Karabük Üniversitesi
Çelik Araştırma ve Geliştirme Dergisi
(JESRED)
e-ISSN: 2757 8224
Cilt 5, Sayı 1
Temmuz 2024, 46-55
İnceleme Makalesi

Karabuk University
Journal of Steel Research and Development
(JESRED)
e-ISSN: 2757 8224
Volume 5, Issue 1
July 2024, 46-55
Review Article

Exploring the Versatility and Affordability of Steel for Environmental Sustainability and Overall Well-Being

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***Received**: 08/05/2024* ***Accepted**: 26/06/2024* ***Published Online:** 01/07/2024*

Abstract
Steel, being the most versatile and cost-effective metallic material, has been scrutinised by researchers as other new metallic materials with superior mechanical properties continue to emerge. Moreover, conventional metallic materials such as aluminium, magnesium, and titanium have been favoured in various engineering applications where lightweight design is crucial. This paper presents experimental results on the reuse of creep-exhausted steel and low-density stainless steel, highlighting their potential to compete with existing conventional metallic materials or newly developed ones like high entropy alloys. The paper argues that steel's availability, versatility, and affordability will continue to position it as the leading metallic material in the years to come. It also provides examples of how steel contributes to environmental sustainability and the overall well-being of the geriatric population. Environmental sustainability and overall well-being are prominent goals within the United Nations' sustainable development agenda.

Anahtar Kelimeler
Creep-exhausted steel; low-density stainless steels; regenerative heat treatment; thermomechanical processing; corrosion; circular economy

Çeliğin Çevresel Sürdürülebilirlik ve Genel Refah İçin Çok Yönlü ve Ekonomik Katkıları

Öz
Çelik, maliyet etkinliği ve çok yönlülüğüyle tanınan bir metalik malzemedir. Araştırmacılar, sürekli olarak üstün mekanik özelliklere sahip yeni metalik malzemeleri incelemektedirler. Özellikle, hafif tasarımın önem kazandığı mühendislik uygulamalarında, alüminyum, magnezyum ve titanyum gibi geleneksel metalik malzemeler tercih edilmektedir. Ancak, çekme-yorulma sonucu kullanılamaz hale gelen çelik ve düşük yoğunluklu paslanmaz çelik gibi malzemelerin, yeni geliştirilmiş metalik malzemelerle rekabet edebilecek potansiyeli bulunmaktadır. Bu makalede, bu malzemelerin yeniden kullanımıyla ilgili deneysel sonuçlar sunulmakta ve çeliğin, mevcut ve yeni geliştirilmiş malzemelerle rekabet edebilecek düzeyde bulunduğu savunulmaktadır. Ayrıca, çeliğin bulunabilirliği, çok yönlülüğü ve ekonomikliği ön plana çıkarılarak, çeliğin önümüzdeki yıllarda da önde gelen metalik malzeme olmaya devam edeceği ifade edilmektedir. Bununla birlikte, çeliğin çevresel sürdürülebilirlik ve yaşlanan nüfusun genel refahına nasıl katkı sağladığına dair örnekler de sunulmaktadır. Bu çalışma, çevresel sürdürülebilirlik ve genel refah gibi önemli hedefler doğrultusunda Birleşmiş Milletlerin sürdürülebilir kalkınma gündemine katkı sağlamaktadır.

Key Words
Çekme-yorulma çelikleri; düşük yoğunluklu paslanmaz çelikler; yeniden kazanımlı ısı işlemi; termomekanik işleme; korozyon; döngüsel ekonomi

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To cite this article: *Michael O. Bodunrin., Exploring the Versatility and Affordability of Steel for Environmental Sustainability and Overall Well-Being, Journal of Steel Research and Development, 5(1), 46-55*

1. Ana Metin

Steel is the second most utilised material after concrete [1]. This is due to its excellent property combinations (high strength, good ductility, god wear resistance, good fatigue properties, just to mention a few), amenability to many processing routes, affordability, and the robustness of the metallurgy of steel. It is quite impossible to imagine a world without iron and steel because the evolution of steel can be considered as the foundation for several industrial revolutions that has been experienced in the world [2]. From staple pins used as stationaries in offices to cutleries used in various homes to structural steels used in construction industries to corrosion resistant steels used in biomedical and chemical industries to creep resistance steels used for high temperature applications, just to mention a few. There is hardly any iconic engineering structure that has been built in the last century without using steel. For example, Burj Khalifa, the tallest building in the world has 39 000 tonnes of reinforced steel [3]. Similarly, SpaceX manufactured a space rocket using stainless steel [4]. Despite its high density, stainless steel was selected for this purpose ahead of composites and other light materials because of its workability, low cost and efficient performance at both cryogenic and elevated temperatures.

In the 1950s, the use of light metallic materials such as aluminium, magnesium, titanium and their alloys became prominent, they were selectively favoured in the fabrication of structural components for the growing transportation industry. The interest in these materials grew further when climate change was linked to emission of green-house-gases from the utilisation of fossil fuels in heavy machineries, cars, trains, and aircrafts. With stringent environmental regulations on emission of green-house gases, the use of light alloys and their composites has continued to gain more ground. Similarly, just after the 1950s, titanium and its alloys became preferred in the biomedical industries until they became the gold-standard materials for making prosthetic implants as we have it today [5]. The use of different grades of stainless steel in the biomedical industry is declining very quickly.

In the last two decades, the emergence of different grades of high entropy alloys and the availability of research funding for this type of research has made researchers, particularly those in the field of physical metallurgy, to focus less on the conventional alloys [6]. It appears that attention given to steel related research is beginning to decline. It appears that enough is known about steel already and focusing on materials like bulk metallic glasses and high entropy alloys seems more challenging and interesting. It appears that the contributions of steel in the society in terms of technological advancement are currently being taken for granted and the desire to develop other metallic materials that will outperform steel has become the central focus of many early and mid-career researchers. While there is nothing wrong with this in principle, it is the opinion of the author that there are quite a number of interesting research problems that affect every one of us, and researchers can leverage on the versatility, affordability, and resilience of steel to tackle these problems. A few examples of such problems will be demonstrated in this paper.

Susceptibility to different forms of corrosion and high density have been the two main disadvantages of iron and steel. For example, plain carbon steels are susceptible to uniform corrosion since the do not form an adherent and protective oxide layer when exposed to corrosive conditions. Even corrosion resistant steel grades, with sufficient amount of Cr and Ni, still undergo localised corrosion such as pitting and crevice corrosion in chloride or sulphate environment or even under atmospheric conditions. These are the conditions where aluminium and titanium alloys have demonstrated superior corrosion resistance. Because ferrous materials are highly dense, they are becoming less favoured in the automotive and aerospace industries where lightweight has become a critical design requirement. Despite these disadvantages, ferrous based materials remain the most investigated and most understood metallic materials, hence they can easily be manipulated to achieve desired properties. In addition, they are readily available and very cheap when compared to other conventional alloys. Consequently, iron and steel have the resilience to compete with existing alternative alloys as well as the emerging ones such as high entropy alloys. This is the main argument in this paper.

In this paper, some of the research on different grades of steels that are currently ongoing in our research group that align with global concerns, particularly in the area of environmental sustainability and general well-being of people, are presented.
In terms of environmental sustainability, there is a global shift towards circular economy model from the usual linear economic model. Example of the research conducted on the reuse of creep-exhausted steels in compliance with the tenets of circular economy model is presented in section 2. Additionally, in section 3, the results obtained from preliminary experiments on the development of new lightweight stainless steels for biomedical application is presented. This new lightweight bio-implant steels are envisaged to contribute towards attaining general well-being of geriatric population in the coming years.

2. REUSE OF CREEP-EXHAUSTED STEEL FOR ENVIRONMENTAL SUSTAINABILITY

As the campaign for sustainable environmental practices continue to increase, a circular economic model has been developed to drive the reuse, reduce and recycling of materials in the manufacturing sectors [10]. This is expected to contribute significantly to the reduction in carbon and water footprints in the environment. In line with this drive, there have been numerous efforts by researchers to extend the service life of steel components used in power plants and rail industries. The aim is to delay the time in which a steel material is taken to scrap yard for recycling purposes. While recyclability is one of the strong attributes of steel, the energy consumed during remelting and subsequent processing of recycled metallic materials is high. It is envisaged that the reuse or repurposing of steel would consume less energy and be more environmentally friendly. Therefore, developing strategies to extend the service life of steel components by reusing them is worth the attention. There have been some research efforts seeking the reuse of creep-exhausted steel components through regenerative heat treatment approach [7] [8].

In the South African context, low alloy 14MoV6-3 and high alloy P91 creep resistant steels are used in power plants due to their high temperature mechanical properties. These alloys are exposed to temperatures ranging from 450-600°C for prolonged hours of about 300 000 hours [8]. These operating conditions induce creep damage which is signified by changing microstructures and deteriorated mechanical properties [8][9]. For P91 steel containing 9-12% Cr, the microstructure consists of ferrite matrix with well-dispersed $M_{23}C_6$ phase and high dislocation density. Exposure to creep damage changes the microstructure such that coarsening of lath martensite around the $M_{23}C_6$ carbides is observed [8]. Additionally, evolution of Laves phases, formation sub grain structure and migration of sub grain boundaries result in depletion of high temperature mechanical properties [8] [9]. The 14MoV6-3 alloy has predominantly ferrite and pearlite grains with fine and evenly distributed MC type carbides that promote creep–rupture strength prior to creep-inducing conditions. After long hours of exposure at 450-600°C, the mechanical properties degrade because the microstructure shows the precipitation of M_2C carbides which reduce solid solution strengthening due to Mo depletion in the matrix [9]. The precipitation of M_6C carbides also reduces creep resistance of the steel [9]. This then leads to decommissioning of the steel components, and they are scrapped for possible recycling. These creep-exhausted steels are dumped for many years without any hope of recycling them.

While recycling is compliant with circular economic model, exploring strategies for reusing these creep-exhausted steel components through regenerative heat treatment or thermomechanical testing techniques may offer superior advantages in terms of energy savings and less emissions for environmental sustainability. We explored both routes in our group and further elaboration on the testing approach and results obtained are presented in Sections 2.1 and 2.2.

2.1. Heat Treatment, Mechanical Testing, Thermomechanical Testing and Microstructural Examination

The regenerative heat treatment parameters were selected based on previous studies [11]. For creep-exhausted P91 steel, normalising was done at 1050°C for 40 min, air cooled, and then tempered at 760°C for 2 hours. The low alloy 14MoV6-3 steel was normalised at 930°C for 1 hour followed by tempering at 720°C for 3 hours. Prior to regenerative heat treatment, the Ac_1 and Ac_3 lines were obtained from Thermo-Calc using the composition of the different steel samples. The microstructures were obtained using Olympus optical microscope or Zeiss Sigma Field Emission Scanning Electron Microscope (FESEM). Prior to microstructural examination standard metallographic procedures were followed and etching was done using Villella's reagent. The microstructure of unused P91 steel and 14MoV6-3 steel were also obtained for comparison. In the case of 14MoV6-3, tensile and impact tests were carried out on the unused, creep-exhausted, and regenerative heat-treated steels for comparison. Thermomechanical testing was evaluated by carrying out hot compression testing on 8mm by 12 mm cylindrical samples for the steel samples under isothermal conditions. Different deformation temperatures (900-1050°C) and strain rates (0.01 -10 s^{-1}) were used. Thereafter, the flow stress was analysed and constitutive parameters such as apparent activation energy for hot working and stress exponent were determined using Arrhenius equation [7].

2.2. Summary of Results

The evidence obtained from comparing the microstructure of unused and regenerative heat-treated steel show that the observed microstructural features differ slightly. For example, in the 14MoV6-3 steel, the unused steel (Fig. 1) has ferrite + pearlite matrix with precipitates within the matrix, and chains of precipitates at the grain boundaries. However, no chain of precipitates was observed at the grain boundaries of the regenerative heat-treated steel sample (Fig. 2). The microstructures of the unused and regenerative heat treated P91 steel show similar features (Figs. 2 and 3), but the prior austenite grain boundaries (PAGBs) are more conspicuous and smaller in the regenerative heat treated P91 steel.

The slight difference in the microstructural features did not have significant influence on the room-temperature mechanical properties of the alloys. As seen in the case of 14MoV6-3 steel in Table 1, the regenerative heat treatment restored the mechanical properties of the creep-exhausted steel. However, the absence of the chains of carbides that precipitate at the grain boundaries in the regenerative heat-treated steel suggest that the steel may not be reused under creep-inducing conditions. This is because these chains of precipitates at the grain boundaries have been reported to pin dislocations and also suppress grain boundary migration at elevated temperatures, hence improving overall creep resistance [9].

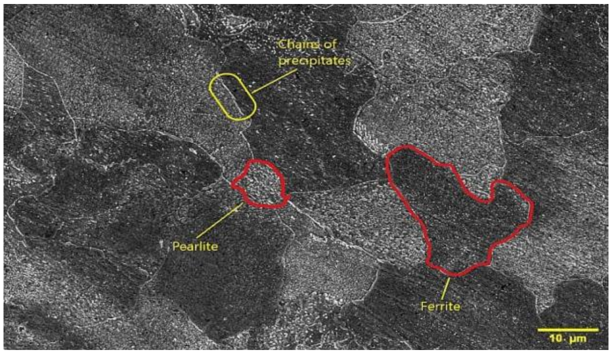


Fig. 1 SEM image showing the ferrite + pearlite microstructure of unused 14MoV6-3 steels with chains of precipitates at the grain boundaries [9]. Yellow ring indicates chains of precipitates at the grain boundaries, while red mark shows ferrite and pearlite phases.

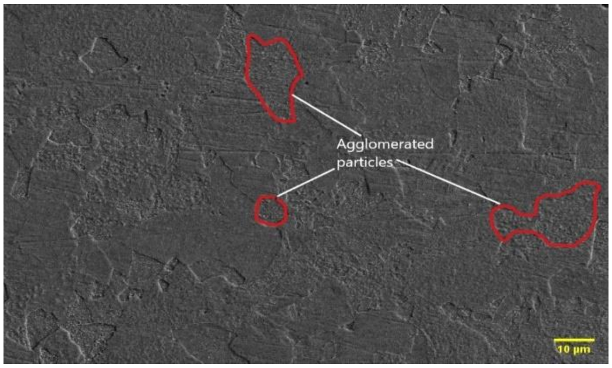


Fig. 2 SEM image showing agglomerated particles in the microstructure of regenerative heat treated 14MoV6-3, no chains of precipitates observed at the grain boundaries [9]. Red mark show agglomerated particles.

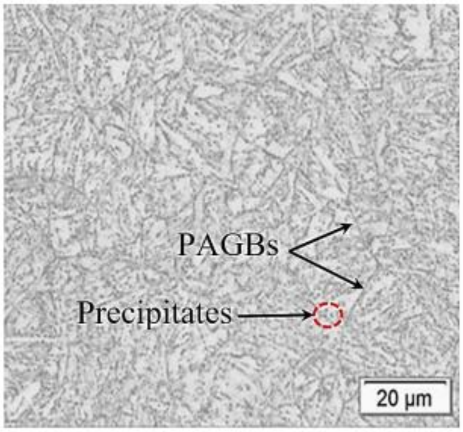


Fig. 3 Optical image showing tempered martensite, precipitates and prior austenite grain boundaries in unused P91 steel [7].

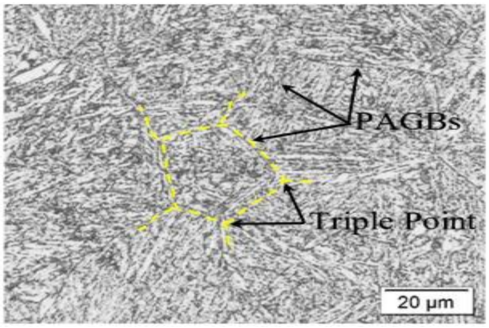


Fig. 4 Optical image showing tempered martensite, and a well-defined prior austenite grain boundaries (PAGBs) with triple point in regenerative heat-treated creep-exhausted P91 steel [7].

Tablo 1. Mechanical properties of 14MOV6-3 steel in different conditions [9]

14MoV6-3 steel conditions	UTS (MPa)	Elongation (%)	Impact (J)
Unused	510±4	28±1	349±6
Creep-Exhausted	569±4	25±2	318±17
Rejuvenated	506±20	29±1	358±0

Since the direct reuse of this regenerative heat-treated steel under creep-inducing conditions may not be possible, one may consider repurposing the rejuvenated steel for other applications, and this may involve shaping process such as machining or hot working. Consequently, the formability of the regenerative heat-treated steel was assessed in comparison with the unused one. Fig. 5 shows that similar deformation mechanism govern the flow behaviour of both the unused P91, and the regenerative heat treated P91 steels. Work hardening dominates at small strain until a saturated stress is reached for the different deformation temperatures. The saturated stress is maintained due to the equilibrium established between the rates of work hardening and flow softening. Dynamic recovery was responsible for the flow softening observed in the P91 steel in both conditions, and this is expected in high stacking fault material like P91 [7].

Despite the similarity in the flow behaviour, the constitutive constants presented in Table 2 show that the regenerative heat treated P91 steel has higher apparent activation energy for hot working (Q_{HW}) and stress exponent (n) than the unused P91 steel. This suggest that regenerative heat treated P91 steel has higher deformation resistance than the unused P91 steel. This may be attributed to the difference in the nature of carbide precipitation in the steel relative to their initial conditions [7]. This requires further investigation using high resolution transmission electron microscopy. Table 3 shows that the peak stress, apparent activation energy for hot working and stress exponent are higher in unused 14MoV6-3 than in the regenerative heat treated one. This indicates that the unused steel has less resistance to deformation and can be attributed to the absence of chains of precipitates at the grain boundaries as previously shown in Fig. 2. These chains of precipitates in the unused 14MoV6-3 steel pinned dislocations and thus induce higher resistance to deformation [9].

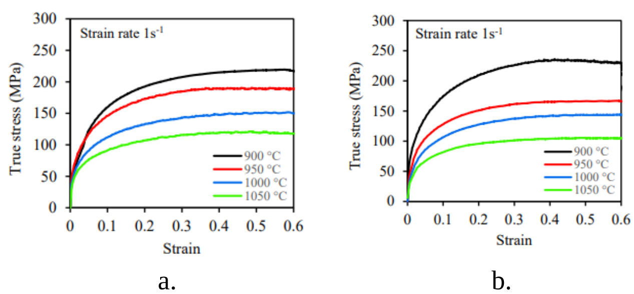


Fig. 5 Flow stress of P91 steel in (a) unused condition, and (b) regenerative heat-treated condition [7].

TABLE 2 Constitutive constants for P91 steel with different initial conditions [7]

P91 conditions	Q_{HW} (kJ/mol.)	n
Unused	473	5.76
Regenerative heat treated	565	6.67

TABLE 3 Peak stress and constitutive constants for 14MoV6-3 steel with different initial conditions [9]

14 MoV6-3 Steel conditions	Peak stress (MPa) @ 900°C and 10 s^{-1}	Q_{HW} (kJ/mol.)	n
Unused	262	439	7.29
Regenerative heat treated	248	312	6.43

The different trends observed in the deformation behaviour of regenerative heat treated P91 and 14MoV6-3 steel indicate that the optimisation of heat treatment parameters for controlled precipitation of carbides is important for deciding whether or not to reuse the steels under creep-inducing applications.

3. DEVELOPMENT OF LOW-DENSITY STAINLESS STEEL AS AFFORDABLE BIO-IMPLANT MATERIAL

By 2050, the world's geriatric population is projected to have doubled, reaching approximately 2.1 billion. About 80% of these people will live in developing countries. Increasing bone fractures and other bone-related diseases have been attributed to aging. Therefore, there is a risk of having unhealthy geriatric population throughout the globe in the next two decades. The cost of implants accounts for more than 50% of medical treatment for bone fractures. This is due to the high cost of titanium which is the gold-standard material for making bio-medical implants like artificial knees and hips. The alternative material that is cheaper is 316L stainless steel, but its high density causes stress-shielding problems in patients, and this often lead to painful and expensive revision surgery. Therefore, targeting a healthy geriatric population in the future requires a proactive approach of developing alternative bio-implant materials that is more affordable than titanium and lighter than 316L stainless steel. This is the thrust for exploring lightweight steel in our research group.

Lightweight steels based on the Fe-Mn-Al-C system was originally developed for automotive applications. A comprehensive review on the development and processing of this class of steel was published by Chen et al. [12]. It is expected that this grade of steel will compete with aluminium alloys and other light metallic alloys in the automotive industry. However, low elastic modulus and poor corrosion resistance are among the challenges limiting the use of these alloys for any commercial scale application. Researchers have reported that the addition of Cr in the range of 3-6 wt.% to Fe-Mn-Al-C offers superior corrosion resistance to some conventional stainless steels. Against this background, the Cr-containing low-density steel was dubbed lightweight or low-density stainless steel (LDSS) by Moon et al. [13]. By considering the low elastic modulus that have been reported on Fe-Mn-Al-C low density steel and the recent improvement in corrosion resistance of low-density steels when Cr is added in controlled amount, we hypothesised that low-density stainless steel may become an alternative to conventional bio-implant alloys like highly-dense 316L stainless steel and highly-priced titanium alloys. A number of preliminary studies are ongoing in our research group to validate this hypothesis.

These studies include assessing the corrosion performance of different grades of low-density stainless steels in simulated body fluids, identifying the main form of corrosion and the mechanism driving it, and developing strategies to improve corrosion resistance in these grades of steel. Further elaboration on the approach and the results obtained are presented in Sections 3.1 and 3.2.

3.1. Alloy Development, Corrosion Testing and Microstructural Control using Thermomechanical Testing

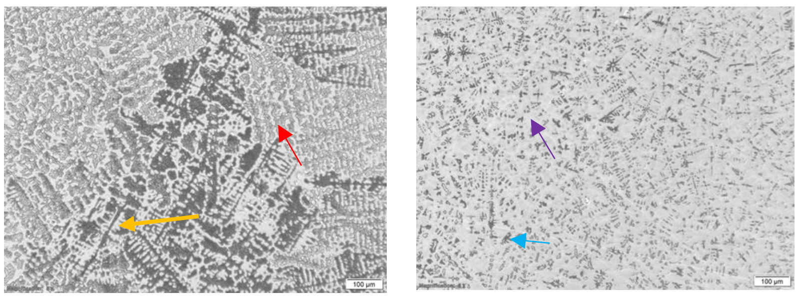
Low-density stainless steels with compositional range of Fe-(20 or 30)Mn - (4 - 15)Al - (0.5 - 1.5)C - 5Cr were developed using electric arc melting. The as-cast LDSS were compared with commercial grade 316L stainless steel. The density of the alloys was at least 14% less than the density of 316L stainless steel depending on the composition. The as-cast LDSS were subjected to microstructural examination using an optical microscope or FESEM. The corrosion behaviour of the alloys was evaluated in two simulated body fluids, 0.9 wt.% NaCl and Hanks Balanced Salt Solution (HBSS). Linear polarisation scans were performed on both commercial grade 316L stainless steel and as-cast LDSS. The corrosion rates were determined following ASTM standard G102-89 [14]. The microstructure of the corroded samples was analysed using FESEM to determine the dominant form of corrosion. Thereafter, thermomechanical processing method was used to control the microstructure of LDSS, and the corrosion tests were repeated on deformed LDSS to evaluate the influence of microstructure on corrosion performance.

3.2. Summary of Results

The microstructure of as-cast Fe-30.9Mn-4.9Al-4.5Cr-0.4C consisted of both dendritic austenite and ferrite phase (Fig.6a), while as-cast Fe-21.3Mn-7.6Al-4.3Cr-1C consisted of an austenitic matrix with M_7C_3 carbides (Fig. 6b) [15]. Fig. 7 show that the corrosion potential of the as-cast LDSS is lower than that of 316L stainless steel in HBSS. This suggests that thermodynamically, the as-cast LDSS is more susceptible to corrosion in HBSS. However, the corrosion rate is lower than that of 316L stainless steel by a factor of 10 *i.e.* Fe-30Mn-15Al-1.5C-5Cr alloy has a corrosion rate of ~0.009 mm/yr. against ~0.086 mm/yr for 316L stainless steel. The low corrosion rate suggests that kinetically, the as-cast LDSS has superior corrosion behaviour in comparison with 316L stainless steel. Similar trend was reported in 0.9 wt.% NaCl solution where corrosion rate was approximately ten times lower in Fe-30Mn-15Al-1.5C-5Cr LDSS (~0.015 mm/yr.) compared to 316L stainless steel (~0.12 mm/yr.) [16]. The SEM image of the corroded sample is shown in Fig. 8, pitting corrosion which resulted from selective attack of the M_7C_3/matrix interface of the dendrites was observed. The dissolution of the interface results in pulling out of carbides, leaving pits in the alloys [16]. To reduce or prevent pitting corrosion, it is envisaged that dendritic structure can be broken down through thermomechanical processing. Fig. 9 shows the thermomechanical processing schedule used in breaking the dendritic structures into a more refined microstructure. Three deformation temperatures (800, 900 and 1000°C) and two strain rates (0.1 and 5 s^{-1}) were used. The LDSS samples were deformed to a total strain of 0.6. Fig. 10 and Fig. 11 show that the microstructure of the deformed LDSS samples. When compared to the as-cast samples, it can be seen that the thermomechanical treatment has transformed the microstructures from dendritic morphology to globular and serrated-globular microstructure.

The corrosion behaviour of the deformed LDSS samples were then evaluated in 0.9 wt.% NaCl. Table 4 shows the corrosion parameters obtained from analysing linear polarisation curves. It can be seen that the deforming the LDSS at 900°C / 5 s^{-1} and 1000°C / 5 s^{-1} gave the lowest corrosion rate. The corrosion rate obtained in this case was lower than that of commercial grade 316L stainless steel (~0.12mm/yr.) as well. Additionally, the corrosion rates are 10 times lower than 0.13 mm/yr., the maximum permissible corrosion rate for bio-implant materials [17]. Corrosion rates were higher than the maximum permissible limit for bio-implants for the other two deformation conditions i.e. 900 / 0.1 s^{-1} and 1000°C / 0.1 s^{-1}. The reason for this currently not clear, however, research efforts are ongoing to further understand the influence of strain rates on the corrosion behaviour of Fe-21.3Mn-7.6Al-4.3Cr-1C LDSS.

Fig. 12 shows the SEM images of deformed LDSS after corrosion experiment. The images were taken in secondary electron mode and at low magnification to cover a larger area on the samples. The pitting corrosion which is promoted by the as-cast dendritic structure in Fig. 8 is rarely seen in Fig. 12. This suggests that the microstructural control obtained via thermomechanical processing has limited the dominance of pitting corrosion in the alloys. The results obtained so far indicate that LDSS is a very promising metallic material that can serve as cheaper alternative to 316L stainless steel or titanium alloys in biomedical application.



a. b.

Fig. 6 Optical micrographs of LDSS (a) Fe-30.9Mn-4.9Al-4.5Cr-0.4C; (b) Fe-21.3Mn-7.6Al-4.3Cr-1C [15]. Red arrow shows dendritic austenite, yellow arrow shows dendritic ferrite, purple arrow shows austenite matrix and blue arrow shows M_7C_3 carbides.

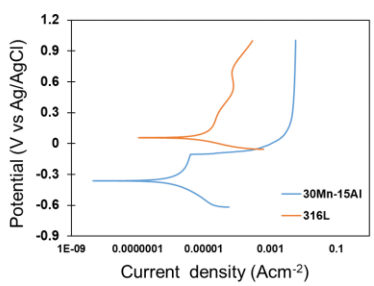
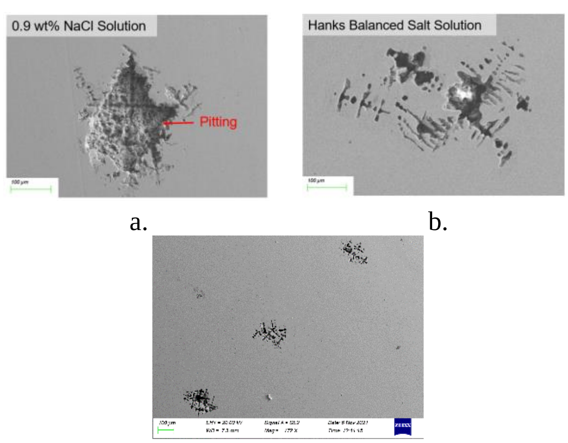


Fig. 7 Polarisation curves of LDSS in Hanks Balanced Salt Solution (HBSS) [16].



c.

Fig. 8 SEM images showing pitting corrosion in the dendritic region of the as cast alloys (a & b) Fe-30.9Mn-4.9Al-4.5Cr-0.4C; (c) Fe-21.3Mn-7.6Al-4.3Cr-1C [16].

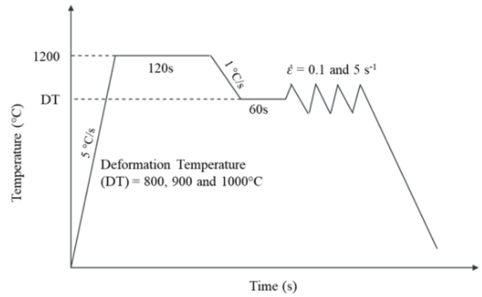
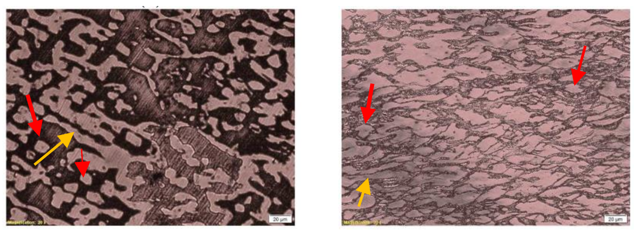
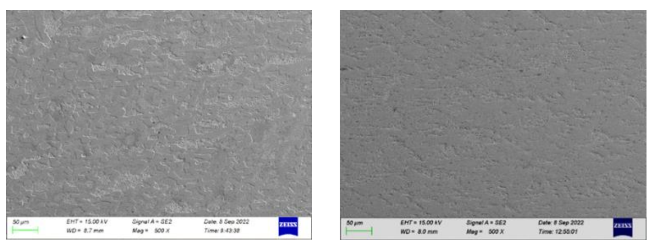


Fig. 9 Thermomechanical processing schedule for ingot breakdown [15].



a. b.

Fig. 10 Optical micrographs of deformed LDSS showing (a) Fe-30.9Mn-4.9Al-4.5Cr-0.4C with elongated and globular ferrite in the austenite matrix; and (b) Fe-21.3Mn-7.6Al-4.3Cr-1C with serrated austenite globules. Deformation was carried out at 950°C/5s^{-1} [15]. Globules are indicated by red arrow, while the elongated and serrated grains are represented by yellow arrow.



a. b.

Fig. 11 Corresponding SEM image of deformed LDSS (a) Fe-30.9Mn-4.9Al-4.5Cr-0.4C; (b) Fe-21.3Mn-7.6Al-4.3Cr-1C [15].

TABLE 4 Corrosion parameters for deformed austenitic Fe-21.3Mn-7.6Al-4.3Cr-1C low-density steels

Deformation condition	E_{corr} (V vs Ag/AgCl)	Corrosion rate (mm/yr.)
900°C/5 s^{-1}	-0.32 ± 0.01	0.011 ± 0.01
1000°C/5 s^{-1}	-0.33 ± 0.04	0.029 ± 0.01
900°C/0.1 s^{-1}	-0.42 ± 0.11	0.25 ± 0.13
1000°C/0.1 s^{-1}	-0.29 ± 0.00	0.37 ± 0.15

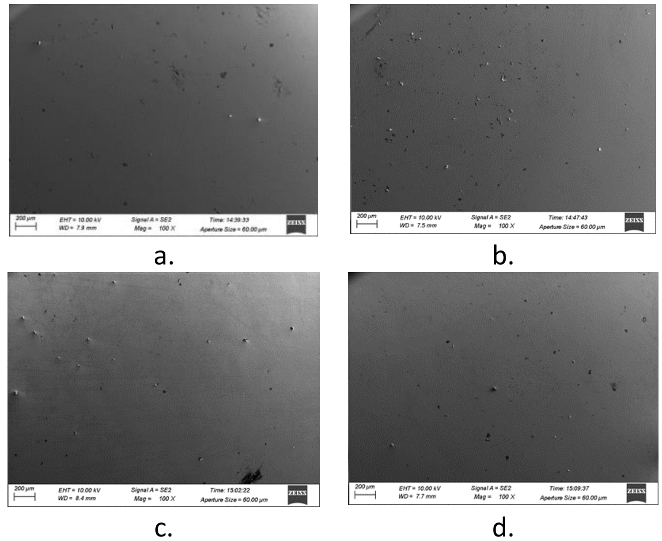


Fig. 12 SEM image of deformed Fe-21.3Mn-7.6Al-4.3Cr-1C after corrosion testing (a) 900°C/5 s^{-1}, (b) 1000°C/5 s^{-1}, (c) 900°C/0.1 s^{-1}; and (d) 1000°C/0.1 s^{-1}[15]

4. CONCLUSIONS

This paper showcased how the versatility and affordability of steel can be explored in addressing two important global concerns, environmental sustainability, and general well-being of geriatric population. The reuse of creep-exhausted steels through regenerative heat treatment was investigated with the aim of satisfying the tenets of circular economic model which drives the environmental sustainability agenda. The results show that although regenerative heat treatment can restore the mechanical properties of creep-exhausted steel, the initial microstructural features were not completely restored. Therefore, repurposing regenerative heat-treated steel for other commercial applications may be more appropriate. This may involve shaping process such as machining or thermomechanical processing. It was shown that although constitutive parameters such as apparent activation energy for hot working and stress exponent may differ, similar deformation mechanisms govern the flow behaviour of the regenerative heat-treated steel. Hence, the common practice of melting creep-exhausted steel scraps which consumes energy and contributes significantly to carbon footprint may be avoided. The development of low-density stainless steel as alternative bio-implant alloys to highly dense 316L stainless steel and expensive titanium alloys was also investigated. The aim is to produce affordable bio-implant material for geriatric population who fall within the middle-and-low-income earning category. The results show that it is possible to obtain corrosion rates that are ten times lower than that of commercial grade 316L stainless steel in simulated body fluids. What is even more encouraging is the possibility to refine the microstructure of LDSS through thermomechanical processing to minimise pitting corrosion. Ultimately, corrosion rates in LDSS can be ten times lower than the maximum permissible corrosion rates or bio-implant materials. With further research to gain understanding on the precipitation mechanisms in regenerative heat treated or thermomechanical-processed creep-exhausted steels, and the influence on strain rate on corrosion of LDSS, the versatility and affordability of steel will continue to give this class of material an edge over emerging metallic alloys that are not only expensive, but yet to be fully understood.

ACKNOWLEDGMENTS

I acknowledge the contributions of my students: Thabiso Masole, Takatso Komane, Nicola Rundora, Anele Dladla, and Shem Maube, who worked diligently in the laboratory to generate the results presented in this paper. I would also like to express my gratitude to co-supervisors and collaborators: Prof. Lesley Cornish, Prof. van der Merwe, Dr. Japheth Obiko, Dr. Desmond Klenam, Dr. Velaphi Matjeke, and Dr. Fred Madaraka for their valuable input. Additionally, I would like to acknowledge the Faculty Research Council of the Faculty of Engineering and the Built Environment at the University of the Witwatersrand for their financial support.

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