*. 82. pp.137–144

[12] R. Hales. (1994) the role of cavity growth mechanisms in determining creep rupture under multi-axial stresses. *Fatigue fracture Engieering Material*. *17*. pp. 579-591

[13] R. Hales. and R.A. Ainsworth. (1995) multiaxial creep-fatigue rules. *Nuclear Engineering and Design, 153(2-3).* pp.257-264

[14] S.R. Holdsworth, and R.B. Davies. (1999) A recent advance in the assessment of creep rupture data. *Nuclear Engineering and design*. pp. 287-296

[15] R. H. Marloff. M. Leven and G.O. Sankey. (1981) creep of rotors under tri-axial tension, proc. *Int. Cof. Om Measurements in Hostile Environments, Brit. Soc. For Strain Measurement*. Newcaslte-upon-Tyne

[16] J. Ewald, (1991) Verminderung des Verformungsvermogen bei mehrachsigen Spanungszustanden im plastichen Zustand und bei Kriechbeanspruchung, *Mat.-wiss. U. Werkstoffech*. *22*.pp. 359-369

[17] S. Seng. (1992) Anwendung von Festigkeishypothesen im Kriechbereich bei mehrachsigen Spannungs-Formanderungszustanden, Dissertation, Universittat Stuttgart

[18] R. Hales. (1994) the role of cavity growth mechanisms in determing creep-rupture under muti-axial stresses. *Fatigue Fract*. Engng. Struct. *17*. pp.279-291

[19] M.W. Spindler. (2004) the multi-axial creep ductility of austenitic stainless steel. *Fatigue. Fract. Engng. Struct. 17*. pp. 279-291

[20] J.D. Parker. and A.W.J. Parsons. (1995), High temperature deformation and fracture processes in 2.25Cr1Mo-0.5Cr0.5Mo0.25V weldments, *International Journals of Pressure Vessels and Piping. 63*, pp.45-54

[21] J.D. Parker. (1995) Creep behaviour of low alloy steel weldments, *International Journals of Pressure Vessels and Piping*, *63*. pp. 55-62

[22] J.D. Parker. and A.W. Parsons. (1994) The tempering performance of low-alloy steel weldments. *International Journals of Pressure Vessels and Piping*, *57*. pp.345-352

[23] P. Mohyla. and V. Foldyna (2009). Improvement of reliability and creep resistance in advanced low-alloy steels, *Materials Science and Engineering: A*, *510–511. (15*). pp. 234-237

[24] J. Dobrzański. (2004) Internal damage processes in low alloy chromium–molybdenum steels during high-temperature creep service, *Journal of Materials Processing Technology*. *157–158*. pp. 297-303

[25] J. Dobrzański, A. Zieliński, M. Sroka, Microstructure. (2009) properties investigations and methodology of the state evaluation of T23 (2.25Cr-0.3Mo-1.6W-V-Nb) steel in boilers application, *32*. pp. 142-153

[26] B. Dyson. (2000) Use of CDM in materials modeling and component creep life prediction, *American Society of Mechanical Engineers. 122(3)* pp. 281-296

[27] M. Fujimoto. M. Sakane. S. Date and H. Yoshia. (2005) Multi-axial creep rupture and damage evalution for 2.25Cr-1Mo Froged Steel, *Soc. Mat. Sci. 54*. pp. 149-154.In Japanese

[28] N. G. Needham. (1983) Cavitation and Fracture in Creep Resisting Steels: Final Report. Commission of the European Communities.

[29] T. Yokobori. A. Jr. (1999) difference in the creep and creep crack growth behavior between creep ductile and brittle materials, *Engineering fracture mechanics.* pp. 61-78

[30] D. Longdale. and P.E.J. Flewitt. (1981) The effect of hydrostatic pressure on the uniaxial creep life of a $2\frac{1}{4}$%Cr1%Mo steel. *Proc. R. Soc.Lond. A 373*. pp. 491-509

[31] Y. Chuman. M. Yamauchi. and T. Hiroe. (2000), Study of evolution procedure of multi-axial creep strength of low alloy steel. *171-174*. pp. 305-312

[32] R.N. Hore and Ghosh. (2011) Computer simulation of the high temperature creep behaviour of Cr–Mo steels, *Materials Science and Engineering: A. 528. Issues 19–20*, pp. 6095-6102

[33] L.M. Kachanov. (1985) Time of the rupture process under creep conditions, *TVZ Akad Nauk SSR Otd Tech*. Nauk 8

[34] Y.N. Rabotnov. (1969) Creep Problems in Structural Members Amsterdam. *North-Holland*

[35] Lemaitre, J. and Chaboche, J.L. (1985). Mécanique des matériaux solides, Dunod, Paris. *Mechanics of Solid Materials*, Springer Verlag, Berlin.

[36] R. Piques. E. Molinie. A. Pineau. (1991) Comparison between two assessment methods for defects in the creep range. *Fatigue and fracture of engineering materials and structures. 14(9).* pp871-885

[37] R.J. Hayhurst, F. Vakili-Tahami, D.R. Hayhurst (2005), Verification of 3-D parallel CDM software for the analysis of creep failure in the HAZ region of Cr–Mo–V crosswelds, International Journal of Pressure Vessels and Piping. 86(8). pp. 475-485

[38] B.F. Dyson, and M. McLean (1990). Modeling the effects of damage and microstructural evolution on the creep behavior of engineering alloys. *ISIJ Int., 30* pp. 802–811

[39] B. Michel. (2004) Formulation of a new intergranular creep damage model for austenitic stainless steels, *Nuclear Engineering and Design. 227(2)*. January, Pages 161-174

[40] J. Lemaitre. R. Desmorat. (2005) Engineering damage mechanics: ductile. Creep. *Fatigue and brittle failures. Springer.* Amsterdam. 2005

[41] M. T. Whittaker. and B. Wilshire. (2013) Advanced procedures for long-term creep data prediction for 2.25 chromium steels. *Metallurgical and materials transactions. 44(1).* Pp. 136-153

[42] F. Kawashima, T. IGRI, T. Tokiyoshi, A. Shiibashi and N. Tada (2004), Micro-macro combined simulation of the damage progress in low-alloy steel welds subject to Type IV creep failure. *47*, pp. 410-418