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Aynı Sıcaklıkta Uygulanan Isıl İşlem ve Farklı Oranda Uygulanan Redüksiyon İşleminin Fren Borularının Mekanik Özelliklerine Etkisinin Araştırılması

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Öz

Bu çalışmada, 3,40 mm ve 4,75 mm dış çapa sahip fren borularına 3,20 mm ve 4,65 mm dış çapa sahip olacak şekilde redüksiyon işlemi uygulanmıştır. Ardından fren borularına 450 °C sıcaklık ve 30 dk. süre ile tavlama ısıl işlem uygulanmış ve numuneler oda sıcaklığında soğumaya bırakılmıştır. Başlangıçtaki 2 adet referans boru ile redüksiyon ve ısıl işlemlerle elde edilen 6 farklı parametredeki numuneler karşılaştırmalı olarak mekanik özellikler ve mikroyapı bakımından incelenmiştir. Uygulanan redüksiyon işlemi ile 4,75 mm dış çap borudan 4,60 mm dış çap boruya düşüşte akma mukavemetinde %20,6 oranında artış, çekme mukavemetinde %11,4 artış, kopma uzamasında %34,3 oranında düşüş tespit edilmiştir. Ayrıca sertlik değerlerinde de %27,1 oranında artış tespit edilmiştir. 3,40 mm dış çap borudan 3,20 mm dış çap boruya düşüşte akma mukavemetinde %4,1 oranında artış, çekme mukavemetinde %0,7 artış tespit edilmiş; malzemeler çok kırılgan olduklarında dolayı kopma uzama değerleri çekme testinde belirlenememiştir. Ayrıca sertlik değerlerinde de %1,5 oranında artış tespit edilmiştir. Uygulanan tavlama ısıl işlem parametrelerinin sıcaklık ve süre olarak yeterli olduğu mekanik özelliklerdeki değişimlerden anlaşılmaktadır. Eğme deneyi sonucunda elde edilen verilerden 4,75 mm dış çap borudan 4,65 mm dış çapa düşüşte diğer mekanik özellikler ile paralel bir davranış sergilediği ancak 3,65 mm dış çap borudan 3,40 mm dış çapa düşüşte bunun tam tersi bir davranış sergilediği gözlemlenmiştir.

Anahtar Kelimeler
Fren borusu, boru redüksiyonu, tavlama, mekanik özellikler.

Investigation of the Effect of Heat Treatment Applied at the Same Temperature and Reduction Process Applied at Different Rates on the Mechanical Properties of Brake Pipes

Abstract

In this study, brake pipes with 3.40 mm and 4.75 mm outer diameters were reduced to 3.20 mm and 4.65 mm outer diameters. Then, the brake pipes were subjected to a temperature of 450 °C and 30 minutes. Annealing heat treatment was applied for a period of time and the samples were allowed to cool at room temperature. Samples with 6 different parameters obtained by reduction and heat treatments, along with the initial 2 reference pipes, were comparatively examined in terms of mechanical properties and microstructure. With the reduction process applied, a 20.6% increase in yield strength, a 11.4% increase in tensile strength, and a 34.3% decrease in elongation at break were detected when decreasing from 4.75 mm outer diameter pipe to 4.60 mm outer diameter pipe. Additionally, a 27.1% increase in hardness values was detected. When decreasing from 3.40 mm outer diameter pipe to 3.20 mm outer diameter pipe, a 4.1% increase in yield strength and a 0.7% increase in tensile strength were detected; Since the materials are very brittle, elongation values at break could not be determined in the tensile test. Additionally, a 1.5% increase in hardness values was detected. It is understood from the changes in mechanical properties that the applied annealing heat treatment parameters are sufficient in terms of temperature and time. From the data obtained as a result of the bending test, it was observed that the decrease from 4.75 mm outer diameter pipe to 4.65 mm outer diameter exhibited a parallel behavior with other mechanical properties, but that it exhibited the opposite behavior when falling from 3.65 mm outer diameter pipe to 3.40 mm outer diameter.

Key Words
Brake pipes, tube reduction, annealing, mechanical properties.

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Bu makaleyi alıntılamak için; *Ozan KOYUNCU ve ark., Aynı Sıcaklıkta Uygulanan Isıl İşlem ve Farklı Oranda Uygulanan Redüksiyon İşleminin Fren Borularına Mekanik Özelliklerine Etkisinin Araştırılması, Journal of Steel Research and Development, 5(1), 1-8.*

1. Giriş

Soğuk boru çekme (redüksiyon), hassas boyutlara, iyi yüzey kalitesine ve yüksek mekanik özelliklere sahip yüksek kaliteli borular üretmek için kullanılan bir metal işleme yöntemidir. Bu yöntem ile üretilen borular, mukavemet homojenliğinin, mikro yapının ve uzun ürün ömrünün önemli tasarım parametreleri olduğu uygulamalar için kullanılmaktadırlar (Bella et al. 2021). Çelik boruların soğuk çekilmesi için kullanılan iki farklı tip işlem vardır: sabit tapayla çekme işlemi ve içi boş batırma işlemi. Sabit tapa ile çekme işleminde, dış çap ve boru duvar et kalınlığı azaltılmaktadır. Giriş besleme stoğunun kalınlığına bağlı olarak sabit silindirik veya sabit konik tapa kullanılmaktadır. Konik tapa, daha iyi malzeme akışı sağlayan geometrisi sayesinde daha yüksek çekme hızının kullanılmasına olanak sağlamaktadır. İçi boş batırma işleminde ise, boru duvar et kalınlığı aynı kalmakta ve dış boru çapı azalmaktadır (Neves and Button 2005; Mojžiš et al. 2016). Deformasyon sırasında duvar kalınlığındaki değişiklik, borunun giriş boyutlarına ve kalıp geometrisine bağlıdır (Pernis 2006).

Soğuk çekme işlemi sırasındaki düşük sıcaklık, dinamik yeniden kristalleşmeye izin vermez ve dolayısıyla dislokasyonların birikmesi nedeniyle malzeme sertleşmesi meydana gelir (Das and Pradhan 2017). Şekillendirme işlemi sırasında taneler ana deformasyon yönünde uzamaktadırlar. Çok yüksek düzeyde deformasyon ve sertleşme, malzeme plastisitesinin tükenmesi ve kusur riskiyle ilişkilidir ve bu nedenle yeniden kristalleştirme tavlaması gerekmektedir. Tavlama sırasında deformasyonsuz yeni eş eksenli taneler oluşmaktadır (Belyakov et al. 2004; Raji and Oluwole 2011). Tavlama iki ana aşamadan oluşmaktadır: geri kazanım ve yeniden kristalleşme. Geri kazanım, yüksek açılı tane sınırlarının hareketini gerektirmeyen depolanmış enerjiyi serbest bırakan tüm süreçleri içermektedir ve düşük açılı hücre sınırlarının oluşturulması yoluyla depolanan enerjiyi azaltmak için dislokasyonların yok edilmesini ve yeniden düzenlenmesini kapsamaktadır. Öte yandan yeniden kristalleşme, depolanan enerjinin etkisiyle yüksek açılı tane sınırlarının yer değiştirmesidir (Almojil 2010).

Bakır kaplı fren boruları ile ilgili daha önce gerçekleştirilen bir çalışmada fren borularına 3 farklı hızda (27 m/dk, 36 m/dk ve 45 m/dk) redüksiyon işlemi uygulanarak 4,75 mm dış çap ölçüsüne sahip fren borularının dış çapları 4,60 mm ölçüsüne getirilmiştir (Koyuncu et al.). Kritik redüksiyon hızının 36 m/dk ile 45 m/dk arasında bir hız olduğu değerlendirilmiştir. Diğer bir çalışmada ise ısıl işlemin bakır kaplı çelik boruların mekanik özelliklerine etkisi araştırılmış ve optimum ısıl işlem parametresi olarak 450 °C sıcaklık ve 30 dk. süre belirlenmiştir (Koyuncu et al.).

Bu çalışmada ise redüksiyon hızı ve redüksiyonun ardından uygulanan tavlama ısıl işlem parametreleri sabit tutulmuş, farklı oranlarda uygulanan redüksiyon ve redüksiyonun ardından uygulanan tavlamanın mekanik özellikler üzerinde oluşturduğu etkiler incelenmiştir.

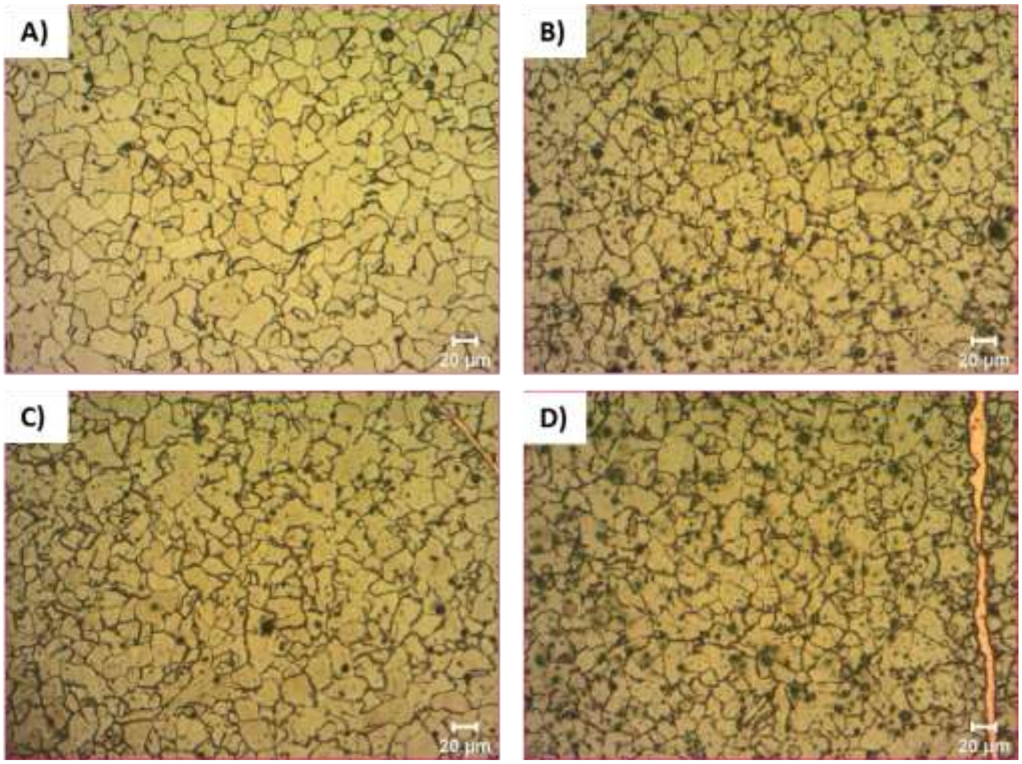
2. Deneysel Çalışmalar

Bu çalışmada kullanılan fren boruları Bant Boru AŞ'den temin edilmiştir. Temin edilen referans numune konumunda olan 3,40 mm ve 4,75 mm dış çapa sahip fren boruları 0,35 mm kalınlığındaki DC03 kalite çelik saçlara 3-5 µm bakır kaplamanın ardından 720° kıvırma yöntemi ile elde edilmiş ve herhangi bir ısıl işlem uygulanmamıştır. Standart olarak üretimi yapılmış olan 3,40 mm ve 4,75 mm dış çapa sahip fren boruları 3,20 mm ve 4,65 mm dış çapa sahip olacak şekilde içi boş batırma işlemi yöntemi ile 36 m/dk hızda redüksiyon işlemi uygulanmıştır. Bu şekilde 4 farklı dış çapa sahip fren borusu elde edilmiştir. Ardından mamul haldeki tüm fren borularına 450 °C sıcaklık ve 30 dk. süre ile tavlama ısıl işlem uygulanmış ve numuneler oda sıcaklığında soğumaya bırakılmıştır. Başlangıçtaki 2 adet referans boru ile redüksiyon ve ısıl işlemlerle elde edilen 6 farklı parametredeki numuneler karşılaştırmalı olarak mekanik özellikler ve mikroyapı bakımından incelenmiştir. Makale akışı boyunca numune kodlarının takibi açısından ısıl işlem görmemiş numuneler numune çap ölçüleri ile kodlanmış (3,20; 3,40; 4,65; 4,75), ısıl işlem görmüş olan numuneler ise çap ölçülerinin yanına "HT" yazılarak kodlanmıştır (3,20HT; 3,40HT; 4,65HT; 4,75HT).

Numunelerdeki mikroyapı değişimleri Nikon Eclipse MA200 ters metalürjik optik mikroskop ile incelenmiştir. Mikroyapı incelemelerinden önce SiC kağıtlarla (200, 400, 600, 800, 1200, 2000, 2500 grit) zımparalama, parlatma (1 ve 3 µm elmas süspansiyonlar) ve dağlama (%5 Nital çözeltisi) metalografik işlemleri uygulanmıştır (Albahlol et al. 2023). Çekme testleri Zwick/Roell Z600 Üniversal Test Makinesinde 2 mm/dk test hızında EN ISO 6892-1 (ISO 2016) metalik malzemelerde çekme deney standardına uygun olarak gerçekleştirilmiştir (Buğan et al. 2022). Boruların kesit alanına uygun olarak uzamanın ölçüldüğü test boyu 20 mm olarak alınmıştır. Vickers mikrosertlik testi, Q10 A+ QNESS mikrosertlik test cihazı ile 1000g yük ve 15 sn bekleme süresi kullanılarak gerçekleştirilmiştir. Numunelerin ortalama sertlik değerleri 5 farklı noktadan alınan ölçümlerden hesaplanmıştır. Eğme deneyi, Zwick/Roell Z600 Üniversal Test Makinesinde 2 mm/dk test hızında EN ISO 7438 standartlarına uygun olarak gerçekleştirilmiştir. Tüm numunelere 90°'lik eğilme açısına ulaşana kadar deformasyon uygulanmıştır.

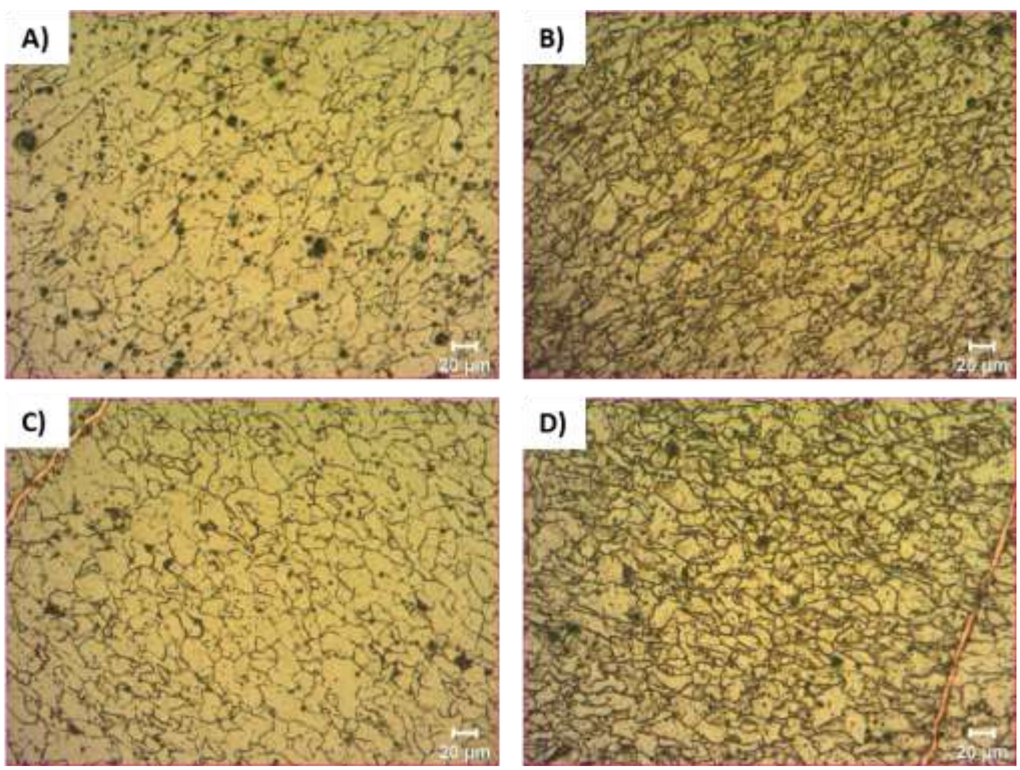
3. Deneysel Sonuçlar ve Tartışma

Fren borularının yan kesitinden alınan optik mikroskop görüntüleri Şekil 1 ve Şekil 2'de verilmiştir. Şekil 1a ve Şekil 1c karşılaştırıldığında yani boru et kalınlığı sabit kalmak şartı ile uygulanmış olan %2,1 oranındaki redüksiyon işlemiyle beraber mikroyapısal olarak belirgin bir farklılık meydana gelmediği gözlemlenmiştir. Bunun sebebi ise redüksiyon ile boru iç alanının daralmasına rağmen boru et kalınlığı sabit kalmasıdır. Şekil 1a ile Şekil 1b veya Şekil 1c ile Şekil 1d kıyaslandığında ise uygulanan ısıl işlem ile de mikroyapısal olarak belirgin bir farklılık meydana gelmediği tespit edilmektedir. Çünkü uygulanan ısıl işlem sıcaklığı (450 °C), çeliğin rekristalizasyon sıcaklığının altındadır (Choi et al. 2002).



Şekil 1. Fren borularına ait optik mikroskop görüntüleri a) 4,75 b) 4,75HT c) 4,65 d) 4,65HT

Boru iç çapının 3,40'tan 3,20'ye düşmesiyle beraber, boru et kalınlığı sabit kalmak şartı ile %5,9 oranında redüksiyon uygulanmıştır (Şekil 2). Mikroyapı özellikleri, %2,1 oranında uygulanan redüksiyon oranına (Şekil 1'de gösterilen numunelere) benzer davranış sergilemiştir.



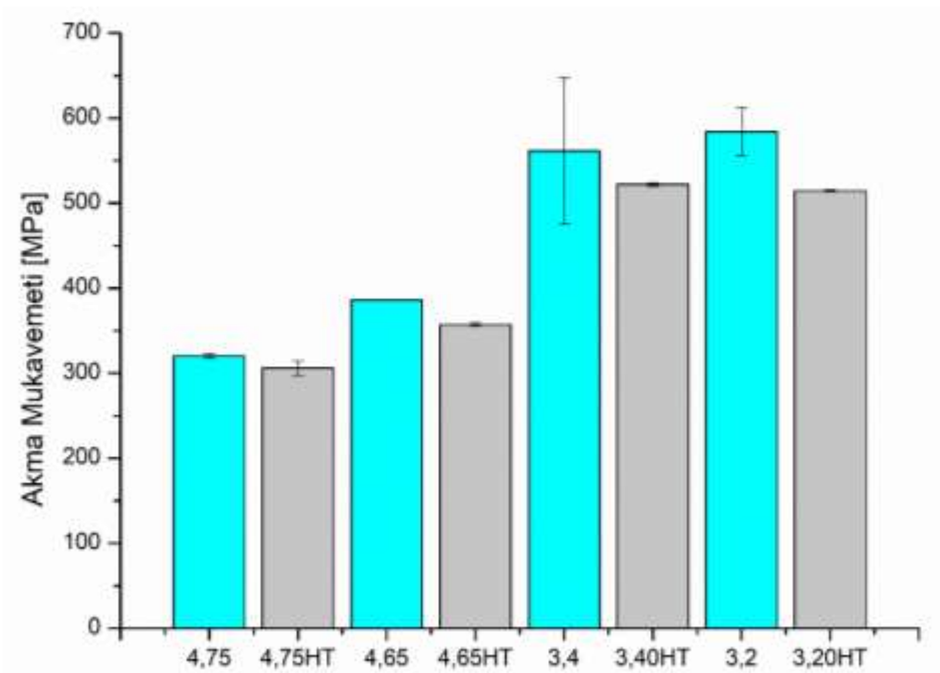
Şekil 2. Fren borularına ait optik mikroskop görüntüleri a) 3,40 b) 3,40HT c) 3,20 d) 3,20HT

Fren borularına uygulanan çekme testi neticesinde elde edilen akma mukavemeti, çekme mukavemeti ve kopma uzaması verilerinin karşılaştırmalı sonuçları Şekil 3, Şekil 4 ve Şekil 5'te sütün grafikleri şeklinde karşılaştırmalı olarak ayrı ayrı verilmiştir. Ayrıca Tablo 1'de tüm mekanik test sonuçları toplu halde verilmiştir.

Tablo 1. Mekanik Test Sonuçları

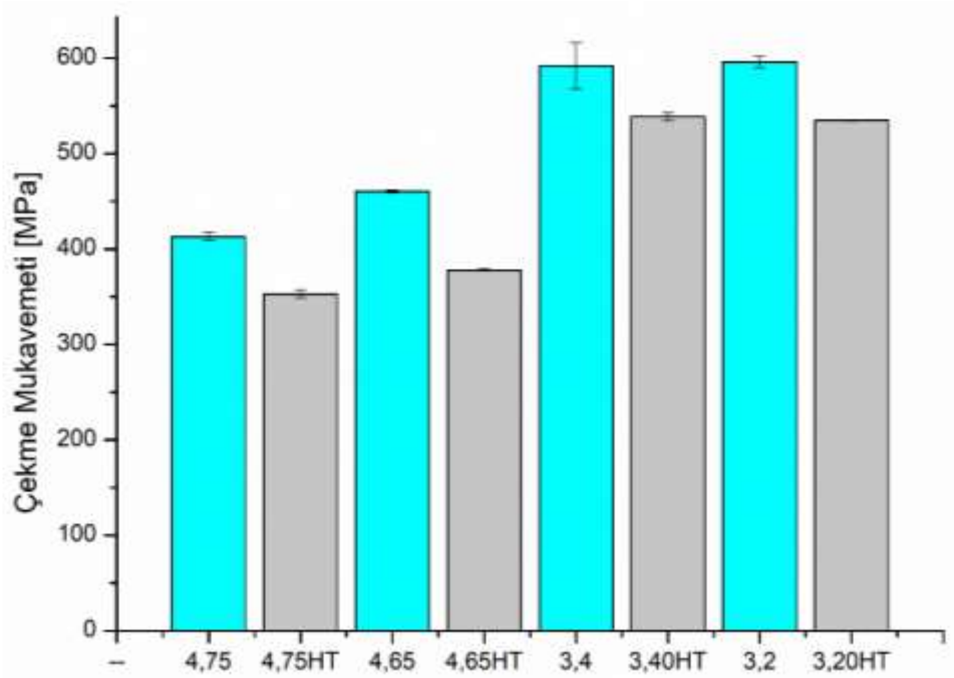
	Akma Mukavemeti [MPa]	Çekme Mukavemeti [MPa]	Kopma Uzaması [%]	Mikro Sertlik [HV]
4,75	320,0±2,8	413,0±4,2	32,1±2,0	142,0±10,6
4,75HT	306,0±8,5	353,0±4,2	37,8±2,2	115,5±4,2
4,65	386,0±0,0	460,7±1,4	21,1±1,3	160,5±2,8
4,65HT	357,0±2,1	378,0±1,4	32,4±1,4	155,5±7,8
3,40	561,3±85,6	592,0±24,0	-	220,5±2,1
3,40HT	522,0±2,1	538,7±4,2	14,6±0,0	202,5±1,4
3,20	584,0±28,3	596,0±5,7	-	223,8±5,7
3,20HT	514,7±0,7	534,7±0,7	18,3±3,9	204,3±0,7

Akma mukavemeti değerleri kıyaslandığında (Şekil 3) uygulanan redüksiyon işlemi ile hem 4,75 mm çaptan 4,65 mm çapa düşüşte, hem de 3,40 mm çaptan 3,20 mm çapa düşüşte belirgin şekilde mukavemet artışı gözlemlenmektedir (turkuaz sütunlar). Bunun sebebi uygulanan redüksiyon işlemi ile birlikte malzeme iç yapısında deformasyon sertleşmesi mekanizmalarının aktive olmasıdır (Almojil 2010). 4,75 mm çaptan 4,65 mm çapa düşüşte %20,6'lık bir artış gözlemlenirken 3,40 mm çaptan 3,20 mm çapa düşüşte ise %4,0'lık bir artış gözlemlenmiştir. Bilindiği üzere uygulanan deformasyonla birlikte malzeme içyapısındaki dislokasyon yoğunluğu artmakta bu da dislokasyonların birbirlerini kilitlemesini kolaylaştırarak mekanik dayanım artışına yol açmaktadır (Li et al. 2022). Uygulanan tavlama ısıl işlemi ile birlikte beklenildiği üzere mukavemet değerlerinde belirgin şekilde düşüşler gözlemlenmiştir (gri sütunlar). Tavlama işlemi deformasyon ile iç yapıda artan dislokasyon yoğunluğu azalarak mekanik dayanımlarda düşüşlere yol açmıştır (Ridzoň et al. 2015).



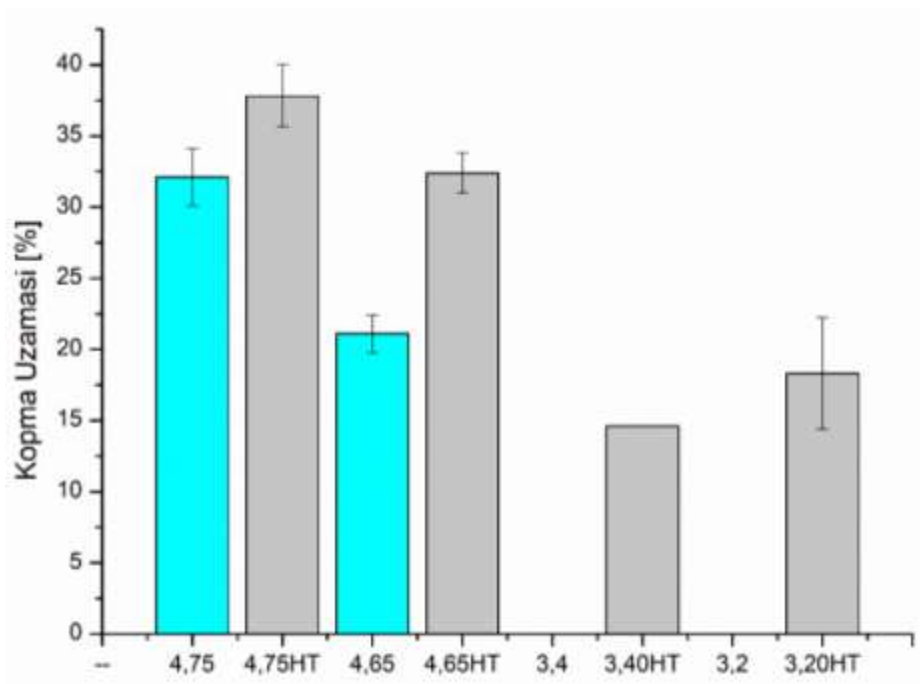
Şekil 3. Çekme testi sonrası elde edilen akma mukavemeti değerlerinin karşılaştırması

Çekme mukavemeti değerleri kıyaslandığında (Şekil 4) akma mukavemeti değerlerindeki değişime paralel şekilde uygulanan redüksiyon işlemi ile hem 4,75 mm çaptan 4,65 mm çapa düşüşte, hem de 3,40 mm çaptan 3,20 mm çapa düşüşte belirgin şekilde mukavemet artışı gözlemlenmektedir (turkuaz sütunlar). 4,75 mm çaptan 4,65 mm çapa düşüşte %11,6'lık bir artış gözlemlenirken 3,40 mm çaptan 3,20 mm çapa düşüşte ise %0,7'lık bir artış gözlemlenmiştir. Uygulanan tavlama ısıl işlemi ile birlikte beklenildiği üzere mukavemet değerlerinde belirgin şekilde düşüşler gözlemlenmiştir (gri sütunlar).



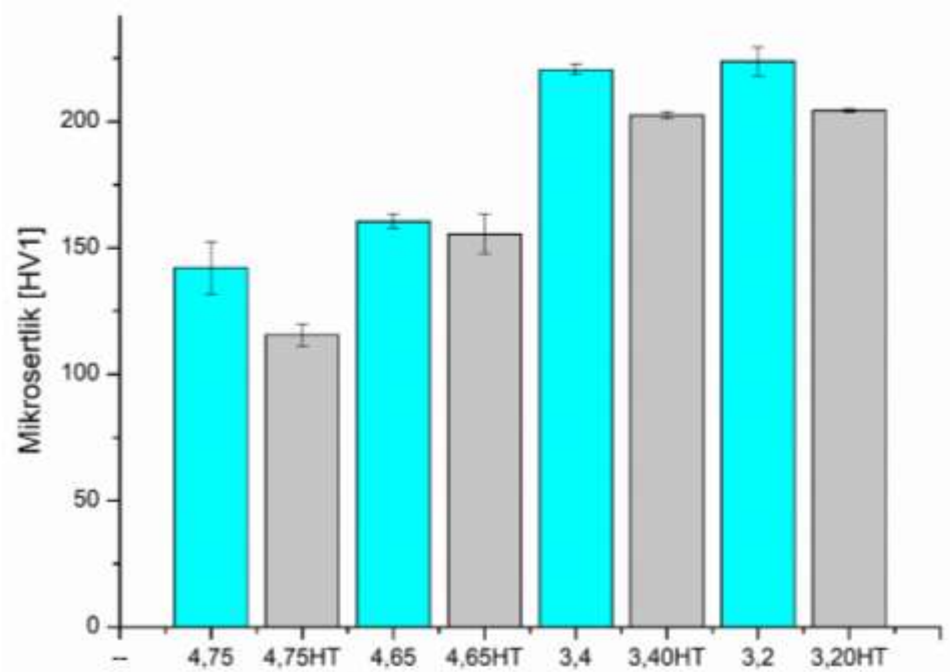
Şekil 4. Çekme testi sonrası elde edilen çekme mukavemeti değerlerinin karşılaştırması

Kopma uzaması değerleri kıyaslandığında (Şekil 5) akma ve çekme mukavemetinde değişimle ters orantılı olarak uygulanan redüksiyon işlemi ile 4,75 mm çaptan 4,65 mm çapa düşüşte kopma uzaması değerlerinde azalma gözlemlenmiştir (turkuaz sütunlar). 3,40 mm çap ve 3,20 mm çap ısıl işlemsiz numunelerden uzama ölçülememiştir çünkü redüksiyon işlemi birlikte numune gevrekleşmiştir, Tablo 1'deki sertlik sonuçları bunu desteklemektedir. Uygulanan tavlama ısıl işlemi ile beklenildiği üzere mukavemet değerlerinde belirgin şekilde düşüşler gözlemlenmiştir (gri sütunlar). Deformasyon sertleşme mekanizmasının bir sonucu olarak dislokasyonların birbirlerini kilitlemesiyle mikroyapıdaki atomsal hareketliliğin kısıtlanmasının bir sonucu olarak kopma uzaması değerlinde düşüşler meydana gelmiştir (Almojil 2010).



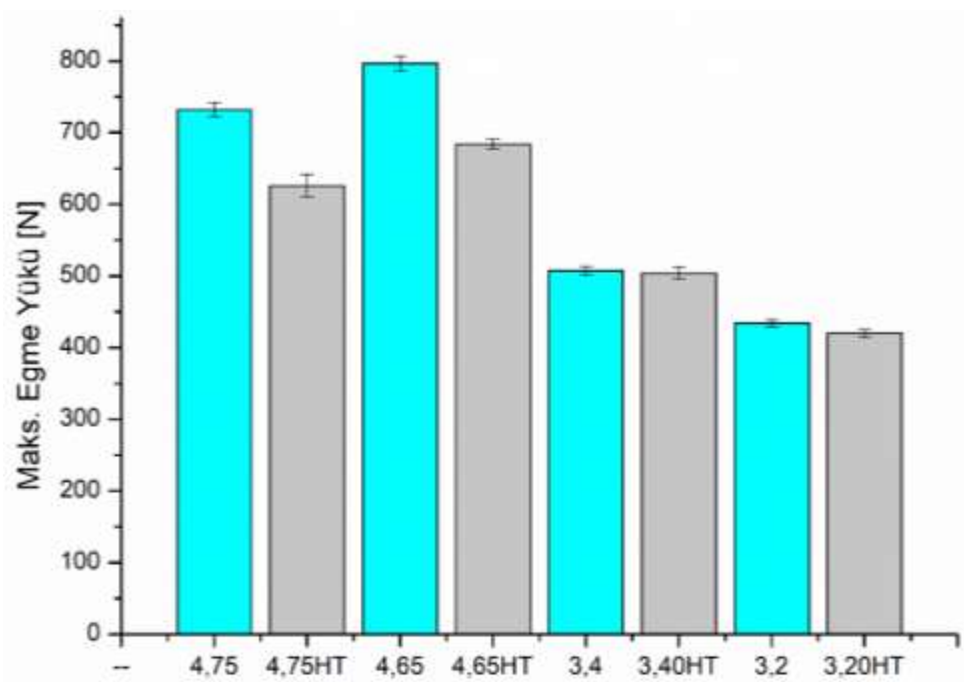
Şekil 5. Çekme testi sonrası elde edilen uzama değerlerinin karşılaştırması

Şekil 6'da numunelere ait Vickers sertlik ölçüm sonuçları karşılaştırmalı olarak verilmiştir. Redüksiyon işlemi uygulanmamış iki numune kıyaslandığında (4,75 ve 3,40) ilk boru üretimi neticesinde 3,40 mm çapa sahip borularda %55 oranında daha yüksek sertliğin elde edildiği anlaşılmaktadır (Tablo 1). Uygulanan redüksiyon işlemleri ile birlikte yani 4,75 mm çaptan 4,65 mm çapa düşüşle birlikte sertlikte %13 oranında bir artış; 3,40 mm çaptan 3,20 mm çapa düşüşle birlikte sertlikte %1,5 oranında bir artış elde edilmiştir. İlk üretimde 3,40 mm çapa sahip malzemenin daha yüksek sertliğe sahip olması yani iç yapıdaki dislokasyon yoğunluğunun daha fazla olması uygulanan redüksiyon işlemi ile beklenen sertlik artışının belirli seviyede kalmasının önündeki en sınırlayıcı etken olarak değerlendirilebilmektedir.

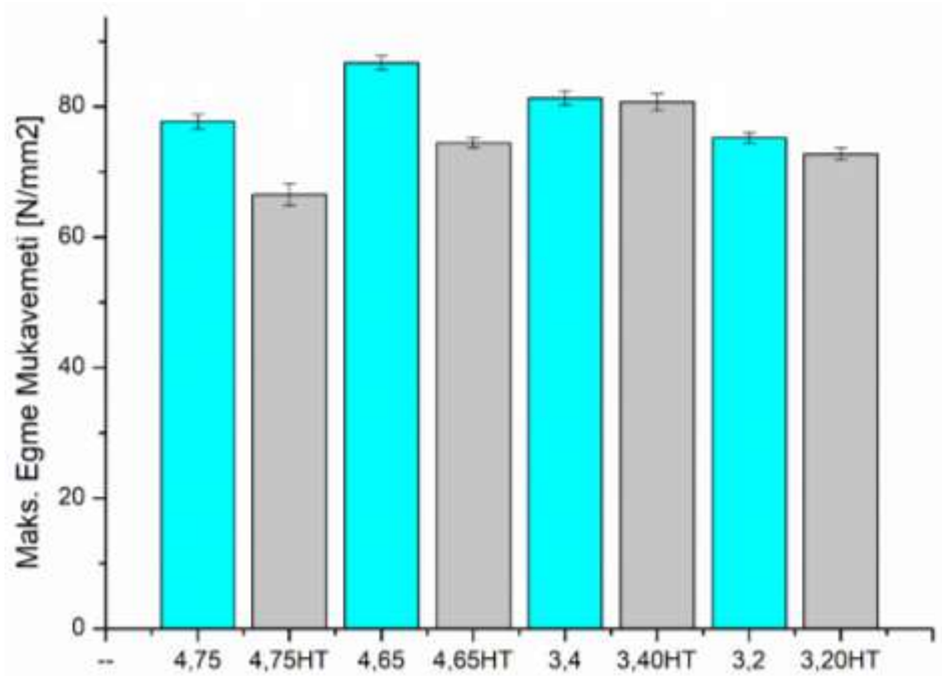


Şekil 6. Numunelerden elde edilen Vickers sertlik değerlerinin karşılaştırması

Numunelerden 90° eğme açısında elde edilen maksimum eğme yükleri Şekil 7'de, bu yüklerin boru kesit alanlarına bölünmesi birlikte elde edilen maksimum eğme mukavemetleri ise Şekil 8'de verilmiştir. 4,75 mm'den 4,60 mm'ye redüksiyon işlemi ile dış çap ölçüsü düşürülen numunelerde akma ve çekme mukavemetleri ve sertlik değerlerine paralel olarak maksimum eğme yükü ve maksimum eğme mukavemeti değerlerinde belirgin bir artışın meydana geldiği gözlemlenmektedir. Tavlama ısıl işlemi ile birlikle bu değerlerde düşüşler gözlemlenmiştir. Ancak 3,40 mm'den 3,20 mm'ye redüksiyon işlemi işe dış çap ölçüleri düşürülen numunelerde ise maksimum eğme yükü ve maksimum eğme mukavemeti değerlerinde artış yerine düşüş gözlemlenmiştir. Ayrı uygulanan ısıl işlemle bilirlikte de bu değerlerde belirgin bir farklılaşma gözlemlenememiştir. Bunun sebebi olarak deformasyona bağlı numune iç yapılarında meydana gelen aşırı dislokasyon yoğunluğu olduğu söylenebilmektedir.



Şekil 7. 90°'lik eğme açısı ile birlikte elde edilen maksimum eğme yükleri [N]



Şekil 8. 90°'lik eğme açısı ile birlikte elde edilen maksimum eğme mukavemetleri [MPa-N/mm^2]

4. Genel Sonuçlar

Bu çalışmada, 3,40 mm ve 4,75 mm dış çapa sahip fren boruları 3,20 mm ve 4,65 mm dış çapa sahip olacak şekilde redüksiyon işlemi uygulanmıştır. Ardından fren borularına 450 °C sıcaklık ve 30 dk. süre ile tavlama ısıl işlem uygulanmış ve numuneler oda sıcaklığında soğumaya bırakılmıştır. Başlangıçtaki 2 adet referans boru ile redüksiyon ve ısıl işlemlerle elde edilen 6 farklı parametredeki numuneler karşılaştırmalı olarak mekanik özellikler ve mikroyapı bakımından incelenmiştir. Elde edilen sonuçlar aşağıdaki şekilde özetlenebilir:

- Uygulanan redüksiyon işlemi ile 3,40 mm dış çap borudan 3,20 mm dış çapa düşüşte hem de 4,75 mm dış çap borudan 4,65 mm dış çapa düşüşte akma mukavemeti ve çekme mukavemeti ve Vickers sertlik değerlerinde artışlar gözlemlenmiştir. Kopma uzaması değerlerinde ise mukavemet değerleri ile ters orantılı şekilde azalmalar meydana gelmiştir (3,40 mm dış çaptan 3,20 dış çapa düşüş hariç).
- Uygulanan tavlama ısıl işlem parametrelerinin sıcaklık ve süre olarak yeterli olduğu mekanik özelliklerde meydana gelen farklılaşmalardan anlaşılmaktadır yani hiçbir parametre için ısıl işlem öncesi ve sonrası değerlerin aynı kalmadığı görülmüştür.
- Eğme deneyi sonucunda elde edilen verilerden 4,75 mm dış çap borudan 4,65 mm dış çapa düşüşte diğer mekanik özellikler ile paralel bir davranış sergilediği ancak 3,65 mm dış çap borudan 3,40 mm dış çapa düşüşte bunun tam tersi bir davranış sergilediği gözlemlenmiştir.

Teşekkür / Bilgilendirme

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The Effect of Hot Rolling Parameters on Mechanical Properties of Steel

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Abstract
The production of steel materials holds a significant place worldwide. Due to their mechanical strength and high resistance to friction, steel materials have been frequently preferred in many industries in recent years. This study investigates the effects of the chemical composition of steel materials, rolling speed, and the water-cooling system applied during rolling on the material's mechanical properties (yield strength, tensile strength, impact toughness). The mechanical behaviours of three different grades of materials were examined. According to the obtained results, a direct effect of manganese, vanadium, and aluminum elements on mechanical properties was observed. An increase in the amount of manganese in the steel material, and the combined use of vanadium and aluminum elements, led to an increase in yield and tensile strength. Increasing the amounts of vanadium and aluminum improved the material's notch toughness. The effects of two other important parameters, rolling speed and the water-cooling pumps in the rolling system, were examined. As a result, it was determined that reducing the rolling speed improves the mechanical properties of the material, and increasing the number of water-cooling pumps also improves the mechanical properties by allowing the material to absorb more water.

Key Words
Mechanical properties, rolling speed, water cooling, chemical analysis

Sıcak Haddeleme Parametrelerinin Çeliğin Mekanik Özelliklerine Etkisi

Öz
Çelik malzemelerin üretimi dünyada önemli bir yere sahiptir. Çelik malzemelerin mekanik direnci ve sürtünmeye karşı yüksek koruması nedeniyle son yıllarda birçok sektörde çelik malzemeler sıklıkla tercih edilmiştir. Bu çalışmada çelik malzemelerin kimyasal bileşiminin, haddeleme hızının ve haddeleme sırasında uygulanan su soğutma sisteminin malzemenin mekanik özelliklerine (akma mukavemeti, çekme mukavemeti, darbe tokluğu) etkisi araştırılmıştır. Üç farklı kalitedeki malzemenin mekanik davranışları incelenmiştir. Elde edilen sonuçlara göre mangan, vanadyum ve alüminyum elementlerinin mekanik özelliklere doğrudan etkisi gözlemlenmiştir. Çelik malzemedeki mangan miktarının artması, vanadyum ve alüminyum elementlerinin bir arada kullanılması malzemenin akma ve çekme mukavemetinin artmasına neden olmuştur. Vanadyum ve alüminyum miktarlarının arttırılması malzemenin çentik tokluğunu arttırmıştır. Ayrıca diğer iki önemli parametrenin, haddeleme hızının ve haddeleme sistemindeki su soğutma pompalarının etkileri incelenmiştir. Sonuç olarak, haddeleme hızının azaltılmasının malzemenin mekanik özelliklerini iyileştirdiği, su soğutma pompalarının arttırılmasının da malzemenin daha fazla su almasına olanak sağladığı için mekanik özellikleri iyileştirdiği belirlenmiştir.

Anahtar Kelimeler
Mekanik özellikler, hadde hızı, su soğutma, kimyasal analiz

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1.Introduction

The production of steel materials has an important place in our country and the world. The durability of steel and its use in the construction sector are among the significant reasons for its preference. Steel structures are widely used in buildings worldwide because of their good seismic performance and high construction efficiency (Jiang et al, 2018). In the early days of its use, the predominant structural steel types used for building construction were carbon steel or mild steel, which have nominal yield strength values of approximately 200–300 MPa, like ASTM A36 steel under the American standard, S235 and S275 under the European standard (Yu et al, 2019). In Europe, the steels with a nominal yield stress equal to or above 460 MPa are called high-strength steel based on the implication of the current European Standard. High-strength steel offers higher performance in tensile stress, yield stress, bending, weldability, and corrosion resistance when compared with steel (Qiang et al, 2012). In addition, the mechanical resistance and friction protection of steel materials are quite high. Steel materials are used in kitchen utensils, railway projects, the automotive industry, bridges, space vehicles, machinery, and external construction systems in many fields. Steel is an alloy of iron (Fe) and carbon (C), produced in two ways by recycling from ore or scrap. The products included in this study are low-alloy steel products and contain 0.1-0.3% carbon. The chemical composition and internal structure of the material determine the different properties of steel. Alloying elements can be added to the steel in different proportions, and its internal structure is controlled by various processes, steel products with different properties are obtained according to the purpose of use. Manganese (Mn), Phosphorus (P), Sulfur (S), and Silicon (Si) are elements present in steel during the production process. Other elements (Cr, Ni, etc.) are also added to steel in specific proportions. Since these materials will be produced in different profiles, each one must undergo a different shaping process. To carry out this shaping process in steel materials, a rolling process is required. Steel rolling is a plastic deformation process where steel is passed between rotating rolls, subjecting it to pressure forces. Rolling is a forming process that provides a wide range of uses, providing final product control and high production. The rolling method is based on loading the material with pressure forces of suitable size (Bartın, 2023). The first stage of this process involves heating the material in the hot deformation zone to increase its workability and reduce the flow stress of the deforming metal (Serajzadeh,2014). During rolling, a change in the dimensions of the material occurs with deformation. Certainly, with the change in this sizing process, changes occur in the internal structure of the material. During hot rolling, the microstructure and mechanical properties of the material change in conjunction with its thermomechanical state, which is determined by composition, reduction percentage, strip thickness, strip speed, and heat transfer (Samarasekera,2001). Although these changes affect the mechanical properties, they are linked to the chemical components that make up the quality of the material. There are two types of rolling processes, hot and cold rolling. In the continuation of the research, the impact of the chemical composition of steel, rolling speed, and water-cooling pumps on the mechanical properties of the material will be investigated (Aydın, 2017). Rolling is the name of the process of shaping the material by passing the steel materials of different profiles and sizes between the cylinders rotating in opposite directions and at certain speeds. In this applied process, while elongation of the steel product is desired, transverse expansion of the material is not desired. The rolling process differs according to the techniques and properties used. The rolling process is also a plastic-forming method. Plastic deformation is based on the plastic property of objects, that is their ability to permanently change their shape. Most of the plastic shaping is done by rolling. The first purpose of the rolling method is to compress the rolled material, making it denser. In this way, bunker and similar gaps are eliminated or reduced. At the same time, slag deposits in the material are expelled. The second purpose is to make the material into a smaller cross-section. Thus, the raw blocks are cast in the steel mill; It is passed through the rolls and formed into shaped sections with the desired internal and external smoothness and in forms that can be used in the technique. It is based on the loading of the steel material with appropriately large compressive forces. During rolling, the dimensions of the steel material are changed by deformation. In the meantime, changes in the internal structure and physical properties of the applied steel material cause changes in the mechanical properties of the applied steel material by changing the dimensions of the material. Steel is an alloy of iron and carbon. The deformation process applied to alloys like steel is called rolling. In all these processes, rolled ingots require a certain annealing step. Steel bloom can be annealed at temperatures ranging from 1100°C to 1250°C. The annealed steel ingots are thinned by the pressing force applied by the rotating roller systems. Hot rolling is considered the primary process applied to a steel material. In terms of cost, the hot rolling process requires much less processing, and therefore, it is more cost-effective. To eliminate the internal stresses that will occur after hot rolling, the material is subjected to a cooling process with water and left on the platform. Rolling the ingots to the desired material thickness requires quite a large amount of deformation. The hot rolling process is required for the realization of this amount of deformation. Strain-hardening makes deformation more difficult, but it also causes the steel material to break and tear to its internal structure. Here, the hot rolling process helps to eliminate the difficulties that occur due to the problems of this structure of steel materials. In the hot rolling process, the material can be deformed at very low loads, which means less energy consumption. There are two purposes for heating raw blocks or semi-finished products before rolling. Firstly, it must provide plasticity to the material, thereby reducing its resistance to shaping. The second is the correction of the inner texture of the steel. To carry out these processes, the materials are heated in annealing furnaces to the required temperature and kept at this temperature for a certain time. The temperature of the ingot at the exit of the furnace is around 1150 ºC. Two events occur in the high-temperature area. Scale formation and carbon burning. Although these formations are not desired, they cannot be prevented. The formation of scale causes loss of material. The material properties deteriorate with the combustion of carbon. Scale causes approximately 1.5-4% material loss. The formation of scale is an undesirable situation. In this study, the effect of the chemical composition of steel materials, rolling speed, and the water-cooling system during rolling on the mechanical properties of the material (yield strength, tensile strength, impact toughness) was investigated.

2.Materials and Methods

2.1 Parameters

This study investigated three different parameters affecting the mechanical properties of hot-rolled products. These are as follows:

- Effects of alloying elements in steel
- Water-cooling pressure
- Rolling speed

During rolling, chemical analysis results were checked for three different grades, the rolling speed value in production was altered, the water pressure value was adjusted during rolling, and how all these values changed the mechanical properties of the products was examined. The rolling speed value was increased every half an hour to observe whether it decreased the mechanical properties, and it was investigated whether the water-cooling pressure, increased with the help of pumps, also changed the mechanical properties. The change in values is shown in Table 1 and Table 2.

Table 1 Rolling speed values in the production line

Production time (minute)	**$V_{Rolling}$ (m/s)**
30	13,4
60	15,2
90	18,7

Table 2 Water-cooling pressure in production

Production order	**Number of water nozzles**	**Water pressure (Bar)**
First Production	3	1,2
Second Production	5	2,1

2.2 Chemical analysis

The chemical analyses were made with a spectrometer The basic principle of the device is based on optical emission. Tests were carried out on pieces of different sizes taken from the production. For proper sample preparation, the sample surface should be well grinded, the surface should be flat so that the surface does not burn while grinding and the surface of the grinder does not miss the light. Chemical analyses have been tested for three different grades. In this study, three different chemical qualities were examined for the prepared 20x5 flat bar using a spectrometer. Considering the chemical analysis, the sample was first ground without burning or damaging the surface.

2.3. Tensile strength test

The tensile strength test was carried out with a 50-ton tensile. It was made by preparing 20x5 flat iron from large sizes. The prepared sample must be free of burrs. In addition, the extracted samples should be properly sized according to the standard and well-shaved from the CNC machine. Tensile sample is shown in Figure 1.

Figure 1. Samples prepared for the tensile test

The amount of flow, shrinkage, and elongation was measured according to quality and different chemical contents. A plastic deformation zone was observed. Three different grades were made separately. First, the L_0 length of the sample was calculated, then the L_1 length was measured, and the amount of elongation was measured. L_0 length was found with the formula cross-sectional area x5.65. The sample was prepared according to EN 10025 standard (Türk Standartları Enstitüsü, 2004). The sample was prepared as a 20x5 flat sheet for the tensile test. The L_0 length was calculated with the formula (cross-sectional area x 5.65). Then, the L_0 length was calculated. Then, the L_1 length was measured manually and the amount of elongation in the sample was calculated.

2.4 Impact test

The impact test was used in the notching device using 300 J. Samples in the size of 55x10x10 were prepared on CNC benches. The sample is shown in Figure 2.

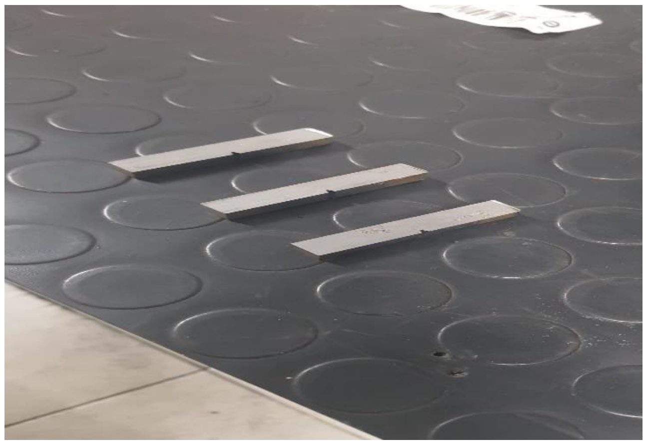

Figure 2. Sample prepared for the impact test

The importance of each millimeter was considered during the preparation of the experiment. In addition, values such as notch depth and temperature were checked. Three different grades were tried, and different temperatures were adjusted according to different grades. The samples were prepared in different conditions, -20 ºC, and room temperature. In addition, the direction of the notch was checked within the standard. According to the EN 10025 standard, a 55x10x10 thick sample was processed and removed on a CNC machine. Then, a notch was made in the middle of the neck. S275 JR quality and S355 JR quality were processed at room temperature, and S355 J2 quality was tested at -20 ºC.

3. Results and Discussion

3.1. Chemical analysis results

According to the results of the chemical tests conducted, it was observed that the quality class of steel changed when the manganese element increased from 0.65-1%. Similarly, it was determined that the quality class became more specialized when the aluminum and vanadium elements transitioned from 0.002% to the range of 0.025-0.029%. It was also noted that the material could produce slag when the copper element exceeded 30%. As shown in Table 3, the carbon values were the same in all samples, but manganese, aluminum, and vanadium differed.

Table 3 Percentage elements in steel products

Quality	C	Si	Mn	P	S	Cr	Ni	Cu	Al	V
S275 JR	0,170	0,240	0,650	0,021	0,016	0,120	0,016	0,300	0,001	0,002
S355 JR	0,170	0,190	1,310	0,021	0,018	0,092	0,082	0,280	0,002	0,003
S355 J2	0,170	0,200	1,220	0,010	0,011	0,090	0,089	0,270	0,025	0,029

Other elements were observed to be close to each other. The values of other chemical elements were not considered as differentiating factors since they were close to each other.

3.2. Tensile strength test results

The results of the tensile test were also examined as another important test. The test results for S275 JR, S355 JR, and S355 J2 have been shown in Fig. 3, Fig. 4, Fig. 5 and Table 4.

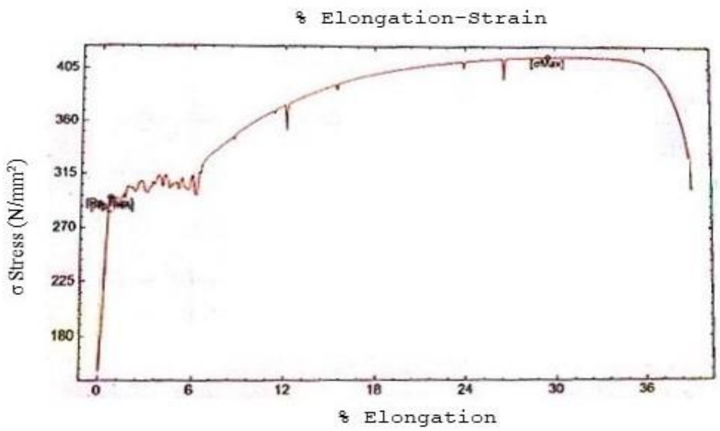

Figure 3. S275 JR tensile test

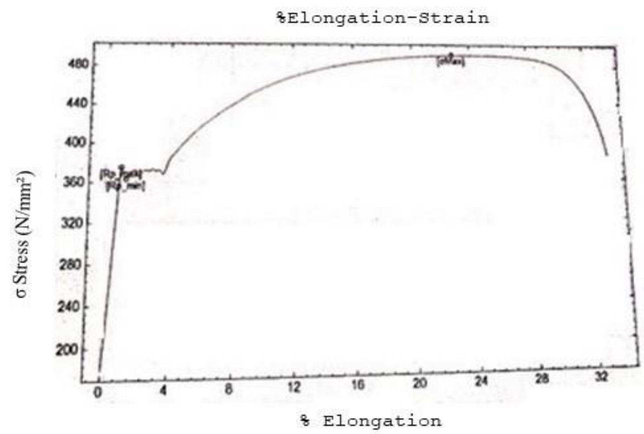

Figure 4. S355 JR tensile test

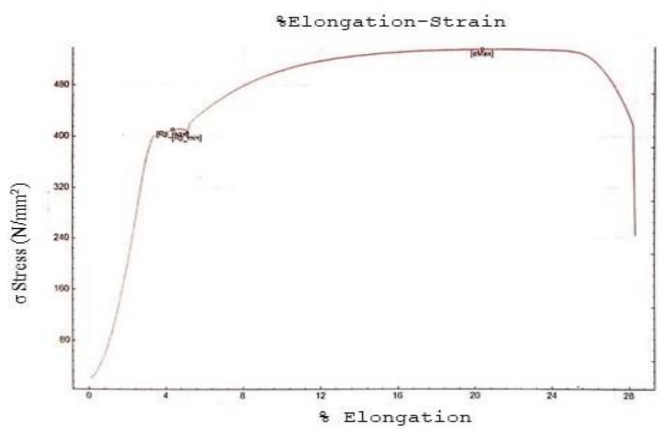

Figure 5. S355 J2 tensile test

Table 4 Tensile test results

Quality	**Yield Value** (N/mm^2)	**Tensile Value** (N/mm^2)	**Elongation** %
S275 JR	293.50	415.12	39.10
S355 JR	368.20	492.67	33.40
S355 J2	403.96	537.35	28.30

A tensile test was carried out for three different samples of S275 JR quality, S355 JR quality, and S355J2 quality. Broken tensile test sample is shown in Figure 6.

Figure 6. A broken tensile test sample

It was observed that the yield strength and tensile value of the S355 J2 sample were higher than that of S355 JR. The values are shown in Table 4. It was observed that the yield strength and tensile strength values of the S355 JR grade are higher than those of the S275 JR grade. Additionally, it was noticed that the material with lower yield and tensile values exhibited a higher elongation.

3.3 Impact test

Finally, notch impact resistance was measured for three different grades. The broken notch sample is shown in Figure 7.

Figure 7. A broken impact test sample

Results for JR grades at room temperature were seen in Table 5, while results for S355 J2 grade were taken at -20 ºC (temperature values according to EN standards) or S275 JR, a value of 33 Joule, for S355 JR, a value of 44 Joule, and for S355 J2 grade, a value of 63 Joule was measured in Table 6.

Table 5 Impact test results for S275 JR and S355JR

Quality	**Impact energy (J) at 25 ºC**
S275 JR	33
S355 JR	44

Table 6 Impact test result for S355 J2 quality

Quality	**Impact energy (J) at -20 ºC**
S355 J2	63

When we combine the three test methods overall, the following observations were made at the end of the experiment: It was seen that the impact resistance of S355 JR quality was higher than the S275 JR quality sample, and the impact resistance of S355 J2 quality was higher than the S355 JR quality. It was observed that vanadium and aluminum elements, which enable the formation of different qualities, increase the impact resistance on hot-rolled steel. As a result of the analysis and experiments, it is seen that the manganese element increased the strength of the steel. The effect of the carbon element on the strength and hardness of steel was observed. However, a discriminator was not used in this test. And then vanadium increased the hardenability of steels to a certain extent and increased the tensile and yield strength. It was observed that it increased the yield strength and impact toughness of aluminum. The mechanical properties of steel at elevated temperatures can be influenced by various parameters, such as the manufacturing process, test methods, rolling speed, and the efficiency of water-cooling pumps (Li et al,2021). The effects of water-cooling pumps and rolling speed were examined during production. When the number of water-cooling pumps decreased, it was observed the flow and shrinkage values of the material decreased. In cases where the rolling speed was increased, there were some physical problems. However, mechanically, the material hardened less because of less water. As a result, its yield and tensile strength decreased.

4. Conclusions

In hot-rolled steel products, it has been observed that the yield strength, tensile value, strength, and hardenability of the steel increase due to the increase in the manganese element in the samples. It has been determined that aluminum and vanadium elements increase the toughness and impact value of steels when used in the range of 0.025-0.029%. The effect of rolling speed on the material's mechanical properties has been observed. When the rolling speed slowed down, the surface of the material was exposed to more water, therefore its mechanical properties increased, and its yield and tensile strength increased. The effect of water-cooling pumps on the mechanical properties of the material was examined. It has been determined that as the number of connected water pumps increases, the yield strength, tensile values , and hardness of the material increase.

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Heat Integration in Synthetic Fuel Production Plants

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Abstract

This study addresses the integration of thermal energy to enhance the quality of energy management in methanol production systems. In this study, the minimum number of heat exchangers (HXs) required for optimum heat transfer was obtained by the pinch analysis method, taking into account temperature ranges and compression temperatures. This approach minimizes energy consumption and maximizes energy recovery, as it allows the waste heat generated within the system to be used in others that need heat. Thus, in order to maintain the system, there is a significant decrease in the amount of heat input and heat loss to the outside. In addition, this study evaluated the carbon emissions from coal at the end of heat integration (HI) and the ability of the system to reduce CO2 emissions. The results show that the heat exchanger network (HEN) optimized by the pinch analysis method significantly reduces the utility consumption and increases the energy recovery in methanol production. Thermal integration leads to a significant increase in emissions reductions, making the process more environmentally friendly. In conclusion, this research highlights the importance of thermal energy integration in methanol production and industrial processes, offering energy efficiency improvements and environmental benefits. As a result of the study, the emission reduction, which was 4513 tons/day with the same number of heat exchangers, increased to 4890 tons/day at the end of heat integration.

Key Words

Heat integration, heat exchanger network, methanol production, thermal load distribution, emissions reduction.

Sentetik Yakıt Üretim Tesislerinde Isı Entegrasyonu

Öz

Bu çalışma, metanol üretim sistemlerinde enerji yönetiminin kalitesini artırmak için termal enerjinin entegrasyonunu ele almaktadır. Bu çalışmada, optimum ısı transferi için gerekli olan minimum ısı değiştirici (HX) sayısı, sıcaklık aralıkları ve sıkıştırma sıcaklıkları dikkate alınarak, pinç analizi yöntemi ile elde edilmiştir. Bu yaklaşım, sistem içinde üretilen atık ısının ısıya ihtiyaç duyan diğer sistemlerde kullanılmasına olanak tanıdığı için enerji tüketimini en aza indirir ve enerji geri kazanımını en üst düzeye çıkarır. Böylece sistemin devamlılığını sağlamak için dışarıya ısı girişi ve ısı kaybı miktarında ciddi bir azalma olur. Ayrıca bu çalışma, ısı entegrasyonu (HI) sonunda kömürden kaynaklanan karbon emisyonlarını ve sistemin CO_2 emisyonlarını azaltma yeteneğini değerlendirmektedir. Sonuçlar, pinç analiz yöntemiyle optimize edilen ısı değiştiricisi ağının (HEN), şebeke tüketimini önemli ölçüde azalttığını ve metanol üretiminde enerji geri kazanımını arttırdığını göstermektedir. Isıl entegrasyon, emisyon azaltımlarında önemli bir artışa yol açarak süreci daha çevre dostu hale getirmiştir. Sonuç olarak bu araştırma, enerji verimliliği iyileştirmeleri ve çevresel faydalar sunan metanol üretimi ve endüstriyel süreçlerde termal enerji entegrasyonunun önemini vurgulamaktadır. Çalışma sonucunda aynı sayıda ısı değiştirici ile 4513 ton/gün olan emisyon azaltımı, ısı entegrasyonu sonunda 4890 ton/gün'e çıkmıştır.

Anahtar Kelimeler

Isı entegrasyonu, ısı değiştiricileri ağı, metanol üretimi, ısıl yük dağılımı, emisyon azaltımı

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1. Introduction

CO_2 capture and storage (CCS) technologies, especially the use of Methyl-Diethanolamine (MDEA) and Piperazine (PZ) adsorbents, when combined with organic Rankine cycles (ORC), playing promising roles in reducing CO_2 emissions and energy consumption Malekli et al., (2023). The chemical reactions and physical distillation that take place in these processes are processes that occur endothermically or exothermically to produce synthetic fuel. Based on this, in order to reduce the total energy need and costs in methanol production, it is possible to meet the energy needs of endothermic processes from exothermic processes by taking into account the temperature levels of the flows Roetzel et al., (2020). Matching the addition and removal of heat utilities in a process is known as heat integration. Heat integration first used in crude preheat trains for oil refinery. Crude oil is first processed in refineries using thermal energy from various product streams before being heated to its final temperature above the atmosphere. Refineries process large quantities of oil; therefore, there is a lot of heat energy in the product streams. The integration of process flow and energy is often implemented even if it provides a low financial return Turton et al., (2008). The ideal way to install a heat exchanger network (HEN) is to install a WHRS or adapt an existing network to perform basic functions at the minimum overall yearly cost; This is determined mainly by operating costs and initial investment cost Masso & Rudd, (1969).

There are mechanical and thermal limitations due to the 1st and 2nd laws of Thermodynamics that must always be taken into account in the design of a system. Therefore, heat is only transferred from the high-temperature stream to the low-temperature stream and vice versa. In addition, the heat transfer amount cannot be greater than the product of the temperature change and heat capacities of one of the flows. In this context, when the temperatures of cold and hot streams are close in HXs, a large heat transfer area is needed (Besevli et al., 2024). Thus, when the driving forces for mass or heat exchange are in lower levels such as temperature difference, the required transfer equipment becomes large, presenting a challenge in design. When looking at systems with multiple HXs exchanging mass or heat (so-called “exchange networks”), it is observed that there is a pinch point, which is a point at which the temperature difference between flows is at a minimum value. Therefore, to ensure the success of designing HENs, the pinch point should be detected, and the characteristics of this point should be used to design the entire network. Boldyryev, S, (2018), the study identified the potential for utilizing waste heat from cement production and determined a site-wide recovery potential using process integration techniques. The author used an energy consumption analysis of a cement factory to determine the minimal energy requirements for production and then suggested ways to increase energy efficiency using a process integration technique. According to the authors, the cement factory's energy use may be cut by 30%. The outcomes contribute to the cement plant's profitability and lessen the industry's negative environmental effects while also promoting sustainability Boldyryev, (2018). Pavia, R. et al, (2023) In this study, a heat integration method for separating monochlorobenzene was suggested. Design and simulation were done for both the traditional process structure and the suggested integrated one. Optimization was conducted with the aim of reducing the expenses related to cooling and heating while simultaneously identifying the optimal operating conditions for heat integration. A simulation of a utility plant was conducted, encompassing both cooling water and steam generation components, in order to attain more precise approximations of CO2 emissions, water and energy usage, as well as operating expenses. The sustainable performances of the processes were assessed through the utilization of the eco-efficiency comparison index method and a range of environmental and economic indicators, namely CO2 emissions, water consumption, and utility costs. This was done to evaluate the benefits of heat integration and compare the processes in question. The study found that the suggested approach lowered nearly 57% of environmental effects and utility expenses. The composite evaluation index revealed that the proposed heat-integrated industrial plant improved the eco-efficiencies of initial processes by up to 83%, indicating a viable and sustainable strategy Paiva et al., (2023). Zhai et al., (2023), was based on heat integration and heat pump techniques, using three energy-efficient pressure-swing distillation processes to address the problem of high energy consumption in traditional pressure-swing distillation. The heat integration and heat pump, with a capital payback time of 3 years, may save 31.44% and 51.30% of the total yearly cost when compared to the planned traditional pressure-swing distillation, respectively Zhai et al., (2023). Liang et al (2023), in this research, an equation-based optimization framework is presented for the simultaneous heat integration and flowsheet optimization of the combined cooling, heating, and power system based on the methanol-steam-reforming proton exchange membrane fuel cell. Researchers applied the framework to a 1000 kW combined cooling, heating, and power generation system, and the integrated design produced a levelized cost of electricity of 0.2374 $/kWh and an energy efficiency of 88.50%. The results indicate that, in comparison to a conventional design, simultaneous heat integration and flowsheet optimization can improve the system's energy efficiency by 5.45 percentage points, exergy efficiency by 2.22 percentage points, and the levelized cost of electricity by 4.50% Liang et al., (2023).

When the literature is examined, synthetic fuel production processes generally focus on issues such as production efficiency, energy consumption of systems and production costs, but issues such as thermal processes in these processes, heat exchanger networks and optimization of thermal load distribution have not been examined much. Since more than one heat exchanger interacts with each other directly or indirectly in long processes such as synthetic moxibustion production, the thermal load of the process should be calculated clearly and whether the system has a thermal requirement from an external source should be examined. In this study, the heat exchanger network of a methanol production facility was considered, and the thermal loads required to maintain the system were calculated. Afterwards, the heat exchanger network was optimized using pinch analysis, and external heat input was eliminated by preventing heat rejections from the process.

2. Material and Methods

Methanol production is important for several reasons. Firstly, methanol is a versatile chemical compound that can be used as a building block for obtaining more complex chemical structures and as a clean-burning fuel with a high-octane number Dalena et al., (2018). Secondly, the biological conversion of methanol through natural and synthetic methylotrophs expands the chemical repertoire and contributes to a one-carbon (C1)-based chemical economy Chen & Lan, (2020). Thirdly, methanol production based on renewable energy provides a sustainable option for fuel production and is extensively used in the chemical industry Vesterinen, (2018). Additionally, methanol can be produced from carbon dioxide, which is abundant due to anthropogenic activities, offering a potential solution for reducing greenhouse gas emissions Sivadinarayana et al., (2020). Overall, methanol production plays a crucial role in various industries and offers potential solutions for reducing environmental impact and meeting energy demands. Thermal energy plays a crucial role in methanol production systems. Concentrated solar thermal technology can be used to produce methanol by utilizing solar heat to generate hydrogen and carbon monoxide, which are the main constituents of synthesis gas Monnerie et al., (2020). Additionally, the use of solar energy in a thermochemical reactor can reenergize carbon dioxide into carbon monoxide, which can then be used in the methanol synthesis process (Mancusi et al., 2021). The integration of different systems, such as catalytic partial oxidation reactors and fluidized bed systems, can optimize the production process and improve energy efficiency Kim et al., (2011); MACHIDA et al., (1998).

The fresh wet hydrogen supply from chlorine generation by salt electrolysis is compressed to 45 bar in (I). The mixture from the methanol plant (VI) and the carbon dioxide from the carbon capture plant are mixed in the mixing chamber and the resultant gas mixture (VII) is heated in the FEHE by the reactor outlet stream (XI) before being fed to a reactor that is isothermally operated at 50 bar. The reactor outlet stream (XII) is cooled down in the FEHE unit and another cooler (XIII) before being flashed in a separator to separate the recycled non-condensable gas components such as CO, CO2, and H2, from the methanol and liquid water liquid. A second compressor receives the recycle stream after it has been purged and combined with the fresh CO2 feed stream. The compressed wet hydrogen stream (I) is fed in counter-current mode to a Stripping Column (SC), where the liquid stream of the flash is transmitted. In addition to drying the hydrogen feed and removing the light ends like CO2 and CO, which are totally recycled, this also eliminates water from the reactor feed. The distillation column (DC), which separates water as the bottom product from methanol as the top distillate, receives the liquid bottom stream from the stripper (XIV-XV). It is important to keep in mind that employing the stripper unit results in a higher-temperature liquid outflow that contains a methanol-water mixture. As a result, the reboiler duty is lowered. A partial condenser that can yield a vapor distillate (lights), a high purity liquid methanol distillate (XVI), and water (XVII) as a bottom product is used to separate the methanol-water stream in a single distillation column. Overall layout of the process was provided in Fig 1.Kiss et al., (2016); Ozcan & Kayabasi, (2021).

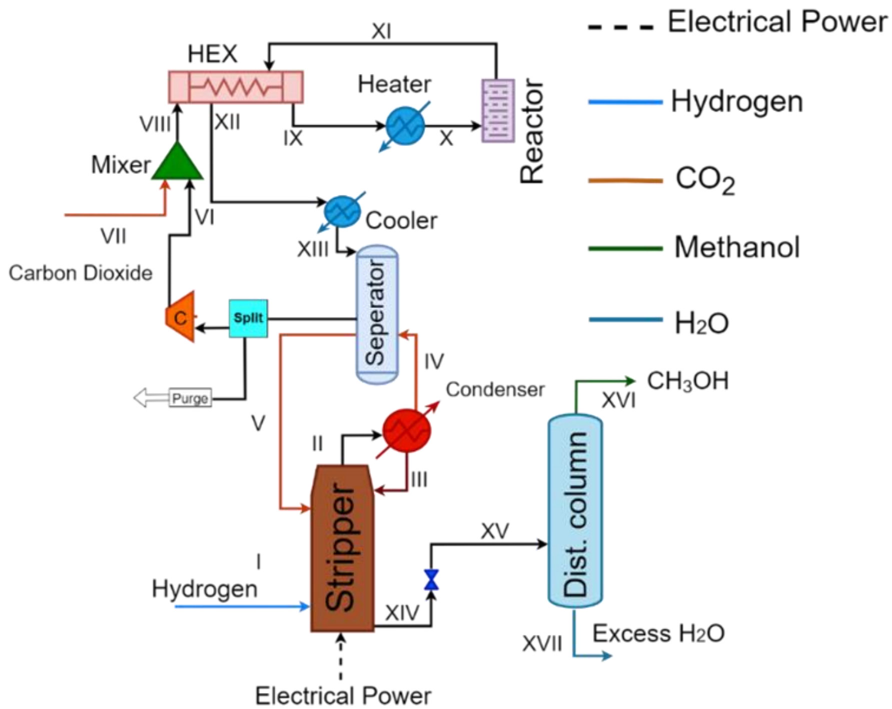

Figure 1. *Flow chart of Methanol production unit with heat integration.*

Oil refineries consist of systems where significant amounts of oil are processed, and product streams carry high amounts of thermal energy. Therefore, process flow and energy balance are widely used to reduce energy costs between thermal processes. Turton et al., (2008). The total number of utilities required to perform energy transfers in these processes can be reduced or, more precisely, increased by the heat integration method for matching the addition and removal of heat.

In this study, a general algorithm was used to determine the minimum thermal resource (utility) required for the given minimum temperature difference. In a HEN, the optimization process is, respectively, determining the lowest approach temperature, temperature diagram showing the temperature ranges, cascade diagram where the pinch temperature is determined, minimum utility requirement and finally calculating the lowest number of heat exchangers. Considering the logarithmic mean temperature difference $(\Delta T_m)_{ln}$ and the overall heat transfer coefficient (U), the heat transfer (Q) equation can be written as:

$$Q = UA(\Delta T_m)_{ln} \tag{1}$$

The ΔT_m is defined as logarithmic mean temperature difference that is indicating any logarithmic mean temperature value between the flows as below:

$$\Delta T_m = \frac{\Delta T_1 - \Delta T_2}{ln\frac{\Delta T_1}{\Delta T_2}} \tag{2}$$

The following relation can be constructed to determine the least number of HXs is employed:

$$N_{min} = N_h + N_c + N_u - 1 \tag{3}$$

Here, N_h, N_c, N_u are number of hot flows, number of cold flows and number of utilities respectively Turton et al., (2018).

The principles for coupling hot flows and cold flows for blocks above the pinch point based on a diagram of temperature ranges that includes all blocks above the pinch point, starting with the lower block and working upward, transferring heat horizontally from the hot side to the cold side. Heat transfer can occur diagonally downwards, but never diagonally upwards. First the hot flow is matched with the product of the smallest heat capacity and temperature difference ($\dot{m}C_p\Delta T$), for flows touching the pinch point $\dot{m}C_{p,hot}\Delta T \leq \dot{m}C_{p,cold}\Delta T$. If this condition is not met, the condition must be met by reducing the heat capacities by dividing the hot flow into two or three. For blocks below the pinch point, a temperature range diagram is drawn up that includes all blocks below the pinch point, and the flows are matched to each other, starting with the upper block and downward, transferring heat horizontally or diagonally downward from the hot side to the cold side. However, it is never matched diagonally upwards. First, the hot flow is matched to the smallest $\dot{m}C_p\Delta T$. For flows touching the pinch point, $\dot{m}C_{p,hot}\Delta T$ must $\leq \dot{m}C_{p,cold}\Delta T$. If this condition is not met, the cold flow heat capacities must be divided into two or three to ensure the condition.

The emissions are estimated using the quantity of fuel utilized in the combustion processes and the average emission factor depending on the process type listed in the related tables in the reports of IPCC. Equation 4 illustrates how the IPCC Tier 1 technique was used to get the C emissions factor from coal IPCC, (1996).

$$C_C = 32.15 - (0.234 \times H_V) \tag{4}$$

Here, H_V is the gross calorific value of coal, which varies from 31 to 37 TJ/kiloton on a dry, mineral-free basis, and C_C is the carbon emission factor in t C/TJ. The system uses a lot of carbon dioxide, which results in a large reduction in GHG emissions. However, there are a lot of indirect greenhouse gas emissions since the system depends so largely on thermal energy. The CO2 reduction capacity of the system may then be computed using Eq. 5.

$$ER_{net} = ER_{utilization} - ER_{generation} \quad (5)$$

Here, $ER_{generation}$ is the quantity of carbon dioxide created during the process, $ER_{utilization}$ is the amount of carbon dioxide utilized in system processes, Total carbon dioxide emissions are represented by ER_{net}.

3. Results and Discussions

We examined the heat Exchange network based on the pinch theory and the thorough instructions supplied by Turton Turton et al., (2018) in order to optimize the energy recovery and decrease the utility consumption of the methanol production system. The minimum heat transfer temperature differential, also known as the minimum driving force for heat exchange, was adjusted to 10°C after taking into account the actual operating circumstances, financial advantages, and heat exchange area of the methanol production system. Following the integration of the process heat, the system's optimized HEN was created. In Fig. 2 and Fig. 3, it is seen that the pinch temperature is 320 °C.

Table 1. Thermal data for streams.

Stream No.	**Flow Type**	**ṁ (kg/s)**	**Cp (kJ/kg °C)**	**ṁ×Cp (kW/°C)**	**T_{in} (°C)**	**T_{out} (°C)**	**$\dot{Q}$ (kW)**
1	Hot	354	2.44	863	523	304	189163
2	Hot	11	8	88	320	303	1496
3	Cold	354	2.65	938	301.2	498	-184757
Total							5902

Every stream was represented as a vertical line in a graphic of temperature intervals, with the streams that required cooling on the left and the streams that required heating on the right. The temperature interval plot is displayed in Fig. 2.

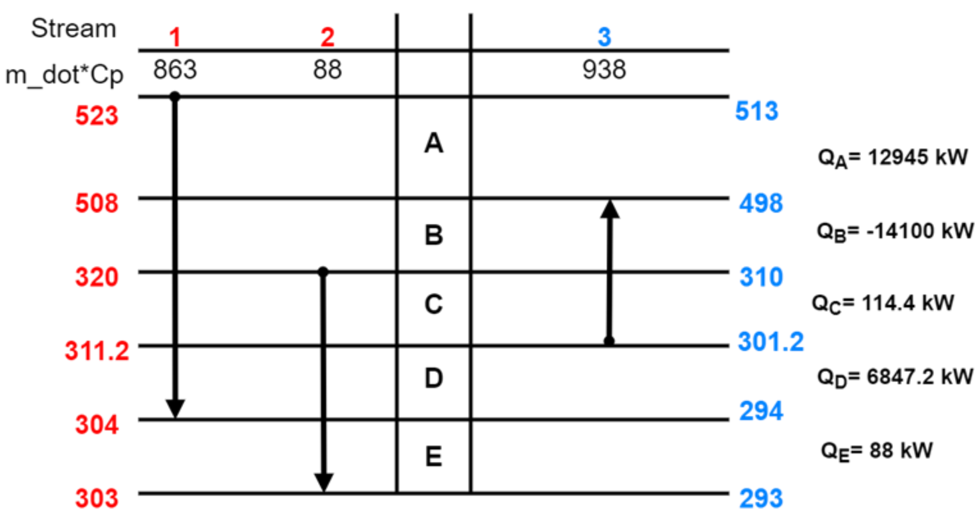

Figure 2. Diagram of temperature intervals.

5894.6 kW is the total enthalpy excess for all streams, as indicated in the right column. The net energy from hot streams to cold streams in each temperature interval is 7049.6 kW, as Fig. 3 illustrates. Point B is where the pinch point appears. Heat is transferred via temperature gradients; if energy is abundant, the hot utility will ultimately need to transfer its excess heat to the cold utility.

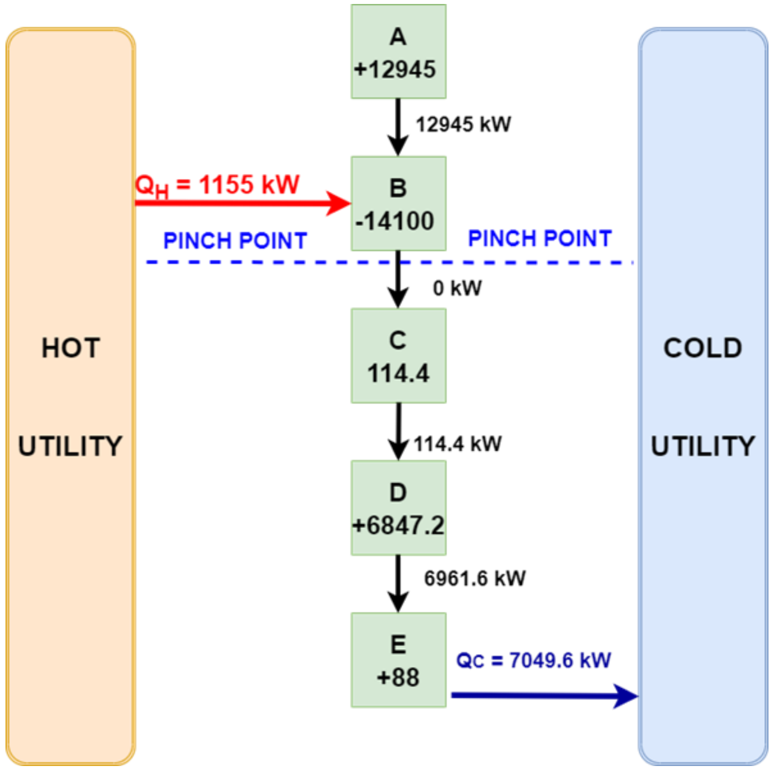

Figure 3. Cascade diagram of HXs.

As seen in Fig. 4, the system's optimal HEN and the least number of HXs required to transmit heat to the minimum facility design were established after the heat integration procedure.

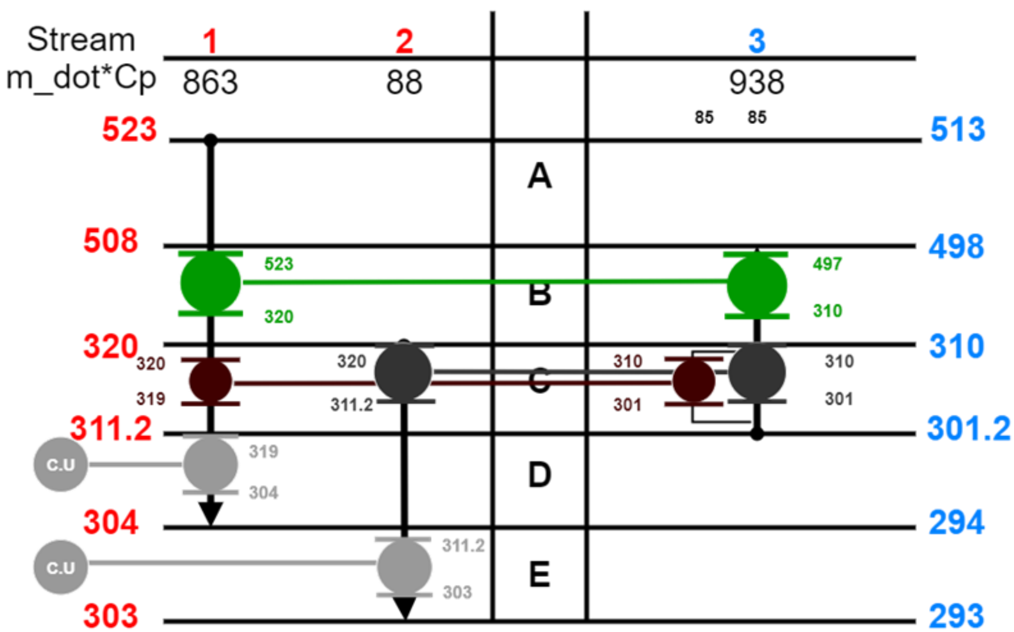

Figure 4. Design of HEN.

For each process HX in networks 1, 2, and 3, the $(\Delta T_m)_{ln}$, surface area, heat transfer, and overall heat transfer coefficient were calculated using Eq. 2. A thorough flow diagram of the HEN is displayed in Fig. 5, and a summary of these results is given in Table 2:

Table 2. Summary of findings for exchangers.

Heat Exchanger	$(\Delta T_m)_{ln}$ (K)	U (kW/m^{2}K)	Q (kW)	A (m^2)
1	16.74	0.5	175189	20924
2	13.61	0.5	863	126.8
3	10.1	0.5	774.4	153.4
Total				21204.2

The final HEN is shown in Fig. 5. This network has the minimum number of HXs, for the minimum utility requirements, using a minimum approach temperature, for ΔT = 10°C.

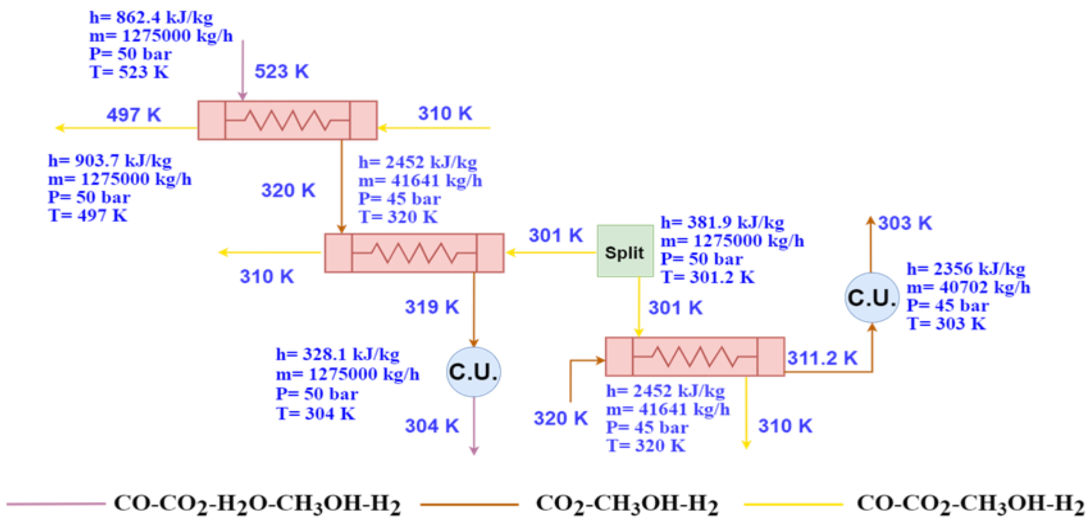

Figure 5. Detailed flow diagram of HEN after heat integration.

Emission reduction before and after heat integration is given in Fig. 6. After the heat integration, it has been revealed that all of the fuel spent to meet the heat need in the facility can be derived from the heat produced in the facility. Accordingly, after heat integration, an increase of 377 tons/day is observed in emission reduction.

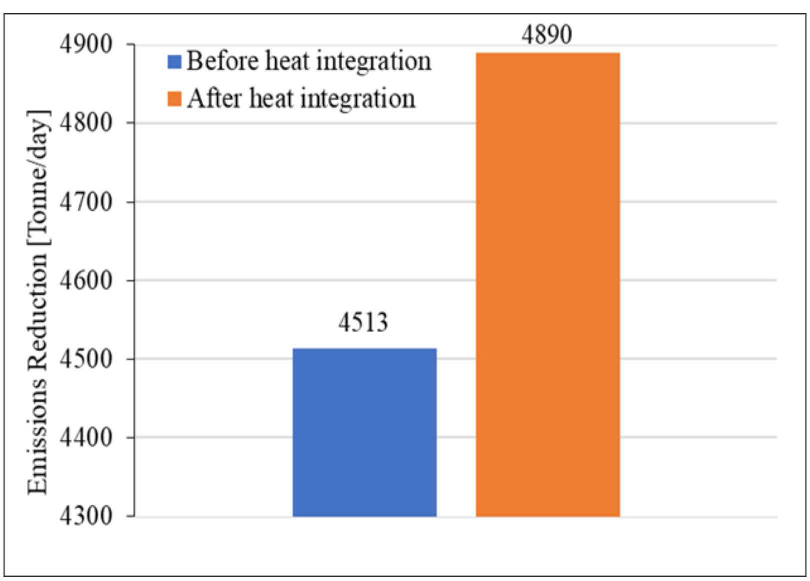

Figure 6. Emissions reduction before and after heat integration.

4. Conclusion

As a result of this study, the application of pinch theory and heat exchange network optimization to the methanol production system has yielded substantial benefits. By carefully matching heat additions and removals within the process, we have achieved a remarkable reduction in utility consumption and emissions. The optimized HEN, designed with a minimum approach temperature of 10°C, effectively utilizes available thermal energy within the system, reducing the reliance on external utilities. This integration not only enhances energy recovery but also contributes to a more sustainable and environmentally friendly methanol production process. The findings highlight the importance of considering heat integration strategies in industrial processes to improve energy efficiency and reduce environmental impact.

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Review Article

Reviewing the Multi-Sectoral Application of Life Cycle Assessment (LCA) for Environmental Impact Evaluation and Integration with Socio-Economic Analysis for Sustainable Practices

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Abstract
This review analyzes the application of LCA in assessing the environmental effects of products, processes, and services in different industries. The study utilizes academic databases and hand-picked papers from 24 countries to examine recent advancements in LCA applications during the past two decades. The objective is to identify prospects for enhancing LCA methodologies and improving environmental impact assessments in diverse sectors and geographic regions. The LCA method is subject to limitations, one of which is its failure to consider socioeconomic factors. In order to tackle these issues, it is necessary to employ additional approaches, such as the Regional Sustainability Assessment Methodology. In order to enhance project management in the construction sector, combining LCA with Building Information Modeling is beneficial. On the other hand, dynamic modeling techniques and quantitative microbial risk assessment are necessary in agriculture. The Packaging Impact Quick Evaluation Tool assists in the decision-making process for food packaging development while integrating LCA with GIS in transportation enhances accuracy and precision. Researchers can assess shipping operations' environmental impact and energy efficiency by integrating LCA with the Energy Efficiency Design Index and Energy Efficiency Operation Index.

Key Words
Life Cycle Assessment (LCA), Sustainability, LCA applications, LCA limitations, LCA development, Geographic Information Systems (GIS)

Çok Sektörlü Yaşam Döngüsü Değerlendirmesi (YDD) Uygulamalarının Çevresel Etki Değerlendirmesi ve Sosyo-Ekonomik Analiz ile Entegrasyonu Üzerine Bir İnceleme: Sürdürülebilir Uygulamaların Değerlendirilmesi

Öz
Bu inceleme, YDD uygulamasının farklı sektörlerdeki ürünlerin, süreçlerin ve hizmetlerin çevresel etkilerini değerlendirmede kullanımını analiz ediyor. Çalışma, son yirmi yıldaki YDD uygulamalarındaki son gelişmeleri incelemek için 24 ülkeden akademik veri tabanlarını ve özenle seçilmiş makaleleri kullanıyor. Amaç, YDD metodolojilerini geliştirmek ve farklı sektörlerde ve coğrafi bölgelerde çevresel etki değerlendirmelerini iyileştirmek için potansiyelleri belirlemektir. YDD yöntemi, sosyo-ekonomik faktörleri hesaba katmaması gibi kısıtlamalara sahiptir. Bu sorunları ele almak için, Bölgesel Sürdürülebilirlik Değerlendirme Metodolojisi gibi ek yaklaşımlar kullanmak gerekir. İnşaat sektöründe proje yönetimini geliştirmek için, YDD'yı Bina Bilgi Modellemesi ile birleştirmek faydalıdır. Öte yandan tarımda dinamik modelleme teknikleri ve kantitatif mikrobiyal risk değerlendirmesi gereklidir. Gıda ambalajı geliştirme sürecinde karar verme sürecine yardımcı olan Ambalaj Etkisi Hızlı Değerlendirme Aracı, YDD'yı Ulaştırmada Coğrafi Bilgi Sistemleri (CBS) ile entegre etmek ise doğruluk ve hassasiyeti artırır. Araştırmacılar, YDD'yı Enerji Verimliliği Tasarım Endeksi ve Enerji Verimliliği İşletme Endeksi ile entegre ederek deniz taşımacılığının çevresel etkisini ve enerji verimliliğini değerlendirebilirler.

Anahtar Kelimeler
Yaşam Döngüsü Değerlendirmesi (YDD), Sürdürülebilirlik, YDD uygulamaları, YDD kısıtlamaları, YDD gelişimi, Coğrafi Bilgi Sistemleri (CBS)

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1. Introduction

1.1. Life Cycle Assessment (LCA) Overview

Assessing the environmental impacts of products, processes, and services, whether the impacts are direct or indirect, is crucial. The Life Cycle Assessment (LCA) methodology is essential for evaluating the environmental impact. LCA offers a thorough assessment that is highly appealing. It evaluates the environmental impact of products, processes, and services throughout their entire lifecycle, from extraction to disposal. The LCA results provide valuable insights into the environmental impact of products, processes, and services. Understanding and acknowledging the benefits and limitations of the LCA tool are crucial aspects of sustainability efforts and informed decision-making for a more environmentally aware future. The comprehensive nature of LCA arises from its consideration of various crucial environmental factors, such as resource consumption, energy usage, air and water pollution, soil degradation, and overall environmental deterioration. This comprehensive approach provides a holistic perspective, enabling stakeholders to recognize opportunities for environmental enhancement and make well-informed choices regarding product development and resource management. Curran (2013) highlights the importance of the LCA methodology in evaluating the environmental impact of products and processes. This methodology is closely aligned with the core objective of sustainability evaluation. This emphasis underscores the significance of LCA in advocating for sustainable practices and directing decision-making towards solutions that are more ecologically sound. Although LCA frequently evaluates the environmental effects of products or processes, it might not fully tackle the broader sustainability factors linked to economic and social aspects (Maier et al., 2016; Padilla-Rivera et al., 2019; Nikolić et al., 2019; Mahmood et al., 2018). These sources assert that LCA primarily emphasizes environmental impacts while occasionally overlooking the social and economic dimensions of sustainability. Maier et al. (2016), Padilla-Rivera et al. (2019), Nikolić et al. (2019), and Mahmood et al. (2018) suggest utilizing alternative methodologies or approaches to assess social and economic impacts. They acknowledge the importance of LCA in evaluating environmental effects. However, previous studies did not adequately explain how the benefits and applications of LCA could serve as the foundation for its development in various sectors.

The LCA method evaluates various materials, highlighting the adaptability of this approach in appraising a wide range of products and materials, with a particular emphasis on their environmental attributes. An important deficiency identified in the literature is the requirement for a more extensive framework that connects life cycle sustainability inquiries to the necessary knowledge for addressing them (Guinée et al., 2010). There is a significant lack of research regarding the sensitivity of LCA modeling choices, specifically when it comes to evaluating the environmental impacts of buildings (Häfliger et al., 2017). Moreover, the absence of a uniform approach for carrying out life cycle sustainability assessments presents a notable obstacle in contemporary LCA research (Nikolić et al., 2019). Moreover, the absence of comprehensive protocols for carrying out LCA studies in particular sectors, such as the geothermal industry, obstructs the ability to compare outcomes and restricts the efficacy of environmental evaluations (Parisi et al., 2020). LCA is an essential tool used to assess the environmental consequences of products, processes, and services. Although LCA provides a thorough evaluation of environmental impacts, it frequently neglects considerations of social and economic sustainability. This study seeks to fill this void by examining the practicability of integrating social and economic factors into current LCA frameworks.

The current research on LCA also emphasizes the necessity of adopting a more cohesive approach and enhancing data collection methods in particular sectors. This study examines the utilization of LCA in eight crucial sectors and highlights opportunities for enhancement, specifically concerning data sensitivity and the absence of standardized protocols in sectors such as geothermal energy.

This research aims to improve the comprehensiveness and applicability of LCA by analyzing and addressing its limitations. We aim to enhance the development of a comprehensive LCA framework that incorporates social, economic, and environmental factors, with the ultimate objective of fostering sustainable decision-making in diverse industries.

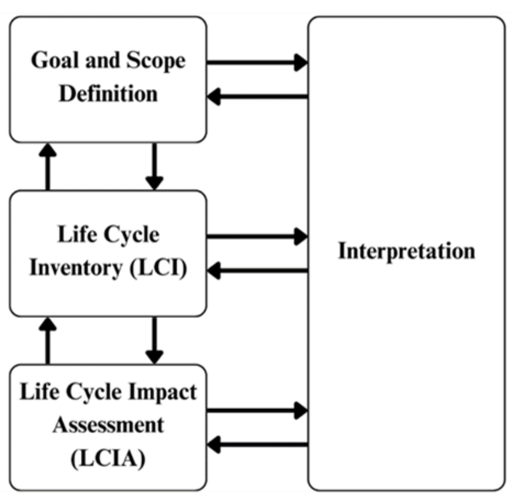

Figure 1. Life Cycle Assessment Framework (Adopted from ISO 14040:2006).

1.2. LCA Framework

The LCA methodology has undergone substantial development to thoroughly assess environmental impacts across diverse sectors. In the 1970s, LCA primarily concentrated on energy analysis. However, it has evolved into a comprehensive assessment of environmental burdens over time (Guinée et al., 2010). Figure 1 illustrates the LCA methodology, which consists of four main steps: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation (ISO 14040:2006; Diyarma et al., 2019).

1.2.1. Goal and scope definition

Prior to conducting an assessment, it is crucial to ascertain the objectives, limitations, and intended applications of the assessment. The definition of goal and scope is the initial and crucial stage that establishes the foundation for a meticulously designed LCA study (ISO 14040:2006). This stage encompasses the identification of the functional unit, the establishment of system boundaries, and the selection of impact categories for evaluation. In order to conduct a thorough assessment, it is essential to establish the parameters for evaluating the various stages of the life cycle, which include production, distribution, use, and disposal (ISO 14040:2006).

During the goal and scope definition phase, it is imperative to establish a process for quality assurance in order to guarantee the dependability and uniformity of the evaluation (Kłos, 2002). In order to conduct the assessment, it is necessary to determine the origins of the data, the methodologies to be employed, and the assumptions to be made. Additionally, it is important to recognize any limitations or uncertainties in the analysis (Finnveden et al., 2009). Multiple scenarios can be contemplated to accommodate fluctuations and uncertainties in technology and the environment. The initial stage of the LCA, as described by Fuc et al. (2016), establishes the limits and objectives of the assessment, providing a definitive plan for subsequent stages, including the life cycle inventory analysis, life cycle impact assessment, and interpretation.

1.2.2. Life cycle inventory (LCI) analysis

The LCI encompasses a comprehensive gathering of data on all the inputs and outputs associated with a product or process. The collected data encompasses the entire life cycle of a product, from the extraction of raw materials to its production, usage, and disposal stages, as defined by the ISO 14040:2006 standard. The significance of this step has been underscored by multiple studies (Diyarma et al., 2019; Chandra et al., 2018; Pons et al., 2018). LCI is the process of methodically measuring and gathering data. This thorough approach includes evaluating the amount of energy used, the materials used, and the resulting outputs throughout the entire lifespan of a product (Pons et al., 2018; Curran, 2013). LCI enables the assessment of environmental performance among different options. This step is crucial for identifying important environmental areas of concern and the processes that have the greatest impact (Mohd Azman et al., 2021). LCI has gained widespread use due to the availability of software tools like OpenLCA, GaBi, and SimaPro. These tools assist in assessing the environmental impacts of various industrial processes.

When comparing these software tools, Open LCA stands out for its user-friendly interface and accessibility to databases like ecoinvent, making it suitable for conducting LCA analyses in a straightforward manner (Pons et al., 2018). Gabi, on the other hand, is known for its comprehensive databases and detailed LCI analysis capabilities, making it ideal for in-depth assessments across different sectors (Pero et al., 2023). SimaPro excels in offering a wide range of impact assessment methods, allowing for a thorough evaluation of environmental impacts in complex systems (Fuć et al., 2016). Overall, The choice of software would depend on the specific requirements of the LCA study and the complexity of the system being analyzed.

1.2.3. Life cycle impact assessment (LCIA)

After finishing the LCI phase, the focus shifts to the life cycle impact assessment (LCIA) phase, which is described in detail by Suryawan et al. (2020) and Acero et al. (2015). During this stage, the product or service's potential environmental impacts are methodically categorized, described, and evaluated for their importance (Young et al., 2021). This crucial phase efficiently converts numerical LCI data into descriptive indicators that express the environmental impact of the product or service across various categories of influence, as defined by the International Organization for Standardization (ISO 14040:2006). The LCIA methodology involves the analysis of various factors, such as resource use, emissions, and their potential impacts on human health, the natural ecosystem, and resource depletion. The evaluation thoroughly assesses the effects in various areas, including global warming, acidification, eutrophication, human toxicity, and resource depletion. Table 1 provides a concise overview of the commonly used impact categories. It is essential to utilize LCIA methods in order to gain a thorough understanding of the environmental consequences of products and services. These methods assess the impacts of resource utilization and emissions across the entire life cycle of a product or service, encompassing activities from the extraction of raw materials to the disposal of waste. It is crucial to take into account the impact assessment categories of these methods. Table 2 displays the LCIA methods, as well as the corresponding impact categories available for each method.

1.2.4. The interpretation

The interpretation stage facilitates well-informed decision-making. It adheres to sustainability principles by pinpointing environmental hotspots and areas for potential enhancement across the product's entire lifespan, encompassing production, usage, and disposal (Hertwich, 2005). It is possible to come to conclusions and make suggestions for improving environmental performance by carefully looking at and making sense of the LCA results from the inventory and impact assessment stages (Palousis et al., 2008). A thorough comprehension of environmental consequences enables the comparison of various products or services, ultimately facilitating the selection of more sustainable alternatives (Flipse, 2014).

Table 1. Short Description of The Most Used Environmental Impact Categories (Acero et al., 2015).

Impact Category	Explanation	Indicator	Damage (Endpoint) Categories
Acidification	The decrease in pH caused by the acidifying impact of human-made emissions	Rise in the acidity levels in water and soil systems	Ecological degradation and biodiversity loss
Climate change	Global temperature change resulting from the presence of greenhouse gases	Disruptions in worldwide temperature and climatic occurrences	- The overall decline in biodiversity, including crops, forests, coral reefs, and other ecosystems. - Thermal fluctuations -Anomalous climatic phenomena, such as intensified cyclones and heavy storms.
Depletion of abiotic resources	The decline in the accessibility of non-biological resources (both non-renewable and renewable) due to their unsustainable utilization.	Diminution of resources.	Destruction of natural resources and potential collapse of the ecosystem
Ecotoxicity	The detrimental impacts of chemicals on an ecosystem.	The decline in biodiversity and the disappearance of species.	Destruction of the ecosystem and extinction of species.
Eutrophication	Nutrient accumulation in aquatic ecosystems.	-Elevated levels of nitrogen and phosphorus concentrations - Production of organic matter through the growth and accumulation of biomass, such as algae.	Ecological degradation.
Human toxicity	Adverse impacts of chemical substances on human health.	The health risks associated with ionizing radiation include cancer, respiratory diseases, and other non-carcinogenic effects.	Health of the human body.
Ionising radiation	Ionizing radiation consists of particles with sufficient energy to free an electron from an atom or molecule.	Consequences of radiation exposure include deteriorating health, increased risk of cancer, and various illnesses.	Impact of human well-being on the quality of ecosystems.
Land use	The effects on the land resulting from agriculture, human settlement, and the extraction of resources.	Loss of biodiversity, erosion of soil, quantity of organic matter, etc.	Depletion of natural resources, both non-renewable and renewable.
Ozone layer depletion	The stratospheric ozone layer is being reduced as a result of human activities that release ozone depleting substances.	The rising in ultraviolet UV-B radiation has led to an increase in the number of cases of skin illnesses.	The interrelationship between human health and the quality of ecosystems.
Particulate matter	These are minute particles that are suspended in the air and are produced by human activities such as burning and extracting resources.	There is an elevation in the concentration of various particles of different sizes that are suspended in the air, specifically particles with diameters of PM10, PM2.5, and PM0.1.	Health of the human body.
Photochemical oxidation	Photochemical smog is formed as a result of the interaction between sunlight, heat, and the emissions of non-methane volatile organic compounds (NMVOC) and nitrogen oxides (NOx).	Rise in the occurrence of summer smog.	The interplay between human health and the quality of ecosystems.

Table 2. The presence of impact categories in method (✓)means that those categories are included in that method, while any categories not included are represented by (–) (Acero et al., 2015).

Methods	Acidification	Climate change	Resource depletion	Ecotoxicity	Energy use	Eutrophication	Human toxicity
CML (baseline)	✓	✓	✓	✓	–	✓	✓
CML (non-baseline)	✓	✓	✓	✓	–	✓	✓
Cumulative Energy Demand	–	–	–	–	✓	–	–
Eco-indicator 99 (E)	✓	✓	✓	✓	–	✓	✓
Eco-indicator 99 (H)	✓	✓	✓	✓	–	✓	✓
Eco-indicator 99 (I)	✓	✓	✓	✓	–	✓	✓
Eco-Scarcity 2006	–	–	✓	–	–	–	–
ILCD 2011, endpoint	✓	✓	–	–	–	✓	✓
ILCD 2011, midpoint	✓	✓	✓	✓	–	✓	✓
ReCiPe Endpoint (E)	✓	✓	✓	✓	–	✓	✓
ReCiPe Endpoint (H)	✓	✓	✓	✓	–	✓	✓
ReCiPe Endpoint (I)	✓	✓	✓	✓	–	✓	✓
ReCiPe Midpoint (E)	✓	✓	✓	✓	–	✓	✓
ReCiPe Midpoint (H)	✓	✓	✓	✓	–	✓	✓
ReCiPe Midpoint (I)	✓	✓	✓	✓	–	✓	✓
TRACI 2.1	✓	✓	✓	✓	–	✓	✓
USEtox	–	–	–	✓	–	–	✓

Table 2 (Continued). The presence of impact categories in method (✓)means that those categories are included in that method, while any categories not included are represented by (–) (Acero et al., 2015).

Method	Ionising Radiation	Land use	Odor	Ozone layer depletion	Particulate matter/ Respiratory inorganics	Photochemical oxidation
CML (baseline)	–	–	–	✓	–	✓
CML (non-baseline)	✓	✓	✓	✓	–	✓
Cumulative Energy Demand	–	–	–	–	–	–
Eco-indicator 99 (E)	✓	✓	–	✓	✓	–
Eco-indicator 99 (H)	✓	✓	–	✓	✓	–
Eco-indicator 99 (I)	✓	✓	–	✓	✓	–
Eco-Scarcity 2006	–	–	–	–	–	–
ILCD 2011, endpoint	✓	✓	–	✓	✓	✓
ILCD 2011, midpoint	✓	✓	–	✓	✓	✓
ReCiPe Endpoint (E)	✓	✓	–	✓	✓	✓
ReCiPe Endpoint (H)	✓	✓	–	✓	✓	✓
ReCiPe Endpoint (I)	✓	✓	–	✓	✓	✓
ReCiPe Midpoint (E)	✓	✓	–	✓	✓	✓
ReCiPe Midpoint (H)	✓	✓	–	✓	✓	✓
ReCiPe Midpoint (I)	✓	✓	–	✓	✓	✓
TRACI 2.1	–	–	–	✓	✓	✓
USEtox	–	–	–	–	–	–

2. Methodology

2.1. Objectives

The objective of this study was to examine the present applications of LCA methodology across various industries. The objective is to enhance the understanding of decision-makers, designers, and practitioners in diverse domains regarding the significance of employing LCA for the sustainable and responsible governance of human activities. This measure will aid in safeguarding human well-being, preserving natural resources, and preserving the overall health of the planet.

2.2. Search Strategy

The academic databases ScienceDirect, Scopus, and Web of Science were used to conduct a literature search on environmental impact assessment. The search strategy utilized the term LCA along with relevant sectors for environmental impact assessment and corresponding keywords for each sector. The sectors encompassed in the study are construction, wastewater treatment, agriculture, waste management, manufacturing, energy, packaging, and transportation. By combining these search terms, the search yielded a comprehensive collection of relevant literature on the environmental impact assessment of various sectors.

2.3. Geographical Scope

The selected papers spanned a broad geographical area, involving research conducted in 24 countries: Australia, Brazil, Canada, China, England, France, Germany, Greece, India, Indonesia, Iran, Italy, Japan, Lithuania, Poland, Portugal, Saudi Arabia, South Korea, Spain, Sweden, Switzerland, Turkey, the United States, and Vietnam.

2.4. Inclusion Criteria

The study's inclusion criteria mandated that the research must have been published between 2005 and 2024 and be written in English. This focus was to concentrate on the most recent developments in LCA applications over the last two decades. A total of 51 scientific papers (comprising 49 research articles and 2 reports) were selected for review. The study prioritized research that showcased the utilization of the LCA methodology in evaluating environmental impacts. The selected papers were categorized into different sectors, with specific keywords used to filter the search:

- Construction (7 scientific papers): Life Cycle Assessment, LCA, Sustainability, Construction materials, concrete, Environmental Impact, Environmental Impact Assessment.
- Wastewater Treatment (7 scientific papers): Life Cycle Assessment, LCA, Sustainability, wastewater treatment, Wastewater, Environmental impact, Environmental impact assessment, Life cycle analysis.
- Agriculture (5 scientific papers): LCA, Life Cycle Assessment, Environmental sustainability, Environmental impact, Environmental impact assessment, Agriculture, Agri-food.
- Waste Management (10 scientific papers): LCA, Life Cycle Assessment, Environmental impact, Environmental impact assessment, Waste management, Recycling, Landfill, incineration.
- Manufacturing (7 scientific papers): Life Cycle Assessment, LCA, Sustainability, Environmental impact, Environmental impact assessment, Carbon footprint, circular economy, supply chain, manufacturing.
- Energy (5 scientific papers): Life Cycle Assessment, LCA, Sustainability, Environmental impact, Environmental impact assessment, energy transition, renewable energy, electricity, heat, energy.
- Packaging (4 scientific papers): Life Cycle Assessment, LCA, Sustainability, Environmental impact, Environmental impact assessment, sustainable packaging, packaging, green packaging.
- Transportation (6 scientific papers): Life Cycle Assessment, LCA, Sustainability, Transportation, Environmental impact, Environmental impact assessment, Greenhouse Gas Emissions.

2.5. Analytical Methods

The emphasis was on studies that demonstrated the practical application of Life Cycle Assessment (LCA) in combination with other models to evaluate environmental impacts, while presenting the primary findings of each study. The objective of this approach is to identify opportunities for enhancing LCA methodologies and improving environmental impact assessments in various sectors and geographic areas.

3. Results

The significance of LCA in environmental management has steadily grown. It provides a method for organizations to assess the environmental impact of a product or service throughout its entire life cycle (Kłos, 2002). The versatility of this technology is evident in its successful adoption in a variety of industries, as shown in Table 3 and discussed in this article.

Table 3. Multi-Sectoral Studies Used LCA Last Two Decades.

Sector	Authors(s) and Year	Country
Construction	Kawai et al. (2005)	Japan
	Hossaini et al. (2014)	Canada
	Kim et al. (2016)	South Korea
	Häfliger et al. (2017)	Switzerland
	Mohammadi & South (2017)	Australia
	Gomes et al. (2019)	Brazil
	Ayagapin & Praene (2020)	France
Wastewater Treatment	Gaterell et al. (2005)	England
	Machado et al. (2007)	Portugal
	Harder et al. (2014)	Sweden
	Risch et al. (2015)	France
	Pretel et al. (2016)	Spain
	Lam et al. (2022)	China
	Rawindran et al. (2024)	Saudi Arabia
Agriculture	Russo and Mugnozza (2005)	Italy
	Bevilacqua et al. (2007)	Italy
	Yang and Suh (2015)	United States
	Turolla et al. (2020)	Italy
	Lulovicova and Bouissou (2024)	France
Waste Management	Lundie & Peters (2005)	United States
	Miliūte & Staniškis (2009)	Lithuania
	Ali et al. (2016)	China
	Corrado et al. (2017)	Italy
	Grzesik (2017)	Poland
	Omid et al. (2017)	Iran
	Haupt et al. (2018)	Switzerland
	Wang et al. (2020)	England
	Garbounis et al. (2022)	Greece
	Avarand et al. (2023)	Iran

Table 3 (Continued). Multi-Sectoral Studies Used LCA Last Two Decades.

Manufacturing	Malmodin et al. (2010)	Sweden
	Cheah et al. (2013)	United States
	Bunnak et al. (2016)	England
	Egilmez et al. (2017)	United States
	Malmodin & Lundén (2018)	Sweden
	Amato et al. (2021)	Italy
	Schoeneberger (2024)	United States
Energy	Malmodin et al. (2010)	Sweden
	Baumgärtner et al. (2021)	Switzerland
	Parisi et al. (2020)	Italy
	Reinert et al. (2022)	Germany
	Wang et al. (2024)	China
Packaging	Bovea et al. (2005)	Spain
	Cappiello et al. (2021)	Germany
	Laso et al. (2017)	Spain
	Molina-Besch & Pålsson (2015)	Sweden
Transportation	Samaras & Meisterling (2008)	Pennsylvania
	Ongel (2015)	Turkey
	Sopha et al. (2016)	Indonesia
	Folęga & Burchart-Korol (2017)	Poland
	Quang et al. (2021)	Vietnam
	Del Pero et al. (2023)	Italy

3.1. Construction

Several studies and articles conducted between 2005 and 2023 seek to measure the ecological consequences of buildings and construction activities using a LCA, as shown in Table 3. The environmental impact of concrete production is a pressing concern. Studies by Kawai et al. (2005) revealed that concrete is responsible for a significant portion of CO_2 emissions, even exceeding steel. Kim et al. (2016) investigated ways to mitigate this impact. Their findings suggest that high-strength concrete can achieve a reduction of 10% to 25% in various environmental impact categories compared to normal strength concrete. However, Häfliger et al. (2017) point out the complexities involved in Life Cycle Assessments (LCA) of buildings. Their research using the Ecoinvent v2.2 database highlights that modeling choices can significantly influence the results, particularly regarding the replacement phase of building materials.

Further research by Mohammadi and South (2017) reinforces the significant influence of cement on concrete's environmental impact. They found the Global Warming Potential (GWP) of concrete products varied considerably, and suggested that using alternative materials or cement with higher mineral additives could be a solution. Their study also identified potential local consequences like acidification and eutrophication. Gomes et al. (2019) offered a promising solution – geopolymer concrete. Their LCA methodology demonstrated a 43% reduction in carbon emissions compared to traditional Portland cement concrete, indicating its potential to address climate change concerns. While Ayagapin & Praene (2020) observed a 37% increase in the Global Warming Potential for construction on Reunion Island, this might be due to the specificities of the project (218 kg-CO_2eq/m^2 of constructed area).

These studies highlight the substantial environmental impact of concrete production but also offer promising avenues for mitigation through the use of high-strength concrete, alternative materials, and geopolymer concrete. On the other hand, in developing the LCA framework, Hossaini et al. (2014) attempted to introduce a comprehensive framework that combines Analytic Hierarchy Process (AHP) with Life Cycle Sustainability Assessment (LCSA) for buildings. The framework is exemplified by a case study of mid-rise structures made of wood and concrete frames in Vancouver, BC, Canada. The findings indicate that the environmental efficiency of buildings in Canada is primarily influenced by the energy consumed over the lifespan of the building, rather than the choice of structural materials. Enhancing the environmental efficiency of buildings can encourage the implementation of low carbon building design using various structural systems. The framework can be utilized for future decision-making in selecting sustainable alternatives in the construction sector, taking into account not only environmental factors but also social and economic factors. Nevertheless, the authors encountered difficulties and constraints in the AHP-based LCSA model, including the presence of confusion and redundancy among various criteria.

3.2. Wastewater Treatment

LCA studies, as shown in Table 3, have thoroughly examined wastewater treatment to assess its environmental effects and investigate different approaches, such as pathogen hazard control. Risch et al. (2015) conducted a comparative analysis that proposed a comprehensive LCA of urban wastewater systems (UWS), which encompasses the construction and operation of sewer systems and wastewater treatment plants (WWTPs). A study revealed that the development of sewer infrastructure has a greater environmental impact than the construction and operation of wastewater treatment plants (WWTPs). The construction phase is the main factor driving this impact in various categories. Gaterell et al. (2005) conducted a study using LCA methodologies to evaluate the environmental effects associated with sewage treatment procedures. They suggested that reducing the energy needed for operations and minimizing the use of synthetic materials for bio-mass growth would enhance environmental performance. In a similar vein, Harder et al. (2014) examined how to incorporate pathogen hazards into LCA by utilizing quantitative microbial risk assessment. Their focus was on the impact on human health, and they estimated that the total risk from pathogens ranged from 0.2 to 9 disability-adjusted life years (DALY) per year of operation for a simulated wastewater treatment system serving 28,600 individuals.

In their study, Machado et al. (2007) employed LCA to evaluate and compare various wastewater treatment techniques suitable for small, decentralized rural communities. The researchers assessed energy-efficient systems, namely the constructed wetland and slow rate infiltration, in comparison to conventional systems such as the activated sludge process. The study emphasized that energy-saving systems have a negligible environmental impact, especially with regards to global warming. Strategies employed to reduce the environmental impact throughout the life cycle included careful selection of construction materials and prolonging the operational lifespan of systems. These measures led to a significant decrease in both CO_2 emissions and abiotic resource depletion. By increasing the operational lifespan of constructed wetland and slow rate infiltration systems by 10%, there was a corresponding decrease of 1% in CO_2 emissions and a 7% reduction in abiotic depletion. Moreover, the replacement of steel with HDPE in activated sludge tanks resulted in a 1% reduction in CO_2 emissions and a 5% decrease in abiotic depletion indicator. Pretel et al. (2016) performed a comprehensive analysis that compared anaerobic membrane bioreactors with aerobic urban wastewater treatment technologies. The study revealed that the anaerobic system, especially when combined with chemical-assisted sedimentation post-treatment, is both environmentally sustainable and economically feasible. It provides significant reductions in global warming potential, marine aquatic ecotoxicity, abiotic depletion, and acidification. Additionally, this system has an impressively low energy consumption of 0.04 kWh per cubic meter and generates minimal sludge. Furthermore, it offers lower life cycle costs, with a minimum value of approximately V0.135 per m^3, when compared to alternative urban wastewater treatment methods.

Subsequent research concentrated on particular advancements and their ecological consequences. Lam et al. (2022) evaluated the ecological impacts of utilizing phosphorus products obtained from wastewater in agricultural systems, employing six distinct recovery techniques. Their research demonstrated substantial advantages in terms of decreased global warming potential, eutrophication, ecotoxicity, and acidification. This underscores the significance of taking into account the long-term consequences and user viewpoints in circular economy practices. In addition, Rawindran et al. (2024) investigated the environmental consequences of employing an integrated membrane bioreactor for the treatment of microalgal wastewater. Their research revealed a significant 63% decrease in the environmental impact in various areas, including freshwater ecotoxicity, eutrophication, and marine ecotoxicity. This highlights the potential benefits of reusing treated wastewater.

3.2. Agriculture

Numerous studies in the agricultural sector have investigated the environmental consequences of agricultural practices. These studies have employed LCA to assess the impact of these practices. Table 3 displays a selection of these studies, which emphasize the significance of employing LCA to attain sustainable agricultural management practices and reduce environmental impacts. In 2005, Russo and Mugnozza conducted a LCA study on greenhouse agriculture in West European territory, comparing the environmental compatibility of horticultural production in different greenhouse typologies. Results show varying environmental impacts for different greenhouse structures, with steel and glass greenhouses having the highest emissions, while wood greenhouses are the most eco-compatible. The study evaluates hydroponic versus soil cultivation, highlighting higher environmental indexes for hydroponic systems due to increased energy consumption and gas emissions.

Bevilacqua et al. (2007) conducted an analysis of the impact assessment results of the entire life cycle of pasta. The effects encompass carcinogens, respiratory organics, climate change, ecotoxicity, acidification, and fossil fuel consumption. The pasta life cycle has the greatest influence on the quality of the ecosystem, particularly in terms of ecotoxicity and acidification. It also significantly contributes to the depletion of nonrenewable resources, specifically minerals and fossil fuels. In a study conducted by Yang and Suh (2015), it was discovered that the ecological health of freshwater systems experienced a 50% decrease in impact per hectare of corn and cotton between 2000-2010. The freshwater ecotoxicity impacts of corn and cotton have decreased due to changes in pesticide usage, primarily due to the widespread adoption of genetically modified crops. The primary cause of this shift is primarily attributed to the cultivation of genetically modified (GM) crops, which have decreased the use of insecticides and relatively harmful herbicides like atrazine. Conversely, soybeans' freshwater ecotoxicity impact has notably escalated due to the proliferation of an invasive species, resulting in an upsurge in the utilization of insecticides.

Turolla et al. (2020) utilized LCA to assess the ecological sustainability of Manila clam farming in aquaculture, taking into account various impact categories. The findings indicate that area preparation, fuel combustion, and plastic bags were the primary factors responsible for the environmental impacts. The carbon sequestration potential of 1 ton of clams has been quantified, along with its ability to reduce eutrophication by fixing nitrogen and phosphorous in shells. This results in a net carbon capture of 444.55 kg, 1.54 kg of N, and 0.31 kg of P annually. In their study, Lulovicova and Bouissou (2024) conducted a prospective investigation to pinpoint regions in the agricultural industry of Finistere, France that have a significant environmental footprint. They employed metrics such as the consequences of climate change and the limited availability of fossil resources. The results indicate that the main environmental areas of concern in the examined local food system originate from indirect factors, such as the production of animal feed or the consumption of diesel fuel. The most environmentally efficient strategies are livestock reduction and conversion to organic farming. These strategies lead to a 25% decrease in the climate change indicator. However, this decrease is not enough to meet their national objectives and is still limited for the land use indicator.

3.3. Waste Management

Waste management is examined using the LCA method, which assesses the environmental effects of a product or process from its creation to its disposal. This methodology is utilized for municipal solid waste (MSW). Lundie & Peters (2005) analyzed the environmental impacts of various waste management options, including home composting, centralised composting, and codisposal of food waste, highlighting key environmental issues. They found that the lowest acidification (3.3×10^{-3} kg SO_2-eq./fu) and eutrophication (9.8×10^{-3} kg P-eq./fu) impact home composting compared to other waste management practices.

The applications of these are figuring out the best ways to handle trash in different areas (Miliūte & Staniškis, 2009; Omid et al., 2017; Grzesik, 2017; Avarand et al., 2023). Miliūte and Staniškis (2009) employed the lifecycle assessment (LCA) methodology to construct a model and examine various waste management scenarios to determine if regional conditions affect the waste management hierarchy. The scenario with the lowest environmental impact was recycling and incineration (RI-4). It had the lowest environmental impacts compared to other scenarios in four categories: global warming (4617 tonne CO_2-eq.), acidification (24 tonne SO_2-eq.), eutrophication (319 tonne O_2-eq.), and photo-oxidants (-11 tonne C_2H_4-eq.). Omid et al. (2017) employed the LCA methodology to evaluate the ecological consequences of waste management systems in a specific area. Four scenarios were identified, and Scenario 4 (consisting of source separation 14%, composting 30%, municipal recycling facility (MRF) 20%, energy recovery 10%, and landfilling 26%) was found to have the least impact. If government assistance is not accessible, it is advisable to opt for the third scenario, which involves source separation at a rate of 14%, composting at a rate of 30%, material recovery facility (MRF) at a rate of 20%, and landfilling at a rate of 36%.

Grzesik, in the year 2017 The modeling results indicate that both landfilling and incineration of residual waste have a detrimental effect on the environment. Nevertheless, incineration has a significantly smaller detrimental effect compared to landfilling. The major impact categories associated with landfilling are photochemical ozone formation (3.5×10^{14}PE), global warming ($6.42\text{x}10^{13}$PE), eutrophication (6.51×10^{13}PE), and human toxicity ($4.04\text{x}10^{13}$PE). On the other hand, significant impact categories for incineration include eutrophication (3.45×10^{5}PE), photochemical ozone formation (13.97×10^{5}PE), acidification (3.57×10^{5}PE), and human toxicity (3.45×10^{5} PE). In their study, Avarand et al. (2023) assessed the life cycle of waste management in Rasht city and determined the most effective strategy for developing its waste management system. The findings revealed that scenario 4, which involved 40% composting, 25% recycling, 20% sanitary landfill, and 15% waste incineration, had the greatest positive impact on the environment. The study revealed that scenario 4, which involves a decrease in landfills, has the most significant beneficial impact on the environment. This scenario results in both energy generation and material retrieval.

Ali et al. (2016) employed LCA to assess the transportation, treatment, and disposal of hospital solid waste. The methods evaluated included landfilling, incineration, composting, and material recycling. The evaluation of these methods was conducted with respect to their greenhouse gas emissions. Landfilling and incineration proved to be the least favorable options for final waste disposal, while composting and material recovery demonstrated significant reductions in emissions. The evaluation of different scenarios determined that an integrated system, which includes composting, incineration, and material recycling, is the most optimal solution. Wang et al. (2020) evaluated the past impact of municipal solid waste (MSW) management in Nottingham on global warming using LCA from April 2001 to March 2017. The LCA findings demonstrate a consistent decline in greenhouse gas (GHG) emissions from municipal solid waste (MSW) management over the course of the study. This reduction can be attributed to advancements in waste collection, treatment, material recycling, and waste prevention. The improvements led to a decrease in greenhouse gas (GHG) emissions from 1076.0 kg CO_2–eq./t of municipal solid waste (MSW) (or 498.2 kg CO_2–eq./Ca) in 2001/02 to 211.3 kg CO_2–eq./t of MSW (or 76.3

kg CO_2–eq./Ca) in 2016/17. An additional decrease of -142.3 kg CO_2-eq./t of MSW (or -40.2 kg CO_2-eq./Ca) could be attained by segregating food waste from incinerated waste, processing organic waste through anaerobic digestion, and pre-treating incinerated waste in a material recovery facility.

Corrado et al. (2017) highlighted the importance of enhancing the coherence of food loss accounting in LCA studies to ensure precise and dependable outcomes. Several approaches have been employed to analyze the environmental consequences of food waste, emphasizing the need for a consistent framework to improve accuracy and enable easier comparisons in LCA studies. To enhance the overall effectiveness, Corrado et al. (2017) recommended that LCA practitioners adopt a systematic approach when accounting for food loss, ensure accurate modeling of waste treatments, and prioritize transparency throughout the modeling process. Researchers can assess the strengths and weaknesses of different approaches to modeling food loss across the supply chain by measuring the environmental impact of food using LCA and evaluating food system management strategies. The main goal is to minimize primary production waste and reduce the overall environmental burden.

In their study, Garbounis et al. (2022) conducted a LCA to measure the environmental effects of seven different approaches for managing Wasted Plastic Pesticide Containers. The researchers then ranked these scenarios based on their environmental footprints. Collecting and recycling WPPC separately has been found to have the lowest net environmental impacts. Scenarios 5 and 6 emerged as the next environmentally optimal technologies, with a combination of recycling and either incineration or landfilling. However, it is worth noting that the landfilling scenario had the most significant environmental impacts.

Haupt et al. (2018) employed material flow analysis (MFA) as the foundation for the LCA, allowing for assessing emissions and impacts of recycling processes based on their inputs. The main objective is combining MFA and LCA to assess environmental efficiency of waste management systems. The framework thoroughly evaluates entire waste management systems by analyzing real waste flows. This analysis offers valuable information on the environmental effects of various recycling processes, which can assist policymakers in making informed decisions regarding waste management.

3.4. Manufacturing

The utilization of LCA in the manufacturing sector is varied and complex. Within the domain of sustainable manufacturing, LCA plays a crucial role in assessing the eco-efficiency and environmental consequences. This procedure offers valuable insights into the environmental efficiency of manufacturing processes, aiding in the identification of areas that can be enhanced and optimized. Bunnak et al. (2016) conducted a comparison between fed-batch (FB) and perfusion-based processes in the production of monoclonal antibodies (mAb). It was discovered that the FB process had a greater level of environmental friendliness compared to the perfusion-based process, even though it had a slightly higher cost of goods sold (COGS) due to a significantly reduced environmental impact. The perfusion process exhibited greater water consumption (35% higher), energy demands (17% greater), and CO_2 emissions (17% higher) in comparison to the fed-batch process, rendering it less environmentally sustainable than the FB process.

Schoeneberger (2024) conducted a study where they utilized a combination of LCA and techno-economic analysis (TEA) metrics to measure the greenhouse gas (GHG) emissions, water usage, and lifetime costs of different technologies across different scenarios. The study revealed that the industrial sector plays a substantial role in global carbon dioxide emissions, with fossil fuels accounting for 73% of its energy composition. The industrial sector in the United States is the primary source of greenhouse gas emissions among all economic end-use sectors. The decarbonization of the industrial sector presents difficulties as a result of varied manufacturing processes, expensive equipment, and competitive markets for products. Significantly, around 50% of manufacturing emissions in the United States can be attributed to the processes involved in generating heat. Industries can utilize Life Cycle Assessments (LCAs) to measure the amount of greenhouse gas emissions. Malmodin et al. (2010) reported that the combined CO_2 equivalent emissions from Information and Communication Technology (ICT) and its subsectors (Mobile telecom, Fixed telecom, PCs) in 2007 were 80 million metric tons, 120 million metric tons, and 250 million metric tons, respectively. Malmodin & Lundén (2018) discovered that the carbon footprint of the intensity metrics for the ICT sector was 134 kg CO_2eq./sub in 2007, 107 kg CO_2eq./sub in 2010, and 81 kg CO_2eq./sub in 2015.

The Entertainment and Media (E&M) sector, including TV, Printed Media, and Other E&M Hardware, has emitted a total of 390, 300, and 130 million metric tons of CO_2-eq. emissions, respectively. These results were correlated with the electricity consumption for each sector. Depletion of resources occurs during manufacturing, which affects the carbon footprint. Egilmez et al. (2017) discovered that the amount of carbon emissions steadily rose from 1970 to 2011. Unfortunately, the rapid increase in economic output obscured the potential advantages derived from reduced CO_2 intensities. The examination of industry data reveals that the five manufacturing sectors with the highest total carbon footprint share are "petroleum refineries," "Animal (except poultry) slaughtering, rendering, and processing," "Other basic organic chemical manufacturing," "Motor vehicle parts manufacturing," and "Iron and steel mills and ferroalloy manufacturing." In their study, Cheah et al. (2013) specifically examined the production of footwear and the resulting emissions. They determined that the carbon footprint of a standard pair of running shoes made from synthetic materials is estimated to be between 11.3 and 16.7 kg CO_2-eq. per pair. The predominant portion of this impact is generated during the materials processing and manufacturing stages, constituting approximately 29% and 68% of the overall impact, respectively. This information helps stakeholders develop strategies to reduce their impact on the environment.

LCA facilitates comparing various manufacturing processes, such as fed-batch and perfusion-based processes, to assess their life cycle costs and environmental impacts. The comparative analysis provides industries with the necessary information to make well-informed decisions about process selection, taking into account sustainability criteria; the results obtained in the study conducted by Amato et al. (2021) in the agricultural sector were not intended to discourage the development of alternatives for enhancing agricultural residues, but rather to highlight the importance of environmental sustainability aspects. The implemented LCA demonstrated the substantial impact of transitioning to renewable energy and the urgent need to identify ecological agents for the efficient and environmentally sustainable production of bio-based products. In addition, LCA can be combined with other tools, such as environmental support tools, to improve sustainability assessments and decision-making in the manufacturing sector.

3.5. Energy

The energy sector holds great significance, and it is essential to prioritize utilizing LCA in every aspect of its production, distribution, and consumption. The energy sector is interconnected with other sectors; 35% of the papers prioritize studying cumulative energy demand and its relationship to climate change (Lotteau et al., 2015). In 2010, Malmodin et al. found that the amount of electricity used by Information and Communication Technology (ICT) and its subsectors (Mobile telecom, Fixed telecom, PCs) in 2007 was 60 TWh, 160 TWh, and 260 TWh, respectively. The LCA is crucial for analyzing national energy systems' environmental impacts, including electricity, heat, and transportation. It comprehensively explains these impacts; to achieve the transition to a low-carbon economy in Germany by 2025, there needs to be a substantial decrease in greenhouse gas emissions by 85% compared to the levels recorded in 1990. Decarbonization strategies that exclusively target greenhouse gas (GHG) emissions may transfer the environmental burden to other forms of impact. This emphasizes the significance of taking into account a wider array of environmental impacts (Baumgärtner et al., 2021).

Furthermore, the geothermal sector has implemented LCA guidelines in order to enhance the consistency of outcomes across various renewable energy technologies (Parisi et al., 2020); they established standardized guidelines for conducting life cycle assessments (LCAs) of geothermal systems to ensure consistent outcomes across various renewable energy technologies. These guidelines provide technical advice on the methodological options, stages of the life cycle, and important components of LCA for geothermal energy production. Following these guidelines makes it possible to achieve comparability between LCA results obtained from different geothermal systems and other forms of renewable energy technologies. The SecMOD framework combines multi-sector energy system optimization with LCA, offering a comprehensive method for analyzing energy systems (Reinert et al., 2022). This integration enables a gradual expansion of systems by incorporating additional products and processes to analyze specific processes and interactions within a particular sector. The SecMOD framework considers the existing infrastructure, making it appropriate for optimizing newly developed and already established projects (Reinert et al., 2022).

Wang et al. (2024) conducted a comprehensive analysis of the environmental impact of the DES system on an actual project using GaBi software. The study highlights that the operation phase has the greatest environmental impact, accounting for 78.37% of the overall combined environmental impact, with the fuel production phase following closely behind. The energy production process has significant environmental consequences, such as resource depletion and climate change. To address these issues, the LCA framework can be utilized to identify areas of high impact and develop strategies to mitigate the environmental effects of energy production sector.

3.6. Packaging

LCA is an essential tool for the packaging industry. It allows for a thorough evaluation of materials and systems, as well as guidance for the development of sustainable packaging solutions. Multiple studies have demonstrated this, as shown in Table 3. LCA provides a thorough approach to evaluate the environmental impact of packaging, starting from the extraction of raw materials and ending with its disposal at the end of its life; by implementing all of the suggested enhancements into the packaging system, the environmental impact can be reduced by 18-45% compared to the current system (Bovea et al., 2005). The comprehensive analysis enables the packaging industry to assess the sustainability of different materials, such as bioplastics, glass, and metal, by evaluating their environmental impact at every stage; in their study, Cappiello et al. (2021) discovered that the bioplastic system outperforms both fossil-based systems and multilayer carton in several categories, including climate change, ozone depletion, human toxicity, freshwater eutrophication, particulate matter, and land use.

LCA, allows industries to make well-informed decisions that decrease environmental burdens by identifying environmentally friendly alternatives; Laso et al. (2017) identified that the most significant stages in the life cycle were the manufacturing of aluminium cans for packaging and the production of extra virgin olive oil, as well as the handling of packaging waste. And suggested implementing measures such as recycling packaging. Studies indicate that reducing the utilization of materials in packaging design is essential, as the extraction and production of these materials have a substantial impact on the environment; Molina-Besch & Pålsson (2015) discovered that companies frequently embrace green packaging for its economic advantages, yet face challenges in assessing trade-offs and environmental benefits due to both internal and external obstacles, LCA assists in identifying the most ecologically sustainable packaging choices by evaluating the complete life cycle of packaging. Despite the resource-intensive nature of LCA methodology, it directly contributes to reduce the packaging environmental impacts by offering valuable insights for sustainable design.

3.7. Transportation

The application of LCA has demonstrated its efficacy in assessing various transportation modes, including ships and tankers. According to Quang et al. (2021), the emissions and impacts resulting from shipbuilding, ship maintenance, and transportation activities are relatively smaller compared to the impacts caused by ship operation and material consumption. LCA offers policymakers essential data to mitigate greenhouse gas emissions and air pollution by examining vehicle emissions, energy consumption, and alternative transportation options. In their study, Samaras and Meisterling (2008) evaluated the GHG emissions throughout the life cycle of plug-in hybrid vehicles. They discovered that these vehicles achieve a 32% reduction in GHG emissions compared to conventional vehicles. However, the reduction in emissions is relatively small when compared to traditional hybrids. Batteries play a crucial role in plug-in hybrid vehicles, and the greenhouse gas emissions linked to the materials and production of lithium-ion batteries contribute to 2-5% of the total emissions throughout the life cycle of these vehicles. The longevity of electricity generation infrastructure means that choices made within the next ten years regarding electricity supplies in the power sector will have a significant impact on the potential for substantial reductions in greenhouse gas emissions through the use of plug-in hybrid vehicles for many decades to come (Samaras & Meisterling, 2008).

LCA is used in road transportation to evaluate noise pollution, demonstrating its adaptability in assessing the environmental impacts of various transportation choices. The health impacts of transportation noise are substantial. They should be considered in the LCA of road transportation and other environmental measures relevant to health outcomes. Ongel (2015) determined that the characterization factors for the nine municipalities in Istanbul varied from 0.005 to 0.09 healthy years lost per person. These factors were calculated based on the amount of noise emitted per meter of each highway segment for a duration of one year, measured in milliwatts (Ongel, 2015). The maritime industry utilizes LCA to assess the environmental impact of activities within the sector; Del Pero et al. (2023) discovered that although the production stage of Yacht superstructures has a greater impact, the innovative solution enables a substantial reduction in GHG throughout the entire life cycle (over 16%). This reduction is primarily due to a decrease in fuel consumption and lower CO_2 exhaust emissions during operation.

Furthermore, Folęga & Burchart-Korol (2017) have employed LCA to evaluate the environmental effects of road transportation; they examined the emissions of greenhouse gases from passenger cars on roads, finding that the emissions amount to 34.2 kilograms of carbon dioxide equivalent per functional unit. 80% of emissions are attributed to the production and consumption of petrol. The LCA method reveals that car fuel emissions are the primary cause of harm to human health and the ecosystem, with petrol production responsible for 66% of natural resource usage. Sopha et al. (2016) conducted a study on evaluating the impact of motorcycles by considering one passenger per kilometer (pkm) as the functional unit. They estimated the resource consumption and emissions throughout the entire life-cycle of a motorcycle. The study revealed that the operation (usage stage) of the motorcycle has had the greatest impact on global warming potential (GWP) and acidification potential (AP), whereas the manufacturing stage has had the greatest impact on human toxicity potential (HTP). Their paper also examines potential interventions pertaining to the manufacturing process, fuel, and usage of the motorcycle to mitigate its environmental impacts.

4. Discussion

Previous studies have shown that Life Cycle Assessment (LCA) is a highly effective tool for promoting sustainability in various industries, including construction, wastewater treatment, agriculture, waste management, and manufacturing. In addition, LCA can be enhanced by incorporating various aspects to promote long-term sustainability. There is no previous study that provides a comprehensive analyze environmental evaluation studies that have utilized life cycle assessment in different domains. This review offers a foundation for further development of life cycle assessment by integrating it with analytical and evaluative tools in various fields. This integration would help address existing gaps in the life cycle assessment methodology. The Life Cycle Assessment (LCA) method has various limitations that necessitate integrating with other assessment methodologies. Assessing impact categories in their current form often lacks consideration for socioeconomic factors. Therefore, it is necessary to utilize supplementary methodologies such as the Regional Sustainability Assessment Methodology (RSAM).

The construction sector utilizes the LCA approach to support the implementation of the circular economy. This approach extends beyond the construction industry and entails integrating Building Information Modeling (BIM) with Life Cycle Assessment (LCA). The research conducted by Inharwararak and Stravoravdis (2023) has demonstrated that the integration of Building Information Modeling (BIM) and Life Cycle Assessment (LCA) results in enhanced construction project management. This integration improves efficiency, reduces costs, promotes sustainability, and enables more precise environmental impact evaluations. These benefits are evident in both the economic and environmental domains.

Outdated inventory data often poses a challenge in conducting Life Cycle Assessment (LCA) studies in agriculture. To address this issue, dynamic modeling techniques are necessary to accurately capture the changing environmental impacts. In addition, it is important to note that life cycle assessment (LCA) may not comprehensively consider the interactions that occur within cropping systems. This can result in uncertainties and limitations when evaluating the environmental effects of agricultural practices (Goglio et al., 2017). In order to fill this void, scientists have devised comprehensive methods such as the Model for Integrative Life Cycle Assessment in Agriculture (MiLA) to consider the interplay between crops and the cycling of nutrients within agricultural systems. This improves the precision of sustainability evaluations in the field of agriculture.

Within the realm of waste management, Life Cycle Assessment (LCA) serves as a valuable instrument for assessing the ecological consequences of various waste management scenarios (Grzesik, 2017). Nevertheless, LCA alone may not encompass all pertinent variables, such as the risks posed by pathogens in wastewater management. Therefore, it is imperative to incorporate quantitative microbial risk assessment (QMRA) in order to thoroughly evaluate the environmental and health consequences of wastewater treatment processes (Harder et al., 2014). LCA neglects to comprehensively assess the various effects in areas such as wastewater systems, emphasizing the necessity for holistic strategies such as evaluating the economic and environmental viability of submerged anaerobic membrane bioreactors, which need more research and study.

The Packaging Impact Quick Evaluation Tool (PIQET) is an environmental assessment tool specifically designed for food packaging. Its purpose is to aid decision-making during the development of packaging by providing a comprehensive evaluation of its environmental impact (Molina-Besch & Pålsson, 2020). By combining PIQET with LCA, stakeholders in the food packaging industry can evaluate the ecological consequences of various packaging choices and make well-informed choices to reduce environmental footprints while preserving packaging functionality and efficiency. There is a need to make the assessment cover the economic aspects side by side with the environmental aspects of the packaging sector.

Integration of various methodologies with Life Cycle Assessment (LCA) is necessary in the manufacturing sector to overcome the inherent limitations of LCA and achieve a more thorough evaluation of sustainability aspects in manufacturing industries. Incorporating methodologies such as life cycle costing, multi-sector system optimization, sustainability principles, LCA-based frameworks, and SLCA with traditional LCA methodologies is crucial for addressing the significant shortcomings of LCA and achieving a more thorough assessment of sustainability aspects in the manufacturing sector. By integrating these approaches, scholars and professionals can carry out comprehensive sustainability evaluations, taking into account ecological, financial, and societal aspects to advance sustainable practices in the manufacturing sector.

Researchers have suggested combining life cycle assessment (LCA) with geographic information systems (GIS) in transportation to overcome spatial resolution difficulties encountered in LCA studies within the transportation industry (Molina-Besch & Pålsson, 2020). By integrating LCA with GIS, researchers can improve the accuracy and precision of LCA analyses, allowing for a more thorough evaluation of the environmental effects of transportation systems in various geographic areas. Moreover, it is imperative to incorporate noise pollution and social life cycle assessment (LCA) in future studies due to the direct correlation between the community and the local transportation sectors.

A comprehensive evaluation is particularly crucial in the energy sector because of its direct and indirect interconnections with all other sectors. The Life Cycle Assessment (LCA) studies in this field are crucial because they provide valuable information beyond just energy production and consumption. These studies consider geographic, social, economic, and efficiency aspects. A comprehensive and forward-looking methodology is created by combining LCA with the Energy Efficiency Design Index (EEDI) and the Energy Efficiency Operation Index (EEOI). This integration is crucial for analyzing shipping operations' environmental effects and energy efficiency. By utilizing the combined perspectives of Life Cycle Assessment (LCA), Energy Efficiency Design Index (EEDI), and Energy Efficiency Operational Indicator (EEOI), researchers can thoroughly evaluate the energy efficiency and environmental responsibility of maritime transportation. This combination not only emphasizes the importance of environmental factors in maximizing energy efficiency in shipping, but also confirms the essential role of Life Cycle Assessment (LCA) in improving energy strategies in the maritime industry.

The emphasis was on studies that demonstrated the practical application of Life Cycle Assessment (LCA) in combination with other models to evaluate environmental impacts and present the key findings of each study. This approach aims to identify opportunities for enhancing LCA methodologies and improving environmental impact assessments across various sectors and geographic regions. In recent decades, there has been an increasing interest in sustainability issues among government bodies and leaders in the private sector. The growing concern has highlighted the need for innovative approaches to tackle sustainability issues. Life Cycle Sustainability Assessment (LCSA) is an increasingly acknowledged and promising approach. Unlike conventional LCA, which focuses mainly on environmental impacts, Life Cycle Sustainability Assessment (LCSA) offers a more holistic perspective. The approach integrates environmental, social, and economic factors into the product design and evaluation process, aiming to achieve a more sustainable outcome (Muthu, 2021).

The environmental consequences of human activities are a critical concern that must be promptly and seriously addressed. In order to assess the magnitude of this influence, well-established methodologies such as LCA are employed, adhering to specific international standards such as ISO 14040:2006. Although it is possible to quantitatively evaluate the environmental impact, assessing the economic and social dimensions of sustainability is more difficult. Muthu pointed out in 2021 that the Life Cycle Sustainability Assessment (LCSA) methodology lacks universally accepted benchmarks. The absence of these benchmarks emphasizes the need for thorough research in multiple fields to establish comprehensive standards that encompass all aspects of sustainability. Through this approach, LCSA can efficiently direct researchers towards embracing sustainable practices and solutions, thereby making a valuable contribution to a sustainable future.

The economic viability of a project can be assessed by considering three key factors: the initial investment required, the ongoing expenses for operation and maintenance, and the costs associated with disposal. The overall financial sustainability and feasibility of any venture are significantly influenced by these factors (Martínez-Orgániz et al., 2024). Initial capital costs pertain to the project's establishment, whereas operating and maintenance costs encompass the ongoing expenses necessary for the project's smooth operation (Rajpurohit, 2024). Disposal costs refer to the financial burdens that arise at the end of a project's lifespan when removing or decommissioning its components (Chianese, 2024). Through a comprehensive examination of these three fundamental components, individuals with a vested interest can make well-informed choices regarding the sustained prosperity and financial feasibility of their undertakings.

The social dimension is the third aspect of LCSA. The evaluation of this dimension can be conducted using Social Life Cycle Assessment (S-LCA), which is a methodology that quantifies the social impacts of products or services across their entire life cycle, encompassing the stages of raw material extraction to disposal. The primary objective of S-LCA is to evaluate the impact on social aspects, including labor conditions, human rights, and community involvement. The Social Life Cycle Assessment (S-LCA) improves traditional Life Cycle Assessments (LCAs) by incorporating social factors, resulting in a more thorough understanding of the overall effects of products or services (Ashby, 2024; Cellura, 2024; Di Noia et al., 2024).

When conducting a Life Cycle Sustainability Assessment (LCSA), it is essential to take into account both the economic and social aspects in addition to the LCA. By systematically integrating these three dimensions in a comprehensive manner, researchers can elevate the benchmarks for environmental aspects as well as economic and social dimensions, thereby promoting a more all-encompassing approach to sustainability. Policymakers and stakeholders should strive to achieve this integration in order to enable organizations to make well-informed decisions for a sustainable future.

5. Conclusion

This review examines the widespread use of LCA in assessing environmental effects in different industries by analyzing 51 scientific papers. LCA is invaluable for advancing sustainability in diverse sectors such as construction, wastewater treatment, agriculture, waste management, and manufacturing. Nevertheless, it is important to note that this approach has certain limitations, including its failure to consider socioeconomic and geographic factors. To tackle these issues, additional approaches such as the Regional Sustainability Assessment Methodology (RSAM) are required. Integrating LCA with Building Information Modeling (BIM) can enhance project management in the construction sector, leading to improved efficiency and cost reduction. In agriculture, dynamic modeling techniques and quantitative microbial risk assessment are essential to capture the evolving environmental effects accurately. The Packaging Impact Quick Evaluation Tool (PIQET) assists in decision-making during the development of food packaging. Meanwhile, integrating LCA with Geographic Information Systems (GIS) in transportation can enhance accuracy and precision.

LCA studies play a vital role in the energy sector by offering valuable insights beyond energy production and consumption. By integrating Life Cycle Assessment (LCA) with the Energy Efficiency Design Index (EEDI) and Energy Efficiency Operation Index (EEOI), researchers can assess the environmental impact and energy efficiency of shipping operations. The LCSA approach incorporates a comprehensive viewpoint that considers environmental, social, and economic considerations when designing and evaluating products. It focuses on the ecological impacts of human actions and does not have widely agreed-upon standards. A project's economic feasibility is evaluated by considering the initial capital investment, recurring expenses, and costs associated with disposal. Social Life Cycle Assessment (S-LCA) measures the social effects of products or services throughout their entire life cycle. Incorporating these dimensions facilitates a more holistic approach to sustainability.

The study emphasizes enhancing LCA methodologies to overcome limitations and integrate additional factors. Subsequent investigations should prioritize enhancing the accuracy and inclusiveness of LCA, formulating novel integration methodologies, and broadening its implementation across additional industries. Through the ongoing improvement of LCA practices, we can enhance our ability to promote sustainable development and responsible management of resources globally.

Future research should prioritize enhancing the socioeconomic and geographic integration of Land Use and Construction Assessment (LCA) methodologies, refining dynamic modeling techniques in agriculture, expanding the integration of Building Information Modeling (BIM) and LCA in construction, developing comprehensive decision-support tools, standardizing Life Cycle Sustainability Assessment (LCSA) practices, assessing long-term sustainability outcomes, exploring new industry applications, and improving public policy and corporate strategies. The purpose of these suggestions is to enhance the accuracy and usability of LCA findings, establish universally accepted standards, evaluate long-term sustainability results, investigate new industry uses, and improve public policy and corporate strategies to develop more efficient sustainability initiatives and regulatory frameworks.

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

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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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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].

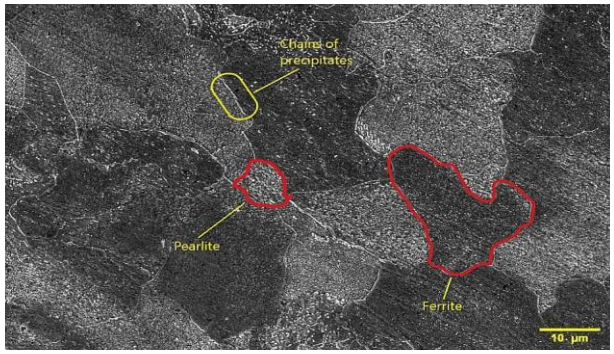


Fig. 1 SEM image showing the ferrite + pearlite microstructure of unused 14MoV6-3 steels with chains of precipitates at the grain boundaries [9]. Yellow ring indicates chains of precipitates at the grain boundaries, while red mark shows ferrite and pearlite phases.

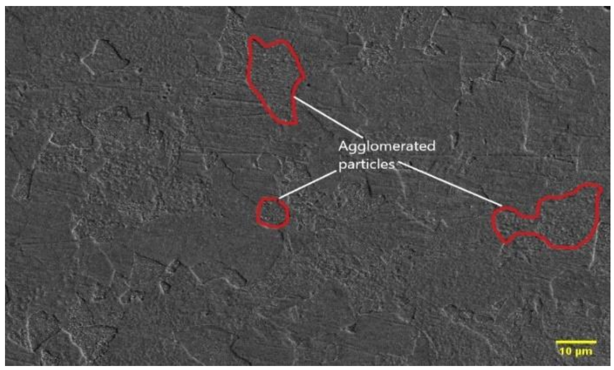


Fig. 2 SEM image showing agglomerated particles in the microstructure of regenerative heat treated 14MoV6-3, no chains of precipitates observed at the grain boundaries [9]. Red mark show agglomerated particles.

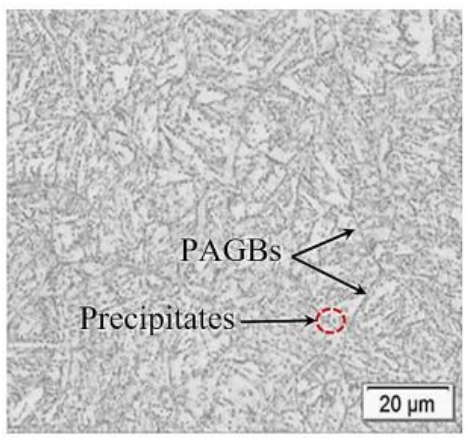


Fig. 3 Optical image showing tempered martensite, precipitates and prior austenite grain boundaries in unused P91 steel [7].

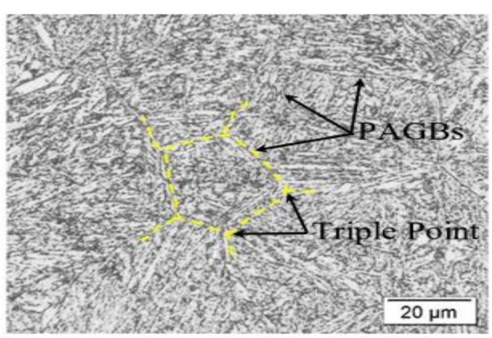


Fig. 4 Optical image showing tempered martensite, and a well-defined prior austenite grain boundaries (PAGBs) with triple point in regenerative heat-treated creep-exhausted P91 steel [7].

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].

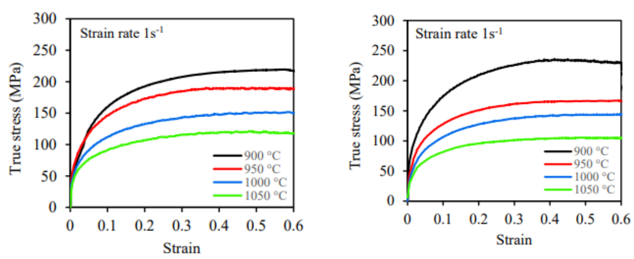


Fig. 5 Flow stress of P91 steel in (a) unused condition, and (b) regenerative heat-treated condition [7].

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

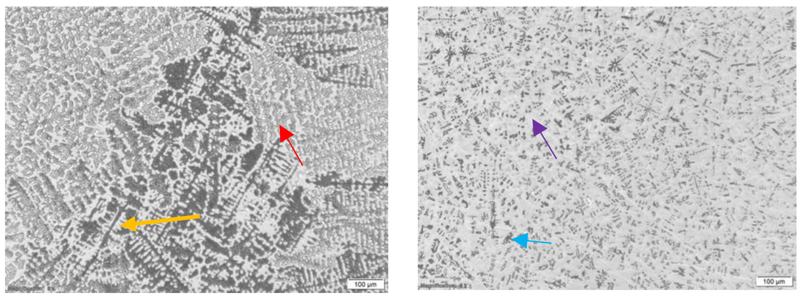
Low-density stainless steels with compositional range of Fe-(20 or 30)Mn - (4 - 15)Al - (0.5 - 1.5)C - 5Cr were developed using electric arc melting. The as-cast LDSS were compared with commercial grade 316L stainless steel. The density of the alloys was at least 14% less than the density of 316L stainless 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.

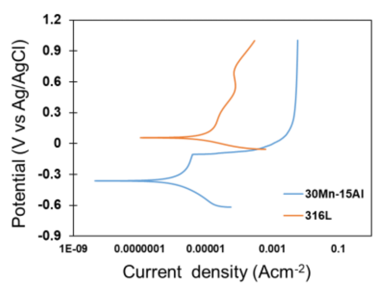
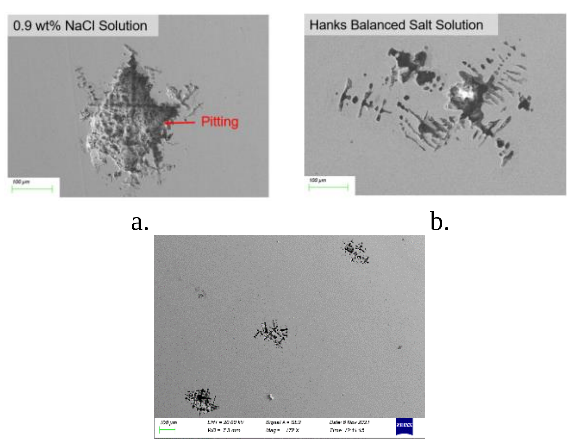


Fig. 7 Polarisation curves of LDSS in Hanks Balanced Salt Solution (HBSS) [16].



a. b.

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].

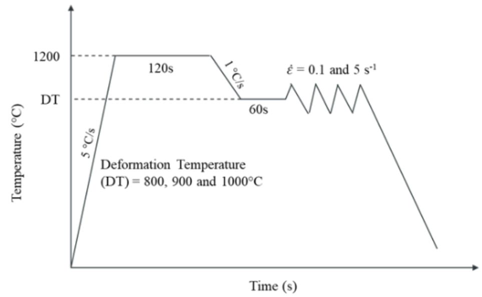
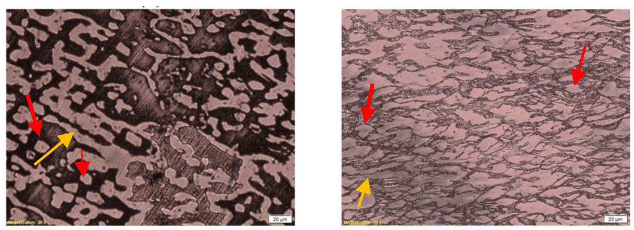
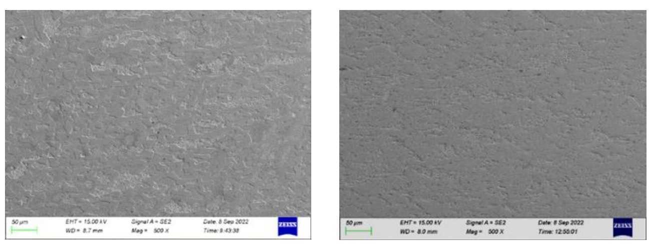


Fig. 9 Thermomechanical processing schedule for ingot breakdown [15].



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

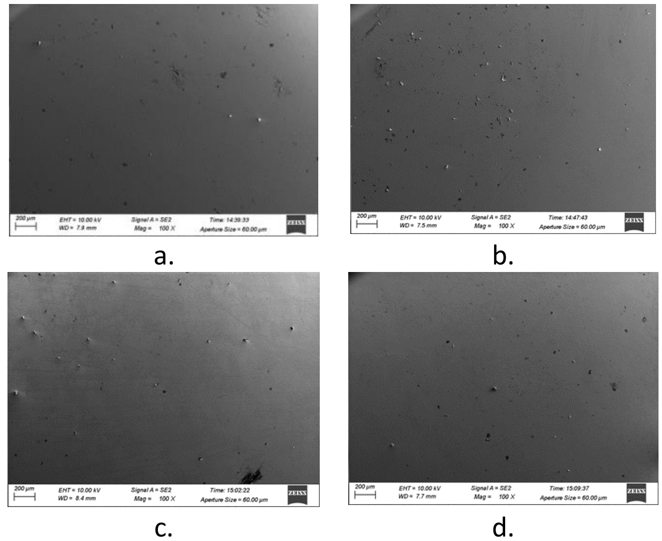


Fig. 12 SEM image of deformed Fe-21.3Mn-7.6Al-4.3Cr-1C after corrosion testing (a) 900°C/5 s^{-1}, (b) 1000°C/5 s^{-1}, (c) 900°C/0.1 s^{-1}; and (d) 1000°C/0.1 s^{-1}[15]

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.

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