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Mechanical characterization of a nickel-based superalloy repaired using MicroPlasma and ESD technology

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Abstract

In this work, the possibility using two different technologies to repair industrial flat components made of Waspaloy superalloy was investigated. Specimens present a V notch in the central zone of the gage length, which has been refilled by MicroPlasma and Electro Spark Deposition in order to recover the original thickness of the material. These specimens have been used for a complete mechanical characterization, carrying out static, low-cycle fatigue and creep tests. Finally, results have been compared to base material. Static and low-cycle fatigue test have been carried out at Room Temperature and 538°C, while creep test considered the temperature of 704°C.
Results of uniaxial tensile tests showed that the two repair process have a different effect on the mechanical properties. While MicroPlasma produced a reduced yield stress and tensile strength but a good performance whit respect to the elongation to failure, Electro Spark Deposition assured a better mechanical strength but a reduced elongation to failure.
Low-cycle fatigue properties have been determined carrying out tests at different temperature (Room Temperature and 538°C). Repaired material showed lower fatigue strength and an increase of the data scatter, especially ESD at 538°C.
Finally, creep test carried out on a limited number of specimens allowed establishing some changes about the creep rate and time to failure. MP behaviour was more similar to base material, while ESD show the presence of a marked tertiary creep.

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Keywords: low cycle fatigue; MicroPlasma; Electro Spark Deposition; nickel-base superalloys.

Declaration: Reg. CE N. 428/2009 Export Classification: no export control technology

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1. Introduction

The presence of a localized damage in a large high-cost component could determine the need to substitute it having a high effect on the exercise cost. A possible maintenance strategy is to repair it removing the damage zone and substituting it with welded material or adding new material. The residual life of the component would be increased with evident economic advantages, on condition that the reliability and the safety of the component are not reduced. In a previous work [1], authors considered the possibility to substitute the damaged material with TIG welded material. At this purpose, the modification that static, low-cycle fatigue and creep properties suffers in presence of a weld cord was determined. If TIG represents a well-known and easy-to-use technique, which is easily suitable for use in practical industrial application, other techniques could lead to better performance of the repaired component in terms of reliability and higher mechanical strength.

In this work authors studied the application of two more sophisticated additive technique for the repair of Waspaloy components. As in the previous work, the mechanical performance of the material has been evaluated and compared to the same properties of the base material. In particular static, low-cycle fatigue and creep test have been carried out on specimen obtained by a laminated sheet having a nominal thickness of 3.1 mm. In most cases, fatigue tests have been carried out with applied strain range $\Delta\varepsilon \leqslant 0.6\%$. This kind of low stress level is associated to limited damage process. In this condition, the damage models are generally inapplicable or lead to inconsistent prediction [2-4]. On the other hand, material behaviour at this stress level is very useful for industrial application, since it is close to component working condition. Therefore, simple and quick indicators of the different behaviour performance for static, fatigue and creep properties have been chosen and calculated. The reduction of performances originated by ESD and MP has been estimated by the percentage variation of these indicators.

Nomenclature

$\Delta\varepsilon$	applied strain range
$\Delta\varepsilon_{max}$	maximum applied strain range
$\Delta\varepsilon_A$	strain range at the reference life N_{ref}
ε_c	creep strain
ε_{min}	applied minimum strain
ε_{max}	applied maximum strain
σ_{min}	resulting minimum stress
σ_{max}	resulting maximum stress
$\Delta\sigma$	resulting stress range
$\Delta\sigma_A$	stress range at the reference life N_{ref}
E_T	tangent elastic modulus
H	hysteresis area
N_{ref}	reference life
RT	Room Temperature
R_ε	strain ratio
R	stress ratio

2. Material and experimental procedure

Waspaloy is a conventional Nickel-based superalloy that is subjected to hardening precipitating heat-treating. Waspaloy is widely used in the aeronautical field due to its good strength to corrosion and to high temperature, in particular for the realization of turbine disk, blade and casing. Mechanical strength is comparable to Haynes R-41 and higher than Inconel 718 at temperature higher than 650-705°C [5]. Microstructure is characterized by a face centered cube matrix with dominant precipitates γ’. Ductility of Waspaloy has been studied in [6], showing a reduction starting from room temperature to about 300 °C, an irregular behaviour up to 600 °C and a quick reduction at higher temperature.

Starting from a laminated plate having a nominal thickness of 3.1 mm, specimens for static, fatigue and creep tests have been realized. In the mid-size of the specimen, a symmetrical groove is obtained to be filled with added material. Two different processes were used to repair the material: the first one was Electro-Spark Deposition (ESD) and the second one is MicroPlasma (MP). After the addition of the new material the original geometry of the specimen was restored removing the exceeding material by milling. Finally a PWHT heat-treating was carried out to obtain a homogeneous microstructure. However, thermal cycle of additive techniques, aging heat-treating and final milling introduced specimen distortions, which was not compatible with the standard required for the execution of the mechanical tests, in particular low-cycle fatigue tests. Therefore, specimens have been plastically deformed at room temperature to respect the straightness tolerance. Moreover, specimens were subjected to an ultrasonic non-destructive control and some of the MP specimens showed the presence of detectable defects. Anyway, these defects were acceptable, since they do not alter the mechanical performance of the material.

Flat specimens are not the usual choice to carry out high temperature mechanical test, due to the highest difficulty for a correct load application and for a reliable strain measurement. However, a particular care has been used in order to achieve correct results from the mechanical test. Load application to specimen was obtained through serrated face grip designed and realized in Udimet720. This grip allows the application of a preload to the specimen in order to guarantee the backlash recover, especially during low-cycle fatigue test. Thermal load was obtained through an induction system controlled by an optical pyrometer. The calibration of the pyrometer signal was preliminarily carried out heating a Waspaloy specimen in a three-zone split furnace and comparing temperature reading of the optical pyrometer and of a K thermocouple mounted on the specimen.

Static test has been carried out following the indication of ASTM E8-04 and E21-09 standards, respectively for room temperature (RT) and high temperature 538°C. Sub-size specimen has been used in order to limit the maximum load during test. All the tests are carried out in displacement control imposing a speed of 0.1 and 0.5 mm and repeated on 3 specimens. Test temperature is measured and controlled using the optical pyrometer in the mid-size of the specimen gage length.

Low-cycle fatigue tests are carried out following the indication of ASTM E606-04 standard, using a triangular waveform in strain control and a frequency of 0.5 Hz. Specimen geometry has been changed with respect to the standard indication increasing the fillet radius to a value of 15 mm, in order to avoid failure due to excessive stress concentration [1]. It was verified that this geometry was able to hold compressive strength close to yield strength without showing buckling and transversal deflection of the specimen. All the test are characterized by a strain ratio $R_\varepsilon = \varepsilon_{min}/\varepsilon_{max} = 0$. Applied strain is in the range $\Delta\varepsilon = 0.4\text{-}0.9$ %, therefore plastic deformation is low or absent and the expected fatigue life is relatively high. Run-out level was fixed at 10^5 cycles, after which test is continued in load control using the stabilized cycle stress range. Experimental test plan considers tests at room temperature (RT) and 538°C. Static and low-cycle fatigue tests were carried out on a servohydraulic testing machine 100 kN MTS810, while extensometers used for strain control test have a 10 mm gage length.

Creep tests are carried out on a dead-weight creep machine NORTEST TC50 equipped with adapters for flat specimen [1]. A single stress levels and a temperature of 704°C has been considered. Each test condition has been repeated on three specimens to guarantee the repeatability of the result.

3. Experimental results and discussion

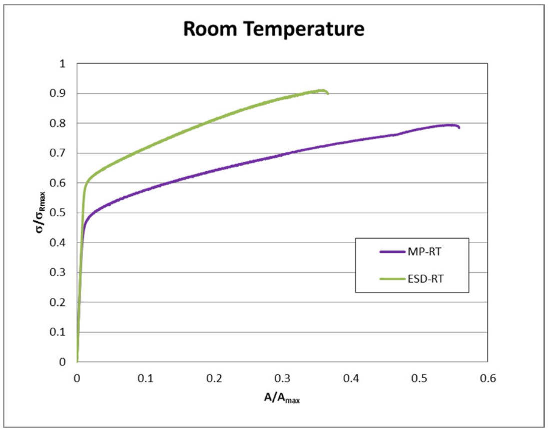
3.1. Static test

Static behavior of ESD and MP specimens are resumed in Table 1, which reports the mean values of the most representative static parameters. All the values have been normalized considering a reference value equal to maximum strength and corresponding to the data of the base material reported in [1].

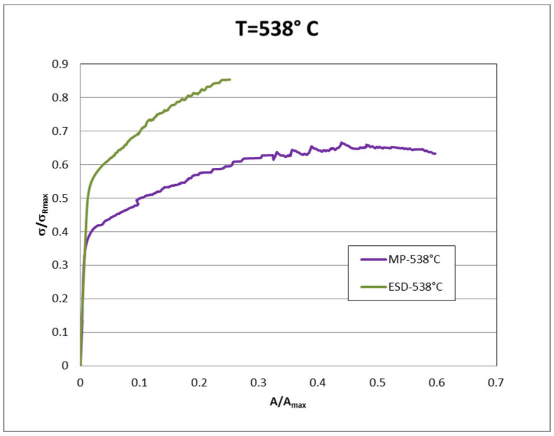
Assuming base material as a reference, the modification of the static behaviour induced by ESD and MP is clearly highlighted. Young modulus is practically not affected by the presence of added material. As expected, a relevant change is represented by the reduction of the plastic zone, with the exception of MP at working temperature of 538°C. Moreover, ESD shows the better performance in terms of achieved stress, which is very close to base material, but the extension of the plastic zone is highly restrained (Fig. 1).

Table 1. Comparison of static properties of ESD and MP specimen against base material.

	Yielding Stress σ_y			Tensile Strenght σ_R			Elongation to failure A			Young Modulus E		
	Base Mat.	*ESD*	*MP*	*Base Mat.*	*ESD*	*MP*	*Base Mat.*	*ESD*	*MP*	*Base Mat.*	*ESD*	*MP*
RT	0.617	0.606	0.474	1.000	0.909	0.782	0.649	0.362	0.532	1.000	0.951	0.942
	var %	-1.73	-23.11	var %	-9.08	-21.84	var %	-44.23	-17.95	var %	-4.94	-5.79
538°C	0.519	0.545	0.401	0.867	0.851	0.655	0.475	0.269	0.528	0.738	0.624	0.702
	var %	5.07	-22.75	var %	-1.79	-24.39	var %	-43.36	11.28	var %	-15.44	-4.84



(a)



(b)

Fig. 1. Static behavior at Room Temperature (a) and 538°C (b).

3.2. Low-Cycle fatigue test

Relevant data about the fatigue tests are resumed in Table 2-5 for each test condition. All data are normalized with respect to a reference value corresponding to the maximum one. Failure is identified by a decay of 10 % of the maximum stress with respect to the stabilized cycle. Specimens that reached the run-out level of 10^5 cycles are marked in bold to indicate that the test was completed in load control up to failure. Two MP specimens at 538°C do not fail in load control and the test was interrupted. In the same tables, the stress range $\Delta\sigma$ and the stress ratio R of the half-life cycle are reported.

As stated in [1], in large part of the test the elastic behaviour is predominant and the loading and unloading curves are practically coincident. Therefore the limited non-linear phenomena that occur during fatigue tests are not suitable to describe the damage process evolution. Also in this case, the use of energy indicator related to hysteresis area to describe damage phenomena has a limited importance for the stress-strain level that is usually present in the working condition of an industrial component. Therefore the extension of scientific theories to the real application, when non-linear phenomena are limited, could be considered an important challenge for the future research.

Nevertheless, it is possible to study the fatigue process in a phenomenological way, determining the different fatigue curves corresponding to the different processes applied to the material. From a quantitative point of view, fatigue behaviour of ESD and MP material is synthetically expressed by the fatigue curves in terms of applied strain range $\Delta\varepsilon$ (Fig. 2) or in terms of measured stress range $\Delta\sigma$ (Fig. 3). In the same graphs, also the fatigue curves of base material are reported [1] for an easy comparison of the effect of the two processes. As expected, the presence of an inhomogeneity of the material due to ESD and MP is clearly highlighted by the reduction of the fatigue performance. At Room Temperature the two processes are practically identical, while at working temperature of 538°C two interesting phenomena appear. First of all, ESD shows the lowest fatigue strength and increased data scatter. Even if ESD does not introduce defects that are detectable with ultrasonic non-destructive control, the prediction of the fatigue behaviour is very difficult. As a practical consequence, this technique is not suitable for a practical repair of any component, at least in point where relatively high stress is applied. The second observation concerns the behaviour of MP specimens at working temperature: a relevant number of MP specimens, in fact, reached 10^5 cycles and two of them (marked by the arrows in Figures 2b and 3b) do not fail also in load control. Nevertheless these specimens have life typical of the high-cycle fatigue, resulting stress are high. Finally, fatigue behaviour is not influenced by the defects detected by ultrasonic control.

Table 2. ESD specimen – Room Temperature: fatigue test results.

	Strain Range	Cycles to failure	Normalized Stress Range	Stress Ratio
	$\Delta\varepsilon/\Delta\varepsilon_{max}$	N_f/N_{max}	$\Delta\sigma/\Delta\sigma_{max}$	$R = \sigma_{min}/\sigma_{max}$
ESD-RT-1	0.795	0.0025	0.8432	-0.71
ESD-RT-2	0.581	0.0058	0.6258	-0.41
ESD-RT-3	0.472	0.0138	0.5303	-0.32
ESD-RT-4	0.456	0.0135	0.5364	-0.39
ESD-RT-5	0.581	0.0135	0.6491	-0.59
ESD-RT-6	0.795	0.0021	0.8108	-0.71
ESD-RT-22	0.363	**0.0779**	0.4360	-0.12
ESD-RT-23	0.473	0.0388	0.5579	-0.32
ESD-RT-25	0.582	0.0054	0.7006	-0.37
ESD-RT-26	0.687	0.0034	0.8524	-0.67

Table 3. ESD specimen – 538°C: fatigue test results.

	Strain Range	Cycles to failure	Normalized Stress Range	Stress Ratio
	$\Delta\varepsilon/\Delta\varepsilon_{max}$	N_f/N_{max}	$\Delta\sigma/\Delta\sigma_{max}$	$R = \sigma_{min}/\sigma_{max}$
ESD-538-24	0.545	0.0065	0.4060	-0.10
ESD-538-27	0.447	0.0054	0.4042	0.12
ESD-538-28	0.429	**0.0876**	0.3233	0.11
ESD-538-30	0.455	0.0051	0.4942	-0.13
ESD-538-31	0.534	0.0008	0.4280	0.02
ESD-538-32	0.565	0.0026	0.5107	-0.26
ESD-538-33	0.562	0.0336	0.4133	0.04
ESD-538-34	0.658	0.0040	0.5101	-0.25
ESD-538-35	0.644	0.0061	0.4997	-0.37
ESD-538-37	0.647	0.0041	0.5646	-0.73

The evaluation of fatigue strength can be quantified interpolating the experimental data to calculate Basquin's law and finally the strain range $\Delta\varepsilon_A$ and the stress range $\Delta\sigma_A$ corresponding to a reference life N_{ref} (Table 6). A careful analysis of these data reveals that the fatigue strength expressed in terms of strain range $\Delta\varepsilon_A$ is increased when temperature test changes from RT to 538°C. On the contrary, fatigue stress in terms of stress range $\Delta\sigma_A$ is reduced in the same condition. This behaviour is showed by the experimental data both for ESD and MP and confirmed what showed for base and TIG welded material [1]. However, not only this observation is not reported in any experimental work existing in literature, but also it is not verified for other experimental data obtained using standard circular specimen. It is very difficult to indicate a clear explanation, but some hypothesis can be formulated. A possibility is to invoke a complex interaction between fatigue and creep damage, which become relevant when applied strain is so low that the load cycle can be considered fully elastic and the test duration is over 24 hours; in this condition the specimen is maintained for a long time at the test temperature and this acts as a further aging heat-treating of the material. Another possibility is to consider that the specimens have been obtained by a laminated plate rather than round bars, as usual: the different influence of the residual stress field existing in the laminated plate could shows its detrimental effect only at Room Temperature, while at higher temperature relaxation phenomena could mitigate the effects. However, no quantitative data or qualitative observations are available to support one hypothesis with respect to others and this constitutes an open problem.

Table 4. MicroPlasma specimen – Room Temperature: fatigue test results.

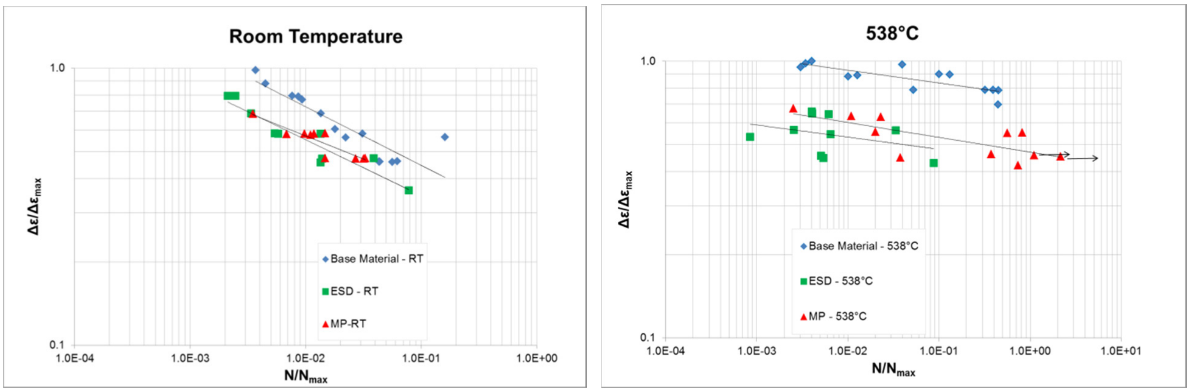
	Strain Range	Cycles to failure	Normalized Stress Range	Stress Ratio
	$\Delta\varepsilon/\Delta\varepsilon_{max}$	N_f/N_{max}	$\Delta\sigma/\Delta\sigma_{max}$	$R = \sigma_{min}/\sigma_{max}$
MP-RT-2	0.582	0.0148	0.6509	-0.70
MP-RT-3	0.581	0.0118	0.6626	-0.65
MP-RT-5	0.685	0.0035	0.7367	-0.71
MP-RT-6	0.578	0.0068	0.7006	-0.78
MP-RT-7	0.581	0.0098	0.6705	-0.69
MP-RT-8	0.473	0.0147	0.5640	-0.43
MP-RT-9	0.472	0.0271	0.5426	-0.39
MP-RT-10	0.473	0.0328	0.5187	-0.47
MP-RT-12	0.472	0.0319	0.5266	-0.37
MP-RT-17	0.574	0.0110	0.6534	-0.67

Table 5. MicroPlasma specimen – 538°C: fatigue test results.

	Strain Range	Cycles to failure	Normalized Stress Range	Stress Ratio
	$\Delta\varepsilon/\Delta\varepsilon_{max}$	N_f/N_{max}	$\Delta\sigma/\Delta\sigma_{max}$	$R = \sigma_{min}/\sigma_{max}$
MP-538-1	0.676	0.0025	0.4844	-0.16
MP-538-4	0.630	0.0230	0.4452	-0.33
MP-538-11	0.448	0.0378	0.4042	-0.24
MP-538-13	0.634	0.0110	0.5444	-0.81
MP-538-14	0.556	0.0201	0.4899	-0.84
MP-538-15	0.461	**0.3736**	0.3178	-0.45
MP-538-16	0.420	**0.7345**	0.3102	0.03
MP-538-18	0.456	**1.1117**	0.3503	-0.46
MP-538-19	0.552	**0.8174**	0.4127	-0.25
MP-538-20	0.452	**2.1505**	0.3336	-0.09
MP-538-21	0.551	**0.5623**	0.4691	-0.36

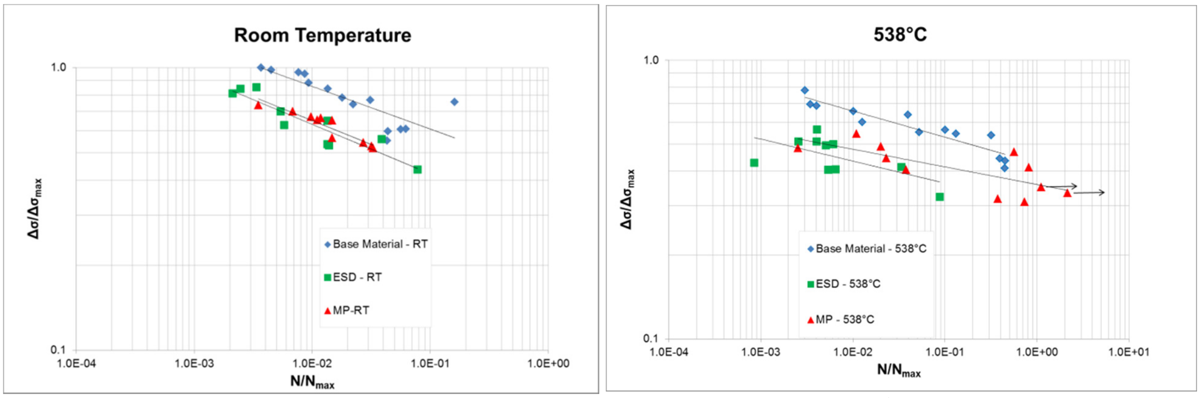
3.3. Creep test

Creep strength of ESD and MP material has been expressed in terms of time to reach a fixed inelastic strain or failure (Table 7). Also in this case data reported in Table 7 are normalized with respect to the maximum measured life and represents the mean values over 3 specimens. It is interesting to observe that MP specimen shows a lower time to reach a fixed strain or failure and the failure happen roughly, without showing the increase of strain rate that usually characterizes the tertiary creep behaviour. If we except the premature failure, creep behaviour of MP can be considered the same of the base material, as showed also for TIG welded specimen [1]. On the contrary ESD specimen shows a marked tertiary creep and higher strain rate (Fig. 4).



(a) (b)

Fig. 2. Comparison of fatigue curves in terms of applied strain range at RT (a), 538°C (b).



(a) (b)

Fig. 3. Comparison of fatigue curves in terms of resulting stress range at RT (a), 538°C (b).

Table 6. Fatigue strength at N_{ref} cycles of ESD and MP specimen against base material.

	$\Delta\sigma_A/\Delta\sigma_{max}$			$\Delta\varepsilon_A/\Delta\varepsilon_{max}$		
	Base Mat.	***ESD***	***MP***	***Base Mat.***	***ESD***	***MP***
RT	0.673	0.475	0.495	0.516	0.399	0.436
	var %	-29.4	-26.4		-22.7	-15.5
538°C	0.565	0.382	0.433	0.862	0.496	0.546
	var %	-32.4	-23.4	0.533	-42.5	-36.7

4. Conclusion

ESD and MP specimens made of Waspaloy have been mechanically tested and static, low-cycle fatigue and creep behaviour have been evaluated. The comparison of the experimental data between these two processes and the base material show that even if ESD showed good static properties, the whole performance of MP specimens assures better mechanical properties. In particular it is to remark the inadequate fatigue behaviour at working temperature of the ESD, which strongly limits its possibility of use.

Table 7. Comparison of creep behaviour of base material and ESD and MP specimen at 427.5 MPa.

	time [h/h$_{max}$]		
σ		427.5 MPa	
N/mm^2	BM	ESD	MP
ε_c = 0.2%	0.0372	0.0065	0.0162
ε_c = 0.5%	0.0976	0.0366	0.0615
ε_c = 1%	0.1919	0.1002	0.1470
ε_c = 2%	0.4047	0.2385	0.3229
failure	1	0.5075	0.3095

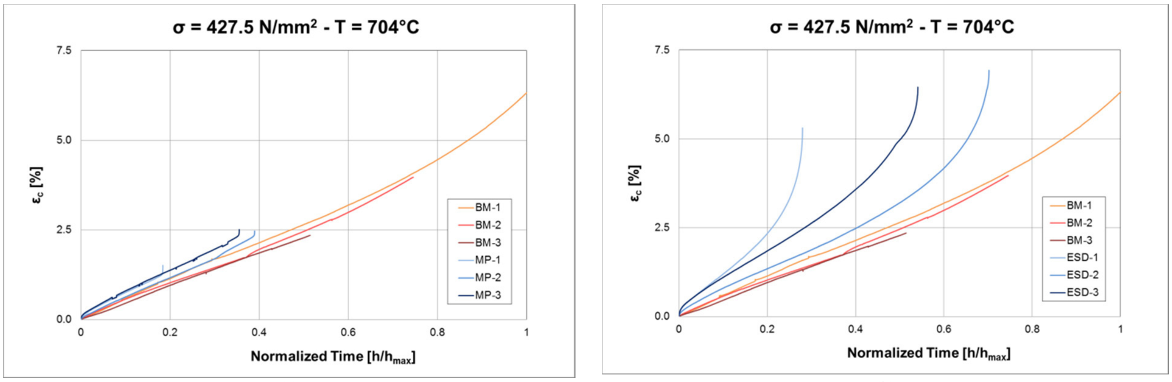


Fig. 4. Comparison of creep deformation against normalized time at 427.5 MPa: MP (a) and ESD specimen (b).

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