ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE ENGINEERING AND TECHNOLOGY

EFFECT OF LASER SURFACE HARDENING PARAMETERS ON IMPACT SLIDING WEAR BEHAVIOR OF A HOT WORK TOOL STEEL

M.Sc. THESIS

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ISTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

LAZER YÜZEY SERTLEŞTİRME PARAMETRELERİNİN SICAK İŞ TAKIM ÇELİĞİNİN DARBELİ KAYMA AŞINMA DAVRANIŞINA ETKİSİ

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Elif NÖBET, a M.Sc. student of ITU Graduate School of Science Engineering and Technology student ID 506161413, successfully defended the thesis/dissertation entitled "EFFECT OF LASER SURFACE HARDENING PARAMETERS ON IMPACT SLIDING WEAR BEHAVIOR OF A HOT WORK TOOL STEEL", which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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To my lovely mother,

FOREWORD

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ABBREVIATIONS

HPDL	**:** High Power Diode Laser
AISI	**:** American Iron and Steel Institute
ASTM	**:** American Society for Testing and Materials
DIN	**:** Deutsches Institut für Normung
HRC	**:** Hardness of Rockwell C
HV	**:** Vickers Hardness
XRD	**:** X-Rays Difraction
SEM	**:** Scanning Electron Microscope
LSH	**:** Laser Surface Hardening
EB	**:** Electron Beam

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EFFECT OF LASER SURFACE HARDENING PARAMETERS ON IMPACT SLIDING WEAR BEHAVIOR OF A HOT WORK TOOL STEEL

SUMMARY

Steel has mainly alloyed and unalloyed types and it has developed day by day with the advent of the technology. One type of the steel is hot work tool steel. Hot work tool steels, which are alloyed tool steels, are used for hot using fields. This type of steel provides own mechanical properties even at high temperatures according to other types of steels. Its wear and toughness properties do not change much with increasing temperature. Especially, wear properties of hot work tool steels is important for high temperature working conditions. For this reason, some workings are doing for improving wear properties of hot work tool steels even at higher temperatures.

In this study, laser surface hardening method was used for hardening of hot work tool steel (QRO90). QRO90 is special manufacturing hot work tool steel. QRO90 has 28 mm diameter and 8 mm thickness. Laser surface hardening process was applied on one side of material as 5 mm width for one tour. In this study, different laser power values, laser beam velocity and temperatures were applied on the QRO90 samples and we compared hardness, depth of hardness, wear properties of these samples. Laser surface hardening temperature range was between 1150°C and 1300°C. Laser beam velocity range was between 3 mm/s and 6 mm/s. Laser power depends on temperature and velocity values of laser beam. That is why, it is not constant.

For investigating wear behavior, laser hardened samples were prepared as metallographic with sandpapering and polishing processes. Then, some characterization tests were done. These were hardness and hardness depth measurement, optical microscope with x50, x100, x200, x500 and x1000 images, XRD experiments, SEM images and profilemeter test. At the result of the XRD experiment, residual austenite is not observed. At the result of the optical microscope, we can see that white microstructure. The microstruce of samples have martensitic formation with different ratio according to different laser hardening condition.

Laser hardened QR O90 samples hardness(with 200 gr loading) and hardness depth(with 25 gr loading) were measured with vickers test and different result handled according to working condition as temperature and laser beam velocity. Additionally, wear behavior of samples were investigated with wear sliding test device and then with profilemeter device, wear behavior was observed.

At the result of the experiments, the best laser hardened condition is 1200-1250 ^{0}C and 5 mm/s laser beam velocity for optimum hardness.

The samples, which have 1250-1300 ^{0}C temperature process condition, are more resistant according to other lower temperatures. When the increasing temperature causes more resistant samples for impact sliding wear behavior.

LAZER YÜZEY SERTLEŞTİRME PARAMETRELERİNİN SICAK İŞ TAKIM ÇELİĞİNİN DARBELİ KAYMA AŞINMA DAVRANIŞINA ETKİSİ

ÖZET

Çeliğin genel olarak alaşımlı ve alaşımsız çeşitleri mevcut olup, gelişen teknolojiyle birlikte günden güne daha da gelişmektedir. Bu çelik çeşitlerinden biri alaşımlı çeşitlerinden olan sıcak takım iş çeliği, yüksek sıcaklığa sahip çalışma koşullarında sıklıkla tercih edilir. Bu tür çelikler yüksek sıcaklıkta bile kendi özelliklerini koruma eğilimine sahiptir. Özellikle beklenen özellik ise çeliğin aşınma direnci ve tokluğunun artan sıcaklıkla beraber değişkenlik göstermemesidir. Özellikle, malzemenin aşınma direnci göstermesi gereken yerde aşınma direncinin sıcaklıktan etkilenmemesi gerekmektedir. Bu sebeple de bu çeliğin yüksek sıcaklıklarda aşınma davranışının değişmeden kalabilmesi için bir takım işlemler uygulanmaktadır.

Lazer yüzey sertleştirme işlemi, yüzey sertleştirme işlemlerinden biri olup, diğer geleneksel sertleştirme yöntemlerine göre minimum deformasyonda işlem kabiliyetine sahiptir. Bunun yanı sıra geleneksel yöntemlerle karşılaşırıldığında enerji verimliliği yüksek, hassas ve belirlenen yüzeylerde sertleştirme, sıcaklığın ayarlanabilir olması sebebiyle yüzeyde erime olmadan yüzey sertleştirme yapılabilmesi, yüksek kalitede homojen sertlik, sertleştirme sonrası ek işlem gerektirmeyen temiz yüzey gibi avantajlara sahiptir.

Lazer ile sertleştirme işlemi genel olarak karbon çeliklerine, dökme demire, takım çeliklerine, ısıl işleme uygun paslanmaz çeliklere uygulanır. Sertlik derinliği , uygulanan çelik türü ve lazer işlem parametrelerindeki değişkenliğe göre 5 mm ile 2 mm arasında seyretmektedir. Sertlik genişliği ise bir tur için 5 mm ile 25 mm arasındadır.

Lazer sertleştirme işlemi günümüzde genel olarak üç tip lazer makinasıyla gerçekleştirilmektedir. Bunlar CO_2 lazeri, Nd:YAG lazeri ve yüksek güçlü diyot lazer olarak aynı amaçlı, fakat farklı proseslerde çalışan lazer cihazlarıdır. En basit farklılığı CO_2 lazerinin malzeme yüzeyine etkiyen lazer ışınının emilimini arttırmak için malzeme yüzeyinde sertleştirilecek alanlarda ilave olarak kaplama olması gerekirken, diğer iki tip lazerde lazer ışınının emilmesini sağlamak için ilave kaplamaya gerek yoktur.

Daha önceki çalışmalarda lazer sertleştirme prosesinden sonra çeliklerde mikroyapısındaki değişim sonucunda yorulma davranışı, aşınma davranışı gibi mekanik özelliklerinde gelişme sağladığını saptamışlardır.

Bu çalışmada çeliğin aşınma direncini geliştirebilmek için yüksek güçlü diyot lazer ile lazer yüzey sertleştirme tekniği kullanılmış olup, sıcak takım iş çeliği olarak özel üretim olan QR O90 tercih edilmiştir. Toplamda 8 adet numune üzerine farklı lazer parametreleri uygulanmıştır.

QR O90 numuneleri 28 mm çapa ve 5 mm kalınlığa sahiptir. Bu numuneler üzerine lazer sertleştirme işlemi sıfır odakta uygulanmış olup, odak genişliği minimum 5 mm'dir. Bu sebeple bir numune üzerine ortalama 4 tur lazer geçilmiştir. Her bir numune hem sıfır yönünde hem de doksan derece yönünde olmak üzere iki farklı yönden sertleştirilme işlemine tabi tutulmuş olup, değişik lazer parametrelerinin malzeme üzerindeki etkisi incelenmiştir. Parametreler genel olarak lazer ışını hızı, sıcaklığı ve bunlara bağlı olarak lazer ışını gücü olarak değerlendirilebilir.

8 adet numunede uygulanan parametrelerde lazer ışını sıcaklığı 1150°C ve 1300°C arasında, lazer ışını hızı ise 3mm/s-6 mm/s arasında değişkenlik göstermiş olup, lazer ışını gücü bu değerlere bağlı olarak kendiliğinden değişmiştir.

Her bir numune lazer sertleştirme işlemine tabi tutulmadan önce cnc taşlama makinasıyla taşlanmış ve düzlemsel hale getirilmiştir. Sonrasında bu numunelerin üzerine lazer sertleştirme prosesi uygulanırken her bir lazer turu atıldıktan sonra malzeme üzerinde oluşan oksit tabakasının temizlenmesi ile zımpara ile gerçekleştirilmiştir. Bu işlemin amacı lazer ışınının temiz yüzeylerde daha iyi işlev görmesi ve bu sebeple oluşabilecek lazer atlamalarının önüne geçilmesidir. Zımparalama işlemi aynı zamanda lazer yönü 90 derece yönüne dönüldüğünde de malzeme üzerine uygulanmıştır. Bu işlemin yanı sıra bu şekilde hem de malzemenin her bir lazer turu sonrası soğuması sağlanmış ve olası menevişlenmenin önüne geçilmesi hedeflenmiştir.

Lazer sertleştirme prosesi uygulanmış QR O90 numunelerinde aşınma davranışını inceleyebilmek maksadıyla her bir numuneye farklı sıcaklık ve farklı lazer hızları uygulanmış ve bu parametrelerin QR O90 çeliğinin aşınma davranışını nasıl değiştirdiğine dair gözlemler yapılmıştır. 1. Numuneye 1200-1250 ^{0}C sıcaklığında ve 4 mm/s hızında, 2. Numuneye 1250-1300 ^{0}C sıcaklığında ve 4 mm/s hızında, 3. Numuneye 1150-1200 ^{0}C sıcaklığında ve 4 mm/s hızında, 4. Numuneye 1150-1200 ^{0}C sıcaklığında ve 5 mm/s hızında, 5. Numuneye 1200-1250 ^{0}C sıcaklığında ve 5 mm/s hızında, 6. Numuneye 1200-1250 ^{0}C sıcaklığında ve 3 mm/s hızında, 7. Numuneye 1250-1300 ^{0}C sıcaklığında ve 5 mm/s hızında, 8. Numuneye 1200-1250 ^{0}C sıcaklığında ve 6 mm/s hızında lazer ışını uygulanmış olup, her bir numune sırasıyla 400, 600, 800, 1200 ve 2500 meşli SiC zımpara kağıtları ile zımparalanmış ve parlatılmıştır. Parlatılmış numunelere ise aynı şartlar altında 10 mm çapındaki çelik bilya ile 3, 5 kg yük uygulayarak 1000 vuruş yaparak darbeli aşınma cihazında oda sıcaklığında aşınma izleri oluşturulmuştur.

Hazırlanan numunelere normal yüzeylerinden 200 gram yük ile sertlik testi yapılmıştır. 25 gram yük ile kesitlerinden sertlik testi yapılmış olup sertlik derinliği tespiti yapılmıştır. Yükün düşürülerek kesitten sertlik ölçüm yapılmasının sebebi sertlik değişiminin takibinin yapılabilmesidir.

XRD analizi, 60-105^0 açı aralığında 1^0 tarama hızında gerçekleştirilmiş olup, kalıntı östenit tespitinde kullanılmıştır.

Optik mikroskop ile x50, x100, x200, x500 ve x1000 boyutlarında büyütülerek inceleme, farklı büyütmelerde SEM analizi yapılmıştır. Bu testlerin yanı sıra darbeli aşınma cihazı ile lazer sertleştirme prosesi uygulanmış olan numunelere, 10 mm çapındaki çelik bilya ile oluşturulan izin profilemetre ile 5 farklı bölgesinden derinlik, genişlik ve alan ölçümleri alınmış ve buna bağlı olarak aşınma davranışları incelenmiş ve sertlik kabiliyeti, oluşan mikro yapı ve aşınma davranışları arasındaki ilişki ve bunlara etkiyen farklı proses parametrelerinin etkileri incelemiştir.

Sonuçlara bakıldığında, sertlik, sertlik derinliği, XRD analizi ve mikroyapı testleri incelenip, malzemenin darbeli aşınma kayma davranışına lazer sertleştirme proseslerinin etkileri gözlemlenmiştir.

XRD analizinde lazer sertleştirme prosesi uygulanan numunelerde kalıntı östenit bulunmadığı saptanmıştır. Optik mikroskop ile yapılan incelemelerde ise QR O90 numune yüzeylerinde martenzit varlığı saptanmış olup, martenzit yapılarının çevrelerinde ferrit yapılarının oluştuğu gözlemlenmiştir. Uygulanan farklı lazer yüzey işlem parametreleri malzemelerin martenzit oranları üzerinde değişime sebep olduğu ise tahmin edilmektedir.

Sıcaklığın 1200-1250 ^{0}C aralığında ve 6 mm/s hızında lazer sertleştirme prosesi uygulanan numunenin yüksek sertlik değerine sahip olduğu saptanmış ve bu numunenin yapılan darbeli aşınma testi sonucunda en düşük aşınmaya sahip olduğu saptanmıştır. Ancak, aşınma alanlarında yapılan SEM sonuçlarına göre test sonucunda malzeme yüzeyinde plastik deformasyon izleri saptanmıştır.

Genel olarak profilemetre cihazından elde edilen sonuçlara göre lazer sertleştirme prosesi uygulanmış numunelerde, sıcaklık arttıkça aşınma direncinde artma saptanmıştır.

1. INTRODUCTION AND PURPOSE

Steel is widely used for most of industries as primary demand since many year ago [55]. It is using for many industry fields such as construction, automotive, medical, aviation, etc.

Chemical composition of steel could be changed or various heat treatment could be applied on steel. These types of processes change microstructure of steel, so the mechanical properties could be changed with this new microstructure.

Tool steels are one type of alloyed steels. Tool steels have high rate alloy elements and they are more strength according to the unalloyed steels. Mechanical properties of tool steels can be changed according to the additional element ratio such as tougness, hardness, high temperature resistance, wear resistance, strength, etc. Also, heat treatment is applied on tool steels for providing the properties more constant.

Hot work tool steel is also one of the tool steels. It has many important using areas and the quality of hot work tool steel change according to its chemical composition, heat treatment type, surface treatments, kind of using areas and tool designs [6].

Wear resistance of hot work tool steel can be improved with heat treatment processes. One of the methods is laser surface hardening. Laser surface hardening improves the surface properties of the steel such as corrosion and wear resistance. The biggest importance of laser surface hardening is minimum distortion according to conventional hardening methods. Therefore, this method eliminates mostly post processing demand. Additionally, laser surface hardening increases only surface part of materials hardness and this event causes inner part of material to be still tough against sudden impacts.

The effects of laser surface hardening on steel could be changed with laser beam type, velocity, temperature, power, etc. [62]. In this study, high power laser diode was used for laser surface hardening of hot work tool steel (QR O90) and the effect of laser parameters, which are laser beam velocity, temperature and power, on QR O90 was studied in terms of hardness, depth of hardness and especially wear

resistance. These properties were investigated via using of X-ray diffraction (XRD) test device, optical microscope, scanning electron microscope (SEM), hardness devices, and impact sliding test.

2. STEEL

The most important element is carbon for steel. [50]

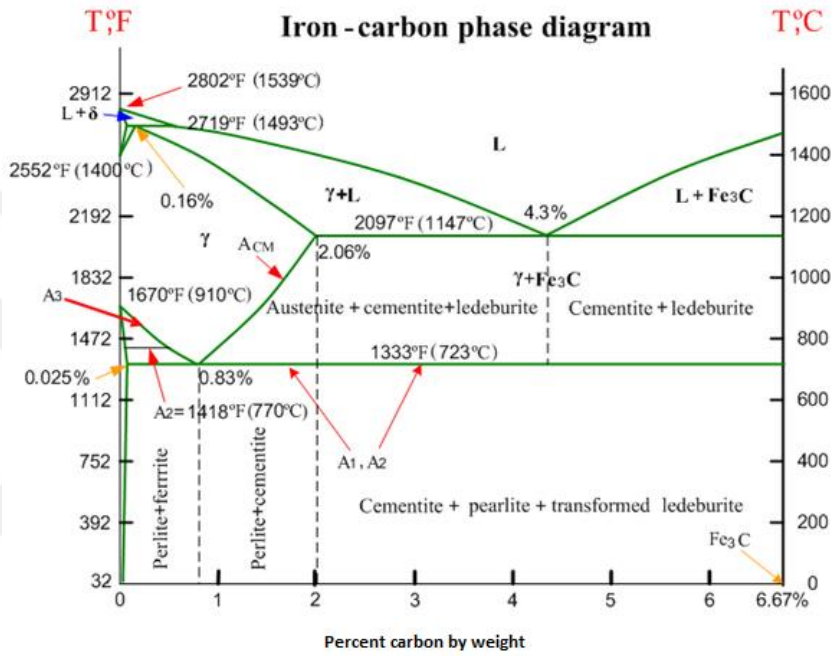


Figure 2.1: Iron-Carbon Equilibrium Diagram. [15]

The amount of carbon, which exist inside of steel hardens of alloy structure and prevents sliding of Fe atoms. The changing of carbon ration inside the steel affects mainly mechanical properties, ductility, wear-impact resistance of steel.[33]

The steels which have carbon, less amount manganese and silicon, are called as carbon steels.[28]

Carbon steels do not have any molybdenum, chromium and nickel elements.

Steels are classified as three types according to their carbon ratio. These are;

1. Low carbon steel 0,08-30% carbon
2. Medium carbon steel 35-55% carbon
3. High carbon steel 60-1,15% carbon

When the carbon rate of steel increase, some properties of steel change. For example;

1. The melting point of steel decreases.
2. Hardness increases.
3. Strength increases.
4. Behavior of brittleness increases.
5. Wear resistance increases.
6. Welding capability decreases.
7. Machining decreases.
8. Heat treatment can be applied easily.
9. Cost increases.[3, 50]

- **Low Carbon Steel**

The most common carbon steel is low carbon steel in terms of low cost and machineable property of the steel. This type of steel is suitable for welding [56]. Addition of low amount of manganese and silicon increases the quality of low carbon steel [28].

- **Medium Carbon Steel**

This type of steel contains between 3-6 % carbon rate. [56]

- **High Carbon Steel**

High carbon steel contains more than 0, 6 % carbon ratio. This type of steel is used generally for manufacturing of drilling bit, saw, spring, mold, etc. [56].

2.1 Tool Steels

2.1.1 General properties of tool steels

Tool steels contains carbon element between 0, 8-1, 5 % and it is produced as a result of many hard processes. [3, 56]

Tool steels are used for industries which are about to machining and chipless machining such as cutting, forged, pressing process. [4, 58]

When the tool steels contain carbon content above eutectoid compound, this situation causes to improvement of wear resistance with high possibility of insoluble carbon content. [5]

Tool steels are classified as four types steel. This classification depends on range of temperature and types of alloying elements. These four types of steel are;

- Cold work tool steel
- Hot work tool steel
- High speed tool steel
- Plastic mold steel [4, 58]

The significant desired properties of tool steels are;

- Hardness and strength, depends on the carbide amounts
- Cutting ability
- High depth of hardness, changes with types of alloying elements and amounts.[3]

2.1.1.1 Cutting performance and hardness

Carbon ratio is so important for hardness of material. Hardness parameter affects on cutting performance of tool steels. This property is desired especially for knife and clippers. Carbide forms occur at the result of increasing of carbon ratio. [24]

2.1.1.2 High wear resistance

Using life is determined by wear resistance property. This wear resistance is main property for cutting tool steels. Carbon ratio has also effects on wear resistance of tool steels. [24]

2.1.1.3 Ductility

Ductility protects the tolls steels for the crack resistance at the result of the strains.this ductility property increases the using life because of preventing crack propagation. Heterogenity of materials, microstructure, martensite ratio, high hardness value affect on ductility behavior of tool steels. [86]

2.1.1.4 Toughness

Before the fraction of steels, elastic and plastic changes inside of steels are called as toughness. High toughness property shows high ratio deformation of steels. Generally, high tougness propery and high wear resistance are inverse proportion each other. It means, ıf the tool steel has high toughness, it has also low wear

resistance. Increasing of carbon ratio decreases the toughness property of tool steels. [55]

2.1.1.5 Heat resistance

High heat transmission increases the resistance of tool steels against heat changings. Molybdenum alloy steels have higher heat resistance according to tungsten alloy steels. Increasiıng alloy ratio causes also decreasing heat transmission.
High toughness property provides also high heat resistance of steels. [55]

2.1.2 Hot work tool steel

External surface temperature of this type of steel is above 200 ^{0}C when it is working.

- Molybdenum, tungsten and vanadium addition provide high temperature resistance.
- Tempering stability is increased with chromium addition for this type of steel.
- Chromium addition, which is using with molybdenum, nickel and manganese, provides hardness capability. [20,74]

Table 2.1: Chemical compounds of hot work tool steels (TS 3920).[20,74]

Steel Type		Chemical Compound (% Weight)						
SHORT VERSION(DIN)	MATERIAL NO	C	Si	Mn	Cr	Mo	Ni	V
55NiCrMoV6	1,2713	0,50-0,60	0,10-0,40	0,65-0,95	0,60-0,80	0,25-0,35	1,50-1,80	0,07-0,12
55NiCrMoV7	1,2714	0,50-0,60	0,10-0,40	0,65-0,95	1,00-1,20	0,45-0,55	1,50-1,80	0,07-0,12
X38Cr5Mo1V	1,2343	0,36-0,42	0,90-1,20	0,30-0,50	4,80-5,50	1,10-1,40	_	0,25-0,50
X40Cr5Mo1V	1,2344	0,37-0,43	0,90-1,20	0,30-0,50	4,80-5,50	1,20-1,50	_	0,90-1,10
X32Cr3Mo3V	1,2365	0,28-0,35	0,10-0,40	0,15-0,45	2,70-3,20	2,60-3,00	_	1,40-0,70

Hot work tool steels are made according to combination of heat, abrasion and pressure. This type of steel is classified as AISI Type H. Every hot work tool steels are used as quenched and tempered. The most important properties are toughness, ductility, creep strength, thermal conductivity, temper resistance, low thermal expansion and high levels of hot strength. [36,64]

This type of steel that needs to preserve its properties at high temperatures. A secondary hardening reaction is the most suitable method for increasing temper resistance. The secondary hardening reaction contains precipitation of alloy carbides. [27,36,51,64]

A perfect secondary hardening effect is provided with strong carbide forming elements such as vanadium, tungsten, molybdenum and chromium. These elements provide high temperature resistance when they precipitate as fine alloy carbides.

The AISI type H steel has three categories. These are chromium hot work tool steel, tungsten hot work tool steel and molybdenum hot work tool steel.

Chromium hot work tool steels (types H10 to H19) are used for die casting dies, forging dies, dies for the extrusion of aluminium and magnesium, hot shears. This type of steel is suitable for working hot-work condition.

Tungsten hot work tool steels (types H21 to H26) are used for making mandrels, hot forging dies and extrusion dies for high temperature applications.

Molybdenum hot work tool steels (type H42) are most likely to tungsten hot work tool steels in terms of identical characteristics. Molybdenum addition with low carbon content provide to more resistant steel for heating. [27,64]

The lifetime of the hot work tools depends on the quality and kind of the tool. Carbon and the other elements content, metallurgical processes, phase transformation as a result of plastic forming and heat processes affects the lifetime.

Chromium increases the behavior of the hardness, thermal shock resistance and strength.

Hot work tool steels must have high abrasion resistance and high strength. This situation directly depends on the hardness. [4,9]

General properties of hot work tool steels are;

- Mechanical and thermal shock resistance
- Machinablity
- High temperature abrasion resistance
- High temperature deformation resistance
- Hot tearing resistance [55]

DIN 1.2344, 1.2343, 1.2365, 1.2367, 1.2714, 1.2581, 1.2606, 1.2713, 1.2885 are the most common types of hot work tool steel. [4]

Table 2.2: Types of hot work tool steels according to ASTM A681.[77]

		Weight(%)					
AISI	UNS	C	Cr	V	W	Mo	Co
Cr Steels							
H10	T20810	4	3,25	4	_	2,5	_
H11	T20811	35	5	4	_	1,5	_
H12	T20812	35	5	4	1,5	1,5	_
H13	T20813	35	5	1	_	1,5	_
H14	T20814	4	5	_	5	_	_
H19	T20819	4	4,25	2	4,25	_	4,25
W Steels							
H21	T20821	35	3,5	_	9	_	_
H22	T20822	35	2	_	11	_	_
H23	T20823	3	12	_	12	_	_
H24	T20824	45	3	_	15	_	_
H25	T20825	0,25	4	_	15	_	_
H26	T20826	5	4	1	18	_	_
Mo Steels							
H42	T20842	6	4	2	6	5	_

Table 2.3: Transformation of some hot work tool steel types between different standards.[76]

Wr. Nr.	DIN	AISI	UNI
1,2343	X38CrMoV5-1	H11	X37CrMoV5-1KU
1,2344	X40CrMoV5-1	H13	X40CrMoV5-1KU
1,2365	X32CrMoV3 3	H10	_
1,2367	X38CrMoV5-3	_	_
1,2714	56NiCrMoV7	L6	56NiCrMoV7KU

2.1.3 Cold Work Tool Steel

Cold work tool steed is used under the 200 ^{0}C temperature as working condition. The main application fields are cutting, bending, benching and powder metallurgy. Generally, they are used for machining and chipless machining. [4, 48]

We can classify the cold work tool steel as two types. These are alloyed and unalloyed cold work tool steel. Unalloyed steels have generally high critical cooling rate and low depth of hardness. These properties of unalloyed sold work tool steel provides to toughness capability for inside of material. Also, cooling types affects the hardness depth and behavior of this type of steel.

Table 2.4: Chemical compounds of some unalloyed cold work tool steels(TS 3941)

Steel Type	Material No	Chemical Compound(% Weight)				
		C	Si	Mn	P(max)	S(max)
C60T	1,1740	55-65	0,15-40	60-0,80	0,035	0,035
C70T2	1,1620	65-0,74	0,10-30	0,10-35	0,03	0,03
C80T1	1,1525	0,75-0,85	0,10-0,25	0,10-0,25	0,02	0,02
C85T	1,183	0,80-0,90	0,25-40	50-0,70	0,025	0,02
C105T1	1,1545	1,00-1,10	0,10-0,25	0,10-0,25	0,02	0,02

Alloyed cold work tool steels have some advantages such as high hardenability capability, high wear resistance according to unalloyed version.

Depth of hardness capability increases with the effect of addition manganese, chromium, molybdenum and nickel.

Steels, which have high wear resistance, are strengthen with carbide of molybdenum, vanadium and chromium and they are used for cutting applications. [20,74]

Carbon rate of cold work tool steels changes 3-2,5 %. The maximum rate could be 3% for high alloy steels. Carbide amount is 5% for the low alloy steel which has 1% carbon rate and also, carbide amount rise 10-30% values for the steels which has more than 2% carbon rate.

The cold work tool steels are standardized with TS 3921, DIN 17350 ve EN ISO 4957. [60]

Table 2.5: Chemical compounds of some alloyed cold work tool steels (TS 3921)

Steel Type	Material No	Chemical Compound(% Weight)							
		C	Si	Mn	Cr	Mo	Ni	V	W
X210Cr12W	1,2436	2,00-2,25	0,10-0,40	0,15-0,45	11,00-12,00	_	_	_	0,60-0,80
X210Cr12	1,208	1,90-2,20	0,10-0,40	0,15-0,45	11,00-12,00	_	_	_	_
X155Cr12V1Mo	1,2379	1,50-1,60	0,10-0,40	0,15-0,45	11,00-12,00	0,60-0,80	_	0,90-1,00	_
145V33	1,2838	1,40-1,50	0,20-0,35	0,30-0,50	_	_	_	3,00-3,50	_
90MnCrV8	1,2842	0,85-0,95	0,10-0,40	1,90-2,10	0,20-0,50	_	_	0,05-0,15	_
40CrMnMo8B6	1,2312	0,35-0,45	0,30-0,50	1,40-1,60	1,8-2,00	0,15-0,25	_	_	_

1.2379, 1.2363, 1.2767, 1.2842 and 1.2436 are the most common types of cold work tool steel. [4]

2.1.4 High Speed Tool Steel

High speed tool steels have the capability to machine materials at high cutting speeds. This type of tool steels has alloying elements as general molybdenum, vanadium, chromium and tungsten. The behavior of hardening response, high wear resistance, good toughness and high resistance to the softening effect of heat are observed for this type of tool steels as general characteristics. [7]

Molybdenum high speed tool steels (M series steels) have higher abrasion resistance according to tungsten high speed tool steels (T series steels) as general. [7,30]

Tungsten is so important for high speed tool steels. The complex carbide of iron, carbon and tungsten enhance wear resistance of high speed tool steels.

The common properties of M series and T series steels are;

- High alloy content
- Includıng enough carbon rate for reaching maximum 64 HRC
- Uniform hardness ability from center to surface
- Hardening ability at high temperatures [7,82]

Table 2.6: Composition of some high speed tool steels. [7,30]

AISI	UNS	C	Si	Cr	V	W	Mo	Co
Molybdenum High Speed Tool Steels								
M1	T11301	0,83	35	3,75	1,18	1,75	8,7	_
M6	T11306	0,8	33	4,13	1,5	4,25	5	12
M15	T11315	1,5	33	4	5	6,5	3,5	5
M41	T11341	1,1	33	4,13	2	6,63	3,75	8,25
M62	T11362	1,3	0,28	3,88	2	6,25	15	_
Tungsten High Speed Tool Steels								
T1	T12001	0,73	3	4,13	1,1	18	_	_
T5	T12005	0,8	3	4,38	2,1	18,25	0,88	8,25
T8	T12008	0,8	3	4,13	2,1	14	0,7	5

2.1.5 Plastic Mold Steel

Remarkable properties of plastic mold steels are corrosion resistance and burnishable surface quality.

The areas of usage are blow molding for corrosive plastics, forming molds such as plastic injection, extrusion, etc.

The most common types of this type steel are 1.2311, 1.2312, 1.2738, 1.2316 and 1.2083. [4,19]

2.2 The Effects Of Alloying Elements On Steels

The main elements of steel are carbon and iron, but besides of these elements many different elements could be exist in the steel. Manganese and silicon are always exist in the steel. Also, Cr, Ni, Mo, V, Nb, W, Co, Ti, Al, Cu, etc. elements could be inside of steel.

The significant effect belongs to carbon. Carbon affects microstructure and general properties of the steel. The most type of steel contains less than 1% carbon ratio.

Some elements are not good effect on steels. For instance, hydrogen, phosphorus, nitrogen and sulphur. These type of elements are not desired in the steel.

The reason why addition of alloying elements are;

- Increasing hardness ability
- Increasing hardness and strength
- Enhancing mechanical properties
- Increasing toughness
- Increasing wear resistance
- Increasing corrosion resistance
- Enhancing magnetic properties [19]

Carbon: The ability of hardness is obtained with this element. Increasing of carbon ratio increases hardness and ultimate strength, but also decreases ductility, welding ability and cutting property of the steel.

Manganese: Manganese increases the strength of steel. This element has positive effect on forging and welding properties. Manganese enhances hardness and strength depends on carbon ratio. The effects of manganese on high carbon steel are higher than low carbon steel.

Silicon: Every steels has silicon element like manganese. Silicon decreases ductility, increases yield strength.

Phosphorus: This element is known as harmful for steels, so the ratio of phosphorus is hold between 0,03-0,05 %.

Sulphur: Sulphur causes brittleness of steels. The ratio of this element should be between 0,025-0,050 %.

Chromium: Chromium increases the strength of the steel, but also it causes to decline ductility property of the steel in small quantities. Chromium increases corrosion resistance.

Nickel: Nickel increases depth of hardness with chromium addition.

3. HOT WORK TOOL STEEL

3.1 Using areas of Hot Work Tool Steels

Hot work tool steels have wear resistance and thermal shock endurance. Also, they have high toughness and high thermal conductivity. Using areas of this steel are injection and extrusion molds of light metals like aluminum, hot forging mold, mold parts, punch, plastic injection molds of abrasive plastics.

Hot work tool steels are used for shaping of ferrous, non-ferrous metals and alloyed metals without cutting. This type of steel has resistance high temperature and pressure. [14]

Table 3.1: Using areas of hot work tool steel and equipments, which are produced from hot work tool steels. [6]

FORGING	EXTRUSION	HIGH PRESSURE MOLD CASTING
Mold(hammer)	Mold	Mold cores
Mold(press)	Dummy block	Socket
Ejection pin	Socket	Ejection pin
	Piston	
	Mandrel	

Hot work tool steels are generally used as engineering materials and they have high chromium content. Hot work tool steels, which are used for extrusion molds and hot

pressing of copper alloys. This type of steel could be characterized with high hardness, ductility and good tempering resistance properties. [78]

Figure 3.1: Example of hot work tool steels.[80]

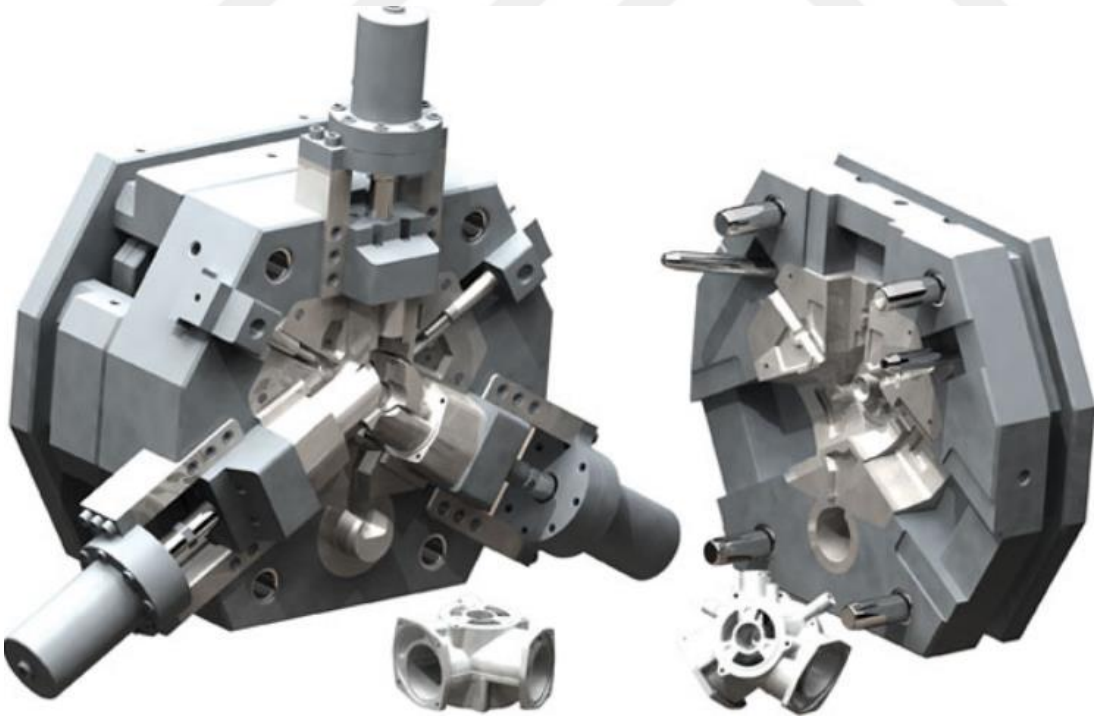


Figure 3.2: The mold which is produced from hot work tool steel. [81]

Table 3.2: Some hot work tool steel application fields. [58]

	INDUSTRIAL APPLICATION FIELDS
DIN 1.2344	Die casting of light metals and molds in metal injection presses, used as plunger, runner, matrix and punch are used.
DIN 1.2714	A standard steel for all forging dies; die-cast molds, printing punches for extrusion presses, matrix (seal) carriers, sleeve and similar suits and hot scissors used.

3.2 Mechanical Properties of Hot Work Tool Steel

The prominent properties of hot work tool steels could be high hardness, sufficient yield & ultimate strength and enough tempering resistance at high temperature. Also, it has to be sufficient wear resistance and thermal conductivity at high temperature.

Some extrusion dies could be have breaking or cracking during use. The reasons are showed as regional over loading, material faults and contact surface wearing of tools. [66]

The most common mechanical crack propagation occurs due to thermal fatigue which occurs retiform structure of surface cracks. The reasons why of this fatigue are generally oxidation and creep.

The quality of hot work tool steel could be increased with better tool choosing and better surface quality of tool. [65]

The chemical composition of this type of steel affects ductility, toughness, thermal expansion coefficient, hot resistance, hot yield strength and thermal conductivity. The production type of hot work tool steel affects its ductility property especially.

Hardness and toughness properties of hot work tool steel could be associated with heat treatment processes. [39]

3.3 Selection of Hot Work Tool Steel

Manufacturing parameters, suitability of steel and heat treatment process, process conditions could be considered to choose hot work tool steel. Also, using conditions are important parameter to choose this steel. For example, hot work tool steel must have to high hot resistance and high wear resistance for light metal extrusion process.

If the process includes impact condition, the steel must have to good toughness property.

The manufacturing of steel with ESR or VAR has advantage according to high ratio purity and good homogeneity. These types of manufacturing prevent thermal fatigue of high rate. Also, heat treatment process choosing is so important parameter in terms of suitability to type of steel. [6]

4. HEAT TREATMENT

4.1 Definition of Heat Treatment and Applications

Thermal processes, which are using for enhancing of physical and some chemical properties is called as heat treatment. The most common using area is metallurgy. Also, additionally glass and ceramic fields could be counted.

Heat treatments, which are applied on metals base on heating and cooling processes. These processes conditions change with melting point of metals. The result of heating and cooling processes, the metals could be hardened and softened.

Mechanical processes, which are enhanced with the help of heat treatments could be counted as hardness, strength, wear resistance, impact resistance, hot resistance and corrosion resistance. Increasing of hardness of metal affects wear resistance positively. Also, fragility increases with the increasing of hardness. The desired metal could be produced with the control of atmosphere, heat and time as simultaneously.

Material or a part of material exposes to thermal cycling and at the result of this process metal properties change. This situation is called as heat treatment by international heat treatment federation. Also, the chemical properties of material could be change during heat treatment processes. [67]

Heat treatment is important parameter for microstructure changing. Changing of microstructure affects mechanical and thermal properties of tool steels. [6]

If the microstructure is defined clearly, the all properties of metal could be known and this provides to choose right heat treatment process for changing these properties.

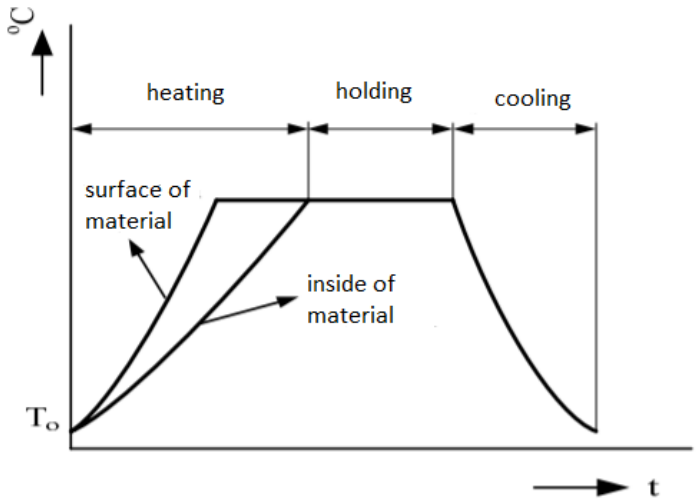


Figure 4.1: Cycling of heat treatment. [18]

The mechanical properties, which are like strength and toughness, act as a function of microstructure of material. Microstructure determines to desired properties of material and with heat treatment processes, microstructure could be changed.

Types of heat treatment processes;

- Hardening (vacuum, oil, water, air)
- Tempering
- Annealing
  - Soft Annealing
  - Stress Relief Annealing
  - Diffusion Annealing
  - Recrystallisation Annealing
  - Hydrogen Annealing
- Sementation
- Nitration
- Oxidation
- Carbonitration
- Normalization
- Subzero processes
- Ageing

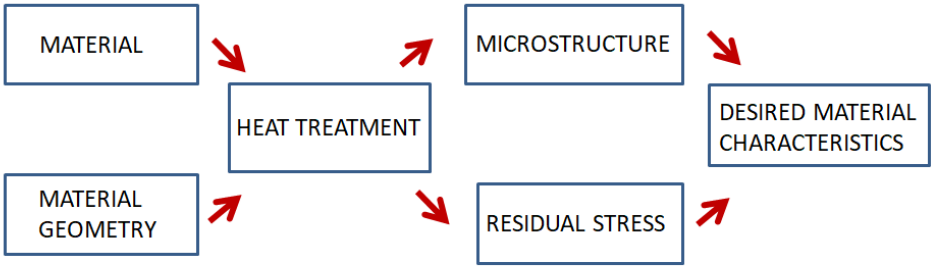


Figure 4.2: The relationship between heat treatment and material properties [67]

4.2 Heat Treatment Of Hot Work Tool Steel

The lifetime of tool steels depend on many factors. Some of these are chemical composition of tool, manufacturing type of steel, dimensions of tool steel and design, manufacturing conditions, heat treatment, etc.

Heat treatment affects metallurgical and mechanical properties of tool steel critically. Although many type of hot work tool steel could be hardened with air and good ratio of hardness of this steel, the improvement of mechanical properties of steel is known to depend on increasing of cooling rate. Additionally, these processes have effects on toughness and tempering resistance of material.

The high performance of hot work tool steel does not depend on only quality of the steel. Is is also about heat treatment.

High hot resistance, toughness, thermal fatigue resistance properties of hot work tool steel could be changed with austentizing, cooling and tempering process negatively or positively. [6]

The tools, which have complex geometry or different sectioned, need stress relief annealing for preventing heat deformation. This process could be applied on hot work tool steels before or after rough mechanical process. [15]

Figure 4.3: Heat treatment of hot work tool steel. [72]

5. SURFACE HARDENING

Surface hardening methods are used to enhance wear resistance of parts without affecting interior of the part. Thanks to surface hardening, the more soft and tough interior could be handled. The combination of hard surface and tough interior of the part is so advantageous for ring gear, bearing or shafts, turbine applications, automotive applications, etc. These types of parts must have so hard surface to resist wear and tough interior to resist impact that happens during operation. [54]

Quality of surface hardening depends on carbon content in the material. The higher carbon content provide to material higher hardenability property. [79]

The reasons of surface hardening processes are;

- To improve wear resistance
- To improve fracture toughness
- To improve fatigue resistance
- To improve corrosion resistance [13, 37, 46, 85]

Figure 5.1: The sample, which belongs to surface hardening process. [75]

There are two different approaches for surface hardening. The first one is processes that change the surface chemical composition. The common types are nitration,

carburization and carbonitriding. The second one is processes that do not change the surface chemical composition. The common types are flame hardening, induction hardening and laser hardening. [54]

5.1 Surface Hardening Methods with Chemical Alteration

Surface hardening methods with chemical alteration are applied on low carbon steel.

The common types of surface hardening methods with chemical alteration;

- Nitration
- Carburization
- Carbonitriding

5.1.1 Nitration

Nitration is type of surface hardening method with chemical alteration.

Appropriate metals for flame surface nitration;

- Low alloy steels, which contain Al element
- Hot work tool steels, which have more than 5 % Cr content
- High speed steels
- Medium carbon steel
- Tool steels, which are hardened with air
- Stainless steels [70]

The temperature of steel is 500-550 ^{0}C for nitration process in this way a hard and thin layer forms on the surface of steel. At the result of nitration process, the surface of material is handled as hard, interior of the material is tough. A high hardness value can be handled with nitration process without any annealing and addition hardening operations. The nitration process need long time to harden the surface of material. For instance, 20 hours is demand for 0, 35 mm depth of hardness of material. [31,75]

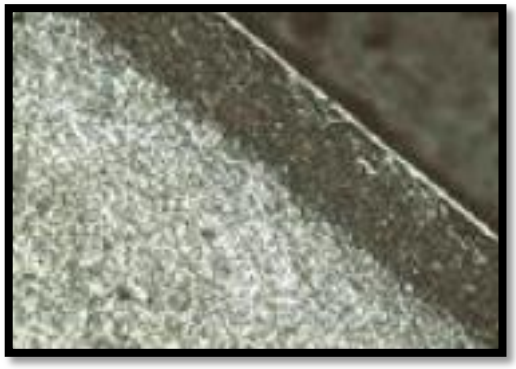


Figure 5.2: Nitration layer on hot work tool steels. [60]

5.1.2 Carburization

Carburization is one of the surface hardness methods with chemical alteration. Mainly, carburization bases on saturation of carbon on surface layer of steels.[16, 37]

The main purpose is firstly increasing carbon content the steels, which have under 0,2 % C ratio, and then providing hardness capability with higher content of carbon. [70]

Carburization is classified as three types according to carbon source. These are;

- Pack carburizing
- Gas carburizing
- Liquid carburizing [16, 37]

Pack carburizing;

- The amount of carbon on the part surface is increased with this method. For example,
  charcoal, coke, charcoal, lignite coal, etc. could be counted as carbon donors.

Table 5.1: Penetration depth-carburization time[31,75].

Penetration depth (mm)	0,5	1	1,5	2	2,5
Carburization time (hour)	$(0,5^2.4)=1$	$(1^2.4)=4$	$(1,5^2.4)=9$	$(2^2.4)=16$	$(2,5^2.4)=25$

Liquid carburizing;

- The amount of carbon on the surface layer could be increased with melt salt baths. Mostly, NaCN bath is used. KCN is used as less.

Table 5.2: Penetration depth-carburization time[31,75].

Penetration depth (mm)	0,4-0,8	0,8-1,2	1,2-1,4	1,4-1,6	1,6-1,8	1,8-2,0	2,0-2,2	2,2-2,4
Carburization time (hour)	1	2	3	4	5	6	7	8

Gas carburizing;

- This method looks like pack carburizing. Gas mixtures are used for carbon source as difference of pack carburizing. [31,75]

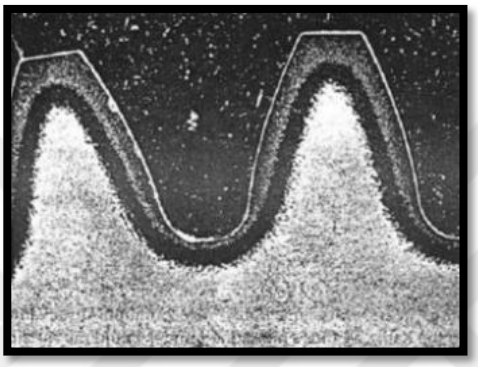


Figure 5.3: Case hardened gear tooth. [73]

The heat treatment temperature of carburization is approximately 850-950 ^{0}C. [70]

The reason why of carburization process mainly bases on obtaining anti corrosion, fatigue resistance, hard and wear resistance on surface of steels. The principle of this hardening method includes enrichment of surface layer with carbon element from 0, 75 to 1, 2 % and cooling process. [2, 37]

Appropriate metals for flame surface carburization;

- Low carbon steel or low alloyed steel [31, 75]

Most frequent using area of carburization process;

- Automobile components; rack and pinion, gears, cam shaft, axles, etc.
- Aerospace components

The important parameters of carburization are the holding time, carburization temperature, carbon potential and cooling time in oil. [75]

5.1.3 Carbonitriding

Carbonitriding is one of the surface hardening method like carburization. With this method, C (~ % 6–0.7) and N (~ % 0.2–3) elements are given to the material. After cooling process, prominent hardness value is handled with less time and lower temperature than carburization.

Solute nitrogen in austenite decreases critic cooling rate. That is why, even if oil or gas cooling is enough to form martensitic microstructure, but slow cooling has more advantageous due to reducing of distortion and deformation rate.

This process can be used for medium carbon steel (% 35–50) and the steels, which has carbon rate is more than 0,25 % [32].

5.2 Surface Hardening Methods without Chemical Alteration

This surface hardening methods has four types;

- Flame hardening
- Induction hardening
- Laser surface hardening (LSH)
- Electron beam (EB) hardening

5.3 Flame hardening

Flame hardening is one of the surface hardening methods. This surface hardening method is a surface heat treatment with hot flame application. Hot flame handled from an oxy acetylene gas mixture.

Heating and cooling processes change according to dimension and chemical properties of steel. [45, 75]

The temperature level of gas flame, which is about to 3000 ^{0}C, is exposed to work piece material. After then, material comes to recrystallization temperature and suddenly cooled by water. Because of these rapid microstructural changes, micro hardness of surface increases. This surface hardening method depends on surface temperature, quenching time and stand-off distance. [63]

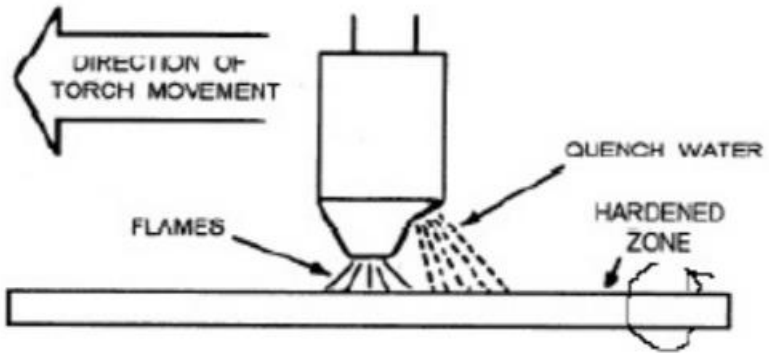


Figure 5.4: Principles of flame hardening process [79]

Flame hardening processes are used for many engineering applications to enhance mechanical properties of materials. This method is economical and also, it helps to improve fatigue strength of material. [38]

Depth of hardness could be changed with regulating the temperature of flame, heating time, rate of heating, speed of torch travel, etc.

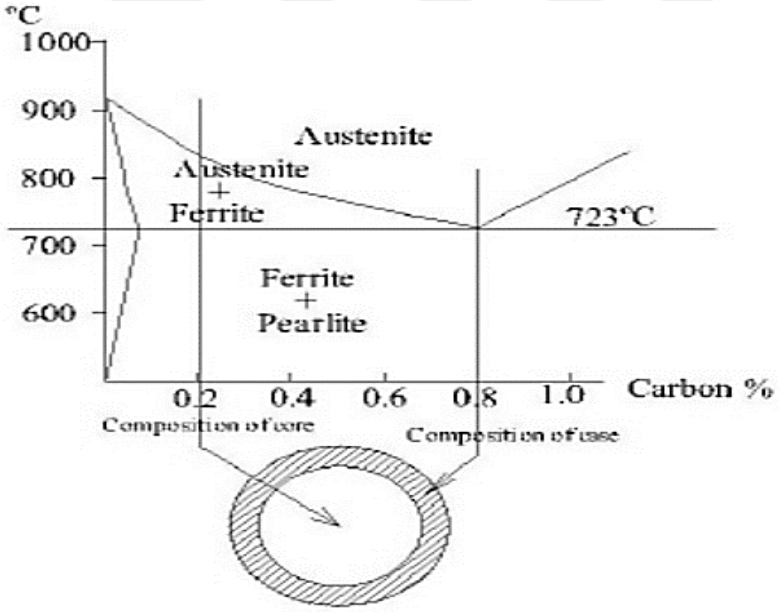


Figure 5.5: Phase transformation during flame hardening. [79]

This figure indicates that the phase transformation at the surface and the core of sample. Martensite formation is observed at the surface layer because of rapid cooling. Also, the pearlite and the ferrite occur at the centre because of slower rate of cooling. The result of this process, a thin hardened surface and tough interior region could be handled. [79]

Figure 5.6: Example of flame hardening. [41]

Appropriate metals for flame surface hardening;

- The steels, which have between 4%-0,8% C ratio
- The steels, which contain Cr-Ni and Cr-Mo elements
- High strength tempered steel
- Cast iron, which has more than 5 % C ratio

Advantages of flame hardening;

- It could be applied easily on steels, which has big dimensions.
- This surface hardening process is economical under particular conditions.
- Flame hardening does not change chemical composition of material.
- Deformation and distortion rate of material are lower.
- The surface quality after the hardening process is not rough.

Disadvantages of flame hardening;

- Non-homogeneous surface hardening for some pieces
- Crack probability of high carbon steel and steel, which has bigger dimensions
- Non-economic method for serial working [45, 75]

5.3.1 Induction hardening

Electric current is used for sudden heating and cooling process. The result of this situation, surface hardening realizes. It is one of them surface hardening methods. This type of hardening method is called as induction hardening.

The difference of this surface hardening method according to flame hardening, the heat is applied as electrical way.

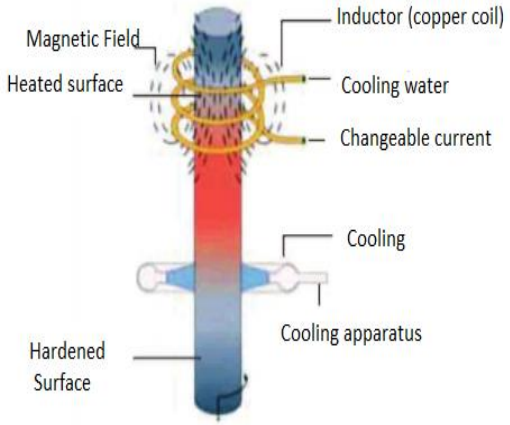


Figure 5.7: Principle of induction hardening [60]

A high frequency alternating current is passed through the coils surrounding the workpiece to obtain a high frequency magnetic field. High frequency current moves on the surface of the material and material starts to reach high temperature because of resistance against to current.

Work piece temperature reach to right level in a few seconds. Inside of the material starts to heat if the time is more than a few seconds. Therefore, time must arrange properly. Depth of hardness could be increased with longer time at particular frequency.

Appropriate metals for induction surface hardening;

- Medium carbon steel, which has between 35 % and 60 % C
- Engine cranks, gears, wedge surface, etc. could be given as induction hardening examples.

Advantages of induction hardening;

- Lower time for surface hardening process and lower heat dissipation to environment
- Less environmental pollution
- Easy applicable even if small production units
- Proper for serial working
- Heating control is higher than flame hardening
- Time, temperature and depth of penetration variables could be arranged by automatically.

Disadvantages of induction hardening;

- Overheating occurs at the sharp edge and corner of material
- Desired hardness values could not be handled for low carbon steel according to other surface hardening methods.
- Cracking risk is high for high carbon steels.
- Qualified employee is so important.
- Complex geometry is not economical for lower number working pieces.
- Building a plant is expensive.

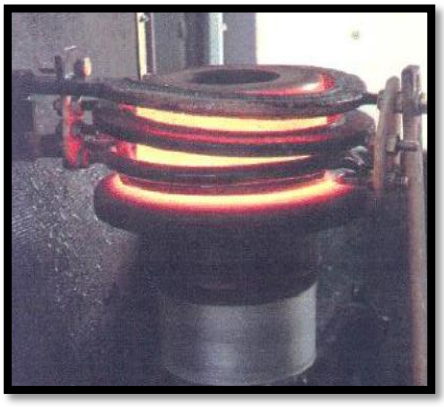


Figure 5.8: A sample of induction hardening [45, 75]

5.3.2 Electron beam hardening

Electron beam (EB) hardening looks like laser hardening. This type of hardening method provides surface hardening of steels. The principle of EB hardening is using of concentrated beam of high-velocity electrons like energy source to heat selected area of ferrous metal.

With EB hardening, rapid cooling of austenite demanded for martensite formation occurs through self- cooling. Also, the depth of hardness change from 0,1 to 1,5 mm.

Advantages of EB hardening;

- Lower distortion of material
- Low energy consumption
- No chemical alteration
- No oxidation formation at the surface
- No preparation of surfaces to be hardened

Electron beam hardening process is applied on vacuum environment. This environment prevents to oxidizing and avoids scattering of the electrons while the beams are travelling at a relatively low speed.

Energy absorbing coatings are not necessary for electron beam hardening, like laser hardening process. [87, 88]

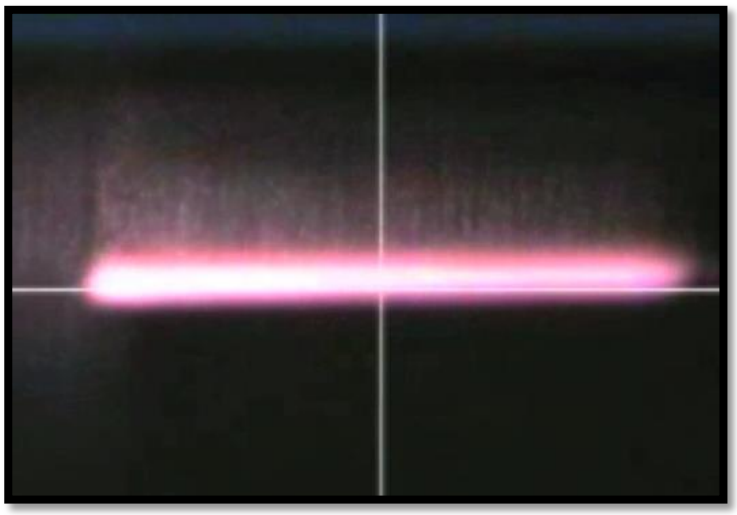


Figure 5.9: A sample of electron beam process [29]

5.3.3 Laser hardening

Laser surface hardening is one of surface hardening method without chemical alteration. It is mainly used for enhancing tribological properties and increasing service life of the steels. This is one of the best technique to harden a surface without sacrificing the internal toughness [35, 47, 62].

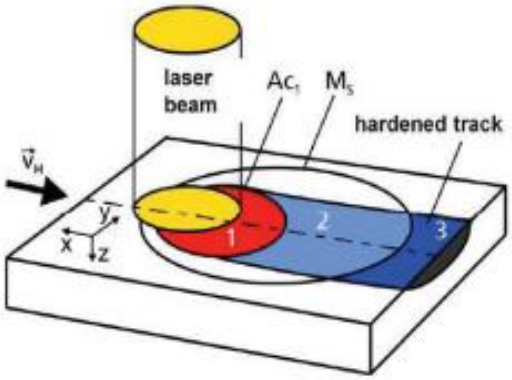


Figure 5.10: Schematically view of laser hardening process [43]

All tool steel, iron cast or medium carbon steel can be hardened with laser to increase wear resistance and corrosion resistance [23, 42].

Most frequent using area of laser surface hardening;

- Turbine blades
- Gear wheels and piston rings
- Shearing and bending tools
- Complex shape casting and pressing moulds

Advantages of laser surface hardening;

- Local hardening
- No requirement of post processing
- Precisely hardening of complex geometry material
- Negligible distortion in the material
- Environmentally friendly [61].

A thin surface zone forms on the surface of material with laser transformation hardening because it is heated and cooled very rapidly. The result of this process, fine martensitic microstructure occurs. [54]

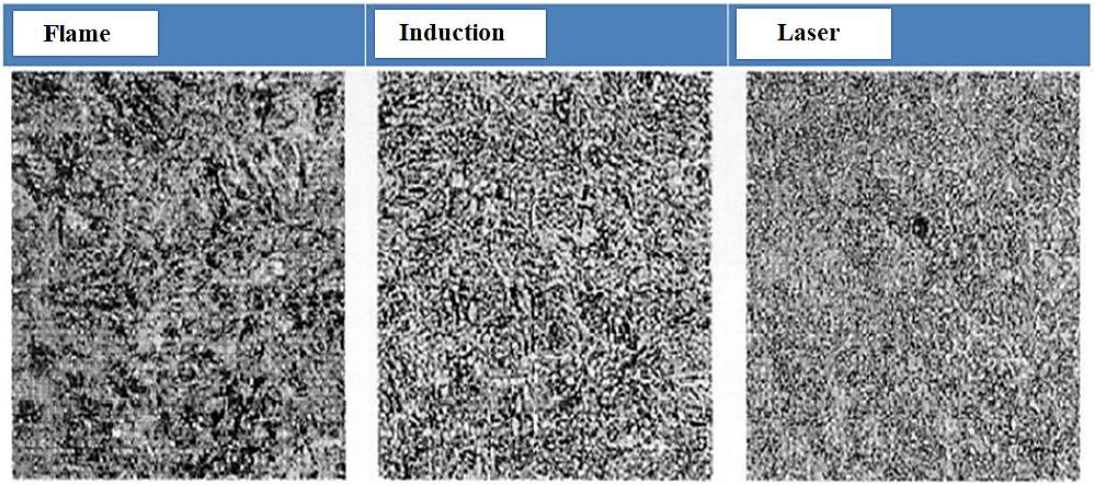


Figure 5.11: Comparison of microstructure with different surface hardening methods [57]

Microstructure of materials can be seen at the figure 5.11. Very fine microstructure is handled with laser surface hardening according to other surface hardening methods. Mechanical properties of materials enhances with finer microstructure. [57]

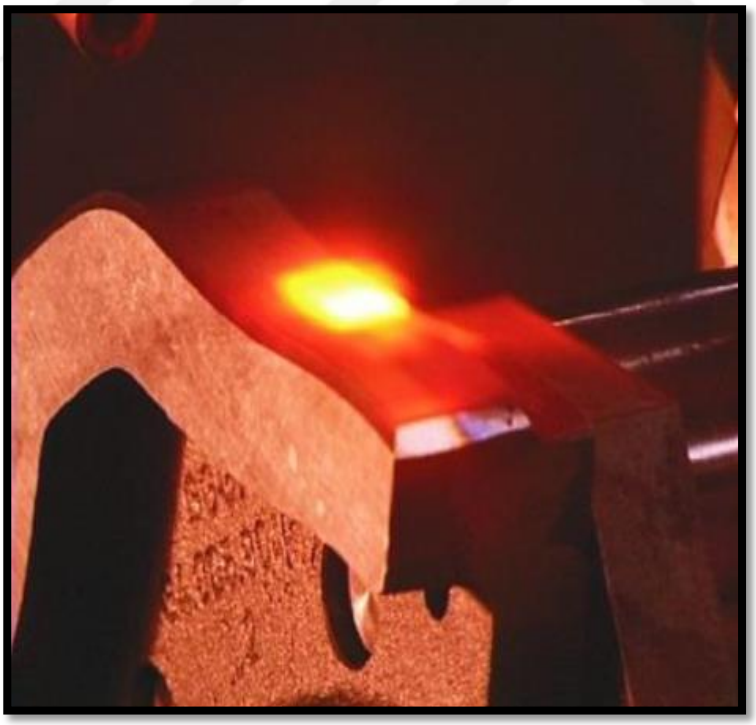


Figure 5.12: Sample of laser surface hardening [57]

Table 5.3: Comparison of surface hardening methods.[26]

Parameter	Laser	Induction Hardening	Carburizing	Flame	Arc	Electron Beam
Max. Treatment	1,5	5	3	10	10	1
Depth, mm	Very low	Medium	Medium	High	Medium	Very low
Distortion	High	Low	Medium	High	High	Medium
Flexibility	High	Medium	Medium	Low	Low	High
Precision	Medium	Medium	Medium	High	High	Medium
Operator Skill	Low	Low	High	Medium	Medium	Low
Quenchant required	No	Sometimes	No	Yes	No	No

6. LASER SURFACE HARDENING

Laser surface hardening is a convenient method for regional hardening on surface of steels which have sufficient carbon rate. [68, 89]

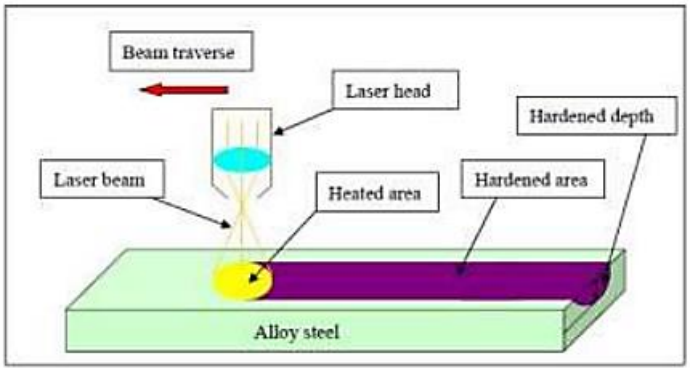


Figure 6.1: Laser surface hardening. [17]

A phase change occurs without melting during laser surface hardening process. Thanks to laser surface hardening, wear, strength, fatigue and lubrication properties of the surface can be enhanced, but some properties of surface could remain unaffected desirable bulk properties such as ductility and toughness. [17]

The laser beam irradiates on steel surface and it provides to heated up locally of material and austenite formation occurs. After that, the material starts to quench very quickly and microstructure transform into martensite. The laser surface hardening method has some advantages when it is compared with other conventional hardening methods such as flame hardening, induction hardening, nitriding, carbonitriding, etc. [40, 68]

There are three important criteria for applying laser heat treatment on surface of materials;

- The desired hardenable zone must be reached austenization temperature.
- Material must be waited for carbon diffusion at substrate austenization temperature between heating and cooling cycling.

- It should be enough mass for critical cooling rate by self diffusion velocity. [1]

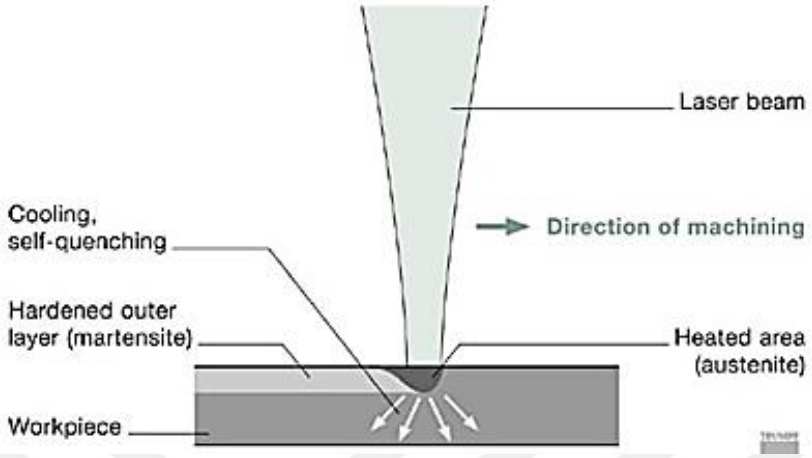


Figure 6.2: Principle of laser hardening [Trumpf GmbH &Co.KG]. [52]

Laser surface hardening has some advantages when it compares to other conventional surface hardening methods. These advantages can be listed as follows;

- A hardened surface layer is handled because of self-quenching of the over-heated surface layer.
- This type of surface hardening is so clean process. After this procedure, there is no need to clean and wash the workpieces. That is why quenching process bases on self-quenching without any agents.
- Energy input can be changed with changing laser source power, focusing lenses with different focuses, different degrees of defocus, different traveling speeds.
- Laser surface hardening is suitable for complex geometry of workpieces or small holes.
- After the heat treatment, small deformations and dimensional changes could be observed.
- There is no need final machining of the workpiece by grinding. [21]

Example for industrial applications of laser surface hardening;

-Piston rings;

The hardened layer is formed on the surface of piston rings. This layer provides wear resistance and high service life. When the piston ring resistance methods are compared with chromium plating or molybdenum spraying and new technique laser hardening, laser hardening of piston ring has many advantages such as economical price, no pollution, energy saving, etc. [11]

6.1 Types of Laser Surface Hardening

The most common types of laser surface hardening source are CO2 laser, Nd:YAG laser and high power diode laser.

CO_2 laser type was the most popular one and which is only provided power density and interaction time at the end of the last century [34].

Materials need the coating for increasing of laser beam absorption for CO_2 laser source.

After this type of laser, Nd:YAG laser could be alternative laser source and which has flash lights and diode pumping. The biggest advantage of Nd:YAG laser is wavelength of laser beam. It is wavelength is lower than according to CO2 laser. This is an advantage in terms of energy efficiency via optic fiber. Nd:YAG laser is suitable for three diemonsional process and it is used with robot entegration and it has high power laser.

High power diode laser developed recent vintage, which has multikilowatts. Its wavelength is about 8 micrometer. Also, it can be used with robot entegration for complex geometry laser surface hardening process.

Without of CO_2 laser type, these two sources do not need any coating for increasing laser beam absorption. Therefore, this property provides to increase energy saving. These two type laser are easier using and lower price according to CO_2 type of laser. [1,144]

6.1.1 CO_2 laser

One of the popular laser type is CO_2 laser. The high intensity CO_2 laser has proved to be succesful in many industrial applications since 1970.

For laser treatment processes, CO_2 laser need to absorbent on surface of material. That is why, the absorbent increases the absorptivity amount of laser beam.[22]

6.1.2 Nd:YAG laser

Nd –YAG laser has relatively low power according to CO_2 and its efficiency wavelength between 0,2-16 μm. Also, this type of laser source has smaller focal-spot diameter and much higher absorbtivity when it compares with CO_2.

6.1.3 High power diode laser

Laser beam unique properties are high intensity, coherency, highly directional nature, monochromotic enhance some properties of materials such as wear behavior, hardness, fatigue life, etc.

A part of laser beam is absorbed by material and a part of laser beam reflects from material surface according to wavelength when high power diode laser interacts with material surface.

Optic absorption of materials is controlled with free electrons. [12]

Energy transmits via lattice phonons with the help of collisions. Light is absorbed as vibrational and electronical. This event causes energy spreading beside atoms and in this way energy converts the heating. When phonon absorption increases, the heating of material increases. That is why increasing of amount of energy.

Interaction time of laser beam depends on laser beam power density, thermophysical properies of materials etc. [1]

6.1.3.1 Parameters of laser surface hardening

Parameters of laser surface heat treatment is controlled by heat and mass criterias.

Power density is affected by some independent parameters such as laser beam diameter. Velocity is affected by laser beam and substrate surface. Other parameters change according to material type, which affects thermophysical properties and absorbtivity of the laser beam.

Dependent variables are hardness, depth of hardness, heat affected zone geometry and heat treated zone metallurgical properties. [34]

The properties of the surface of steel and temperature depends on power density and travel speed of laser beam. [40,83]

6.1.3.1.1 Laser beam diameter and intensity distribution

Special intensity distribution is the main parameter for determining how to behave of laser beam. For example, two different laser beam could occurs laser sign with different laser power and different diameter during process.

Different laser sign on material surface could be seen because of laser beam gauss or non-gauss profile property.

Gauss profile is defined as laser beam density changing according to center distance. If the material is at the center of laser beam, laser beam intensity distribution has maximum value. If the distance increase between material and laser beam, laser beam intensity distribution decrease. [34]

In theory, laser beam behavior could be expected, but it could be have different behavior when the production parameters include in this process. These parameters could be counted as lens tolerances, mirrors, etc. [1]

6.1.3.1.2 Power density

When the increasing of power density, depth of hardness increase. This depth of hardness value changes according to material type, but there is maximum value for each material and this value could not be increased with increasing power density after this maxium point.

After the maximum point, increasing of power density causes melting at the surface of the material [34].

6.1.3.1.3 Travel speed

Travel speed determines interaction time. The travel speed has inverse proportion with depth of hardness. If the variables have maximum value, travel speed should be increased. Therefore, depth of hardness starts to decrease until the reaction starts on material.

Travel speed is so important parameter for determining depth of hardness and hardness values. When the travel speed choosing is so low, the melting starts on material surface and hardness value starts to decrease. [34]

6.1.3.1.4 Absorptivity

Absorption of light energy depends on heat transfer.

Absorptivity of CO_2 laser, which has approximately 16 micrometer wavelenght, is lower than Nd-YAG, which has approximately 1,06 micrometer, laser due to high wavelength of CO_2 laser.

Coating technology is used for increasing absorptivity. Sodium and potesium silicate coatings are known as an important factor for the increasing absorptivity amount. Coating thickness, coating material grain size, coating adhesion amount affect quality of absorptivity. This coating technology is current for CO_2 laser. There is no need for Nd-YAG laser because of its shorter wavelength and higher quality self-absorptivity amount.

Absorptivity amount depends on wavelength and incidence angle. [1]

6.1.3.1.5 Thermophysical properties of the materials

Thermal diffusivity is an important thermophysical properties of materials. Thermal diffusivity ,a, where a ¼K/rc (where K is the thermal conductivity, r the density and c the heat capacitance). Thermophysical property of materials affects the time of accepting and conducting thermal energy. Also, this factor is current for all unsteady-state heat flow processes.

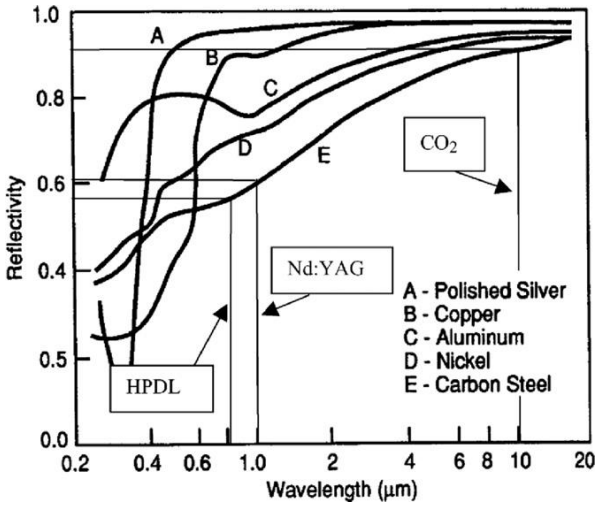


Figure 6.3: Reflectivity as a function of wavelength for various materials [34].

6.2 Laser Transformation Hardening

Laser surface hardening process can be applied all steel which have sufficient carbon rate. Increasing carbon rate has effect on positive way for increasing response of steel hardening, but plain carbon steel (0.2%C) will harden at very high cooling rate.

Hardenability rate is controlled with pearlite existence and distance between cementite lamels. [1]

6.2.1 Microstructure and hardness improvement

Depth of hardness and microstructure changes with laser power density and laser velocity. Hardened region occurs from thin martensite layer on surface of material, mixed microstructure and tempered bainite under the martensite layer.

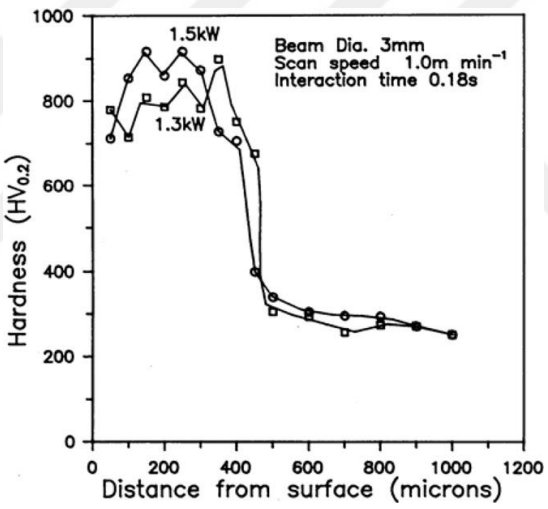


Figure 6.4: Hardness profile along depth direction of laser hardened En18 steel [59]

Figure 6.4 shows the hardness profile for EN18 steel with different laser power. Increasing laser power causes changing depth of hardness on the surface of the material. [49]

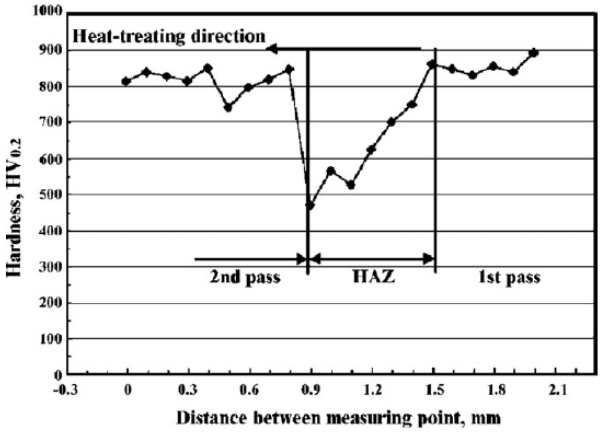


Figure 6.5: Distance and hardness profile. [25]

Drawback of laser hardening occurs with multipass laser hardening process. Hardness values decrease between laser treated zones.

Effect of drawwback of laser hardening could be decreased with with beam integrator, which provides to homogen distribution. [25]

6.2.2 Wear improvement

There is no need to harden all places of material for preventing wear. Trybological system is different. Wear improvement is just necessary for operation region of material.

6.2.3 Fatigue improvement

After laser heat treatment, steel and cast irons can be better in terms of fatigue improvement.

7. EXPERIMENTAL STUDIES

7.1 The Purpose of Experiments

This project aims to compare laser hardening process parameters for hardness, depth of hardness, microstructural development and impact sliding wear behaviors on hot work tool steel.

7.2 Material and Preparation of Samples

QR 90 is used for this experiment. QR 90 is type of hot work tool steel and it has special manufacturing patent. Its chemical composition is given table 7.1.

Table 7.1: Chemical compositions of QR O90.

C	Si	Mn	Cr	Mo	V
38	3	0,75	2,6	2,25	0,9

Table 7.2: Nontreated QR O90 steel hardness value.

QR O90	185 vickers

Samples have 28 mm diameter and 8 mm thickness.

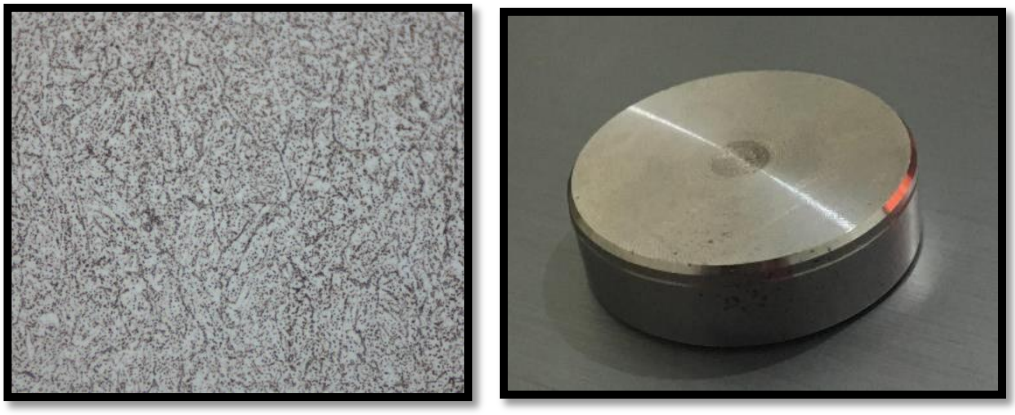


Figure 7.1: a.)Nontreated QR O90 microstructure and b.)image of QR O90 sample.

In this experiment, the laser surface hardening process applied on the samples. Laser surface hardening machine is Alotec Dresden (figure 7.2.) and this process was realized by Rukosen Abkant Punch Press Takımları Limited Şirketi.

Figure 7.2: Laser surface hardening machine general aspect.

Alotec Dresden GmbH is high power diode laser and it has 8 axis.

Before the laser surface hardening process, the samples were cleaned with alcohol and abrasive paper. That is why, this process is necessary for doing properly.

Figure 7.3: Abrasive paper cleaning process.

7.3 Experiments

7.3.1 Heat treatment process

In this study, 8 samples were used for laser surface hardening process. These samples have different parameters each other such as temperature and travel speed of laser beam.

Table 7.3: Laser surface hardening process parameters of QR 90 samples.

Process Parameters	
Temperature	1150-1300 ^{0}C
Travel speed	3, 4, 5, 6 mm/s
Laser Power	900-1200 W
Zoom	zero: 5 mm

Table 7.3 shows the parameters of the 8 sample experiment.

Table 7.4: QR 90 samples laser surface hardening experiment variables.

Samples	**Temperature**	**Travel Speed**	**Power (start)**	**Zoom(Beam Diameter)**
1	1200-1250 ^{0}C	4 mm/s	2200 W	5 mm
2	1250-1300 ^{0}C	4 mm/s	2200 W	5 mm
3	1150-1200 ^{0}C	4 mm/s	2200 W	5 mm
4	1150-1200 ^{0}C	5 mm/s	2200 W	5 mm
5	1200-1250 ^{0}C	5 mm/s	2200 W	5 mm
6	1200-1250 ^{0}C	3 mm/s	2200 W	5 mm
7	1250-1300 ^{0}C	5 mm/s	2200 W	5 mm
8	1200-1250 ^{0}C	6 mm/s	2200 W	5 mm

Laser surface hardening process is applied as two direction on all sample. These are 0^0 and 90^0. Additionally, every sample has four tour on the surface for each direction.

Power start and beam diameter are constant. Temperature, travel speed are variable for this study.

Figure 7.4: Laser surface hardening first tour.

Figure 7.4 shows the first tour of laser surface hardening on material. Process was applied on dark and after the process the sample is like the figure 7.4 in the light.

Figure 7.5: Laser surface hardening every tour images.

Figure 7.5 indicates the sample zero degree laser surface hardening. The offset amount is 6 mm between the every tour of laser beam tour.

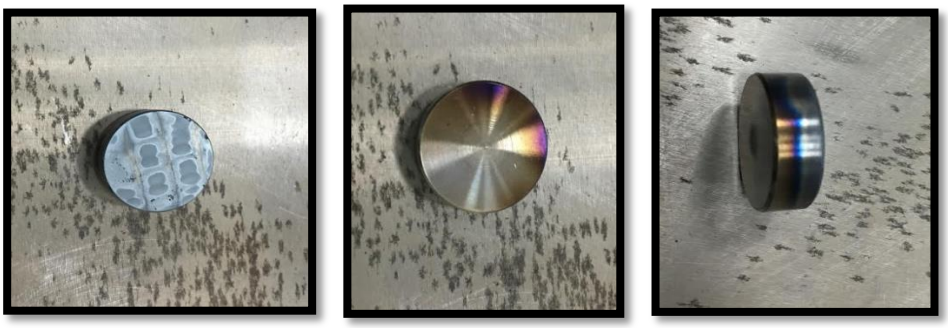


Figure 7.6: After the 90^0 laser surface hardening process a) front,b) back and c)side view of sample

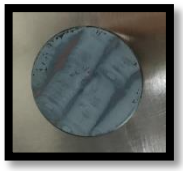
Table 7.5: Laser surface hardening power values average of samples.

	Power Mean Values	
	1. sample 0 degree	**1. sample 90 degree**
1. tour	1057.1 W	1122.06 W
2. tour	1089.62 W	1029.37 W
3. tour	1075 W	987.2 W
4. tour	1029.53 W	974.16 W

	Power Mean Values	
	2. sample 0 degree	**2. sample 90 degree**
1. tour	1106.0 W	1078.32 W
2. tour	10463 W	1032.87 W
3. tour	10237 W	925.26 W
4. tour	972.5 W	1029.7 W

	Power Mean Values	
	3. sample 0 degree	**3. sample 90 degree**
1. tour	10157 W	1077.52 W
2. tour	992.9 W	1057.26 W
3. tour	1034.72 W	1112.26 W
4. tour	1026.85 W	1027.1 W

Power Mean Values		
	4. sample 0 degree	**4. sample 90 degree**
1. tour	1146.92 W	1067.57 W
2. tour	1052.6 W	1038.87 W
3. tour	1043.87 W	1044.92 W
4. tour	1018.82 W	1014.22 W



Power Mean Values		
	5. sample 0 degree	**5. sample 90 degree**
1. tour	1128.4 W	1115.22 W
2. tour	907.98 W	1102.38 W
3. tour	1061.52 W	1042.45 W
4. tour	1067.32 W	1093.57 W

Power Mean Values		
	6. sample 0 degree	**6. sample 90 degree**
1. tour	936.06 W	1029.46 W
2. tour	996.42 W	930.97 W
3. tour	979.92 W	958.47 W
4. tour	926.60 W	913.25 W

Power Mean Values		
	7. sample 0 degree	**7. sample 90 degree**
1. tour	1122.92 W	1162.92 W
2. tour	1208.07 W	1079.62 W
3. tour	1089.12 W	1069.85 W
4. tour	1108.77 W	1043.23 W

	Power Mean Values	
	8. sample 0 degree	8. sample 90 degree
1. tour	1166.93 W	1193.0 W
2. tour	1239.70 W	1239.86 W
3. tour	1058.58 W	1164.42 W
4. tour	1182.47 W	1188.65 W

Figure 7.7: After the laser surface hardening process all samples images respectively 0 and 90 degree.

7.3.2 Wear experiments

Before the wear, hardness and characterization experiments, the samples were cleaned.

The first step was grinding of samples between 400-2500 mesh SiC sand paper with Mecapol P 220S and then they were polished with 1µm diamond polisher via Metaserv 250 Grinder-Polisher. Clean surface was demanded for impact abrasion test.

Figure 7.8: Sandpapering and polishing process.

Wear behavior of QR 90 samples were investigated by impact sliding wear test device (figure 7.8). During the test, 3.5 kg impact force was applied for one cycle with 10 mm diameter steel ball. After this step of test, the force was increased until 15 kg during the sliding stage. Totally, 1000 impact and sliding cycles was applied on samples.

Figure 7.9: Impact sliding wear test device and wear sample.

After this wear experiment, wear regions of samples were analysed with 2D Profilometer device. This device measures the depth and width of the wear tracks of samples after laser surface hardening process.

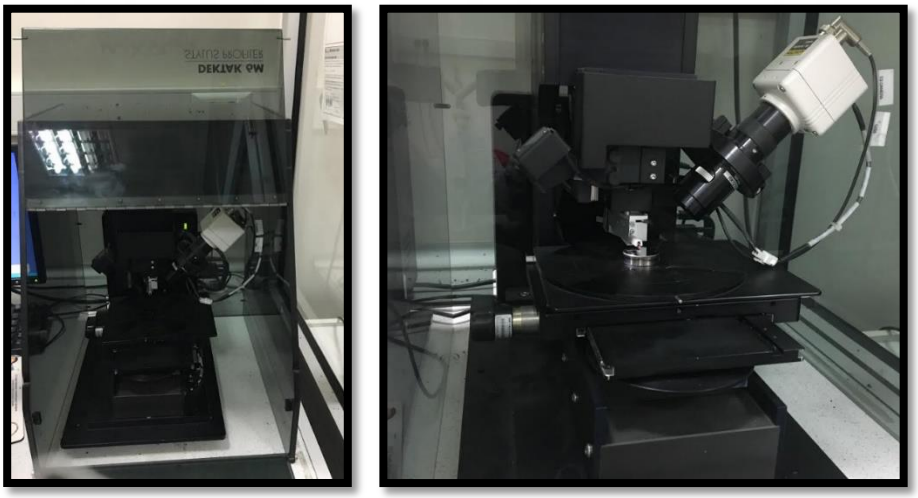


Figure 7.10: Profilemeter device (Dektak).

7.3.3 Hardness

Hardness measurements of laser hardened QR 90 samples was done with Shimadzu Micro Hardness Tester (figure 7.11). Hardness test type is vickers and its working principle bases on pricking. The hardness tests are applied with 0,2 kg force on each

sample. Applying time is 10 second of the force. In this study, the results of hardness measurement were used as statistical average.

Figure 7.11: Vickers hardness test device.

7.3.4 Microstructural analyses

The samples were made bakalite and they were prepared for investigating metallographic process as optical microscope and scanning electron microscope.

The first step was sandpapering of samples between 400-2500 mesh SiC sand paper and then they were polished with diamond polisher. After the polishing, the samples were made etching with 2 % nital solution.

Optic microscope investigation was done with Olympus Optic Microscope and scanning electon microscope(SEM) investigation was done with Hitachi TM-1000 scanning electron microscope.

Structural characterization investigation was done with X-ray difrection (XRD). The device brand of XRD is GBC MMA 027. With this process, structural phases of samples were determined after the laser surface hardening.

Process conditions of XRD;

- Cu-Kα radiation,
- XRD 2θ between 60-105º degrees,
- Scanning velocity is 1º/minute.

Using these conditions, XRD investigations of each sample were done.

8. RESULTS AND DISCUSSION

8.1 XRD and Optical Microscop Results

After laser surface hardening process, XRD experiment was applied on all samples. We can see three groups XRD patterns and optical microscope images for 1000x magnifications as categorized according to the same temperature and different laser beam velocity, the same velocity and different temperature at figure 8.1, 8.2 and 8.3, you can see as below.

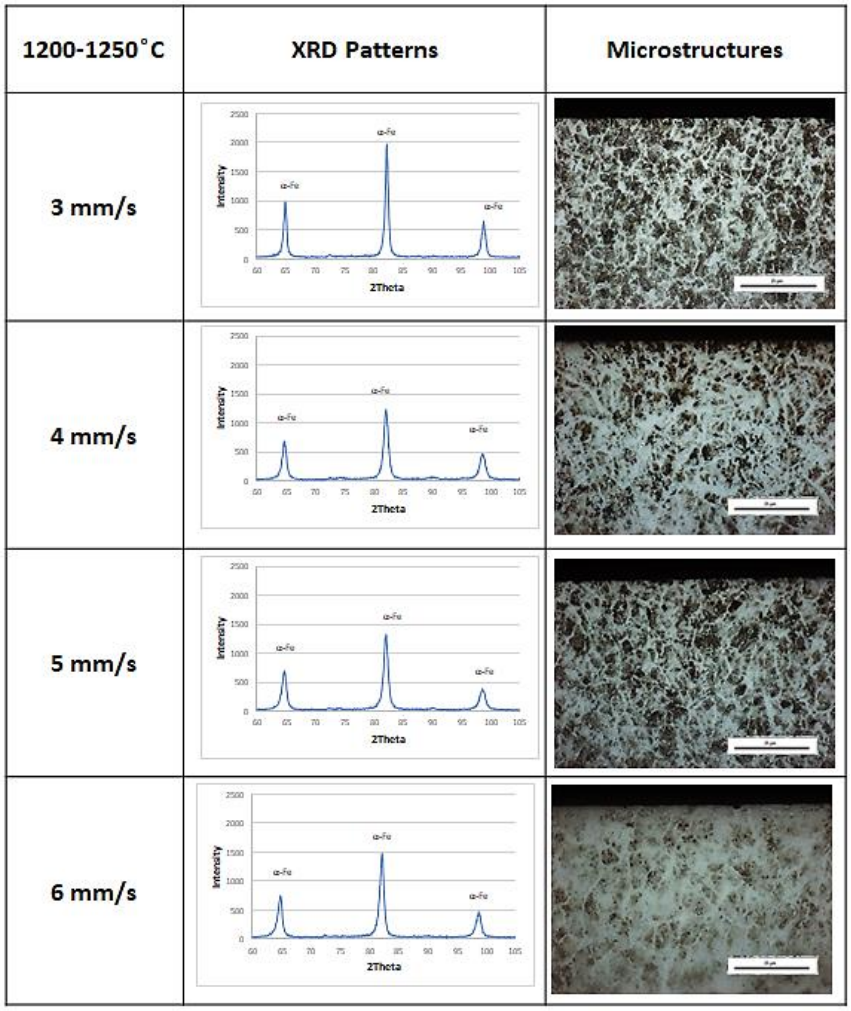


Figure 8.1: XRD patterns and microstructures of laser hardened samples at the same temperature(1200-1250 ^{0}C) and different laser beam velocity (3, 4, 5, 6 mm/s).

Figure 8.1 shows laser hardened samples XRD patterns and microstructures for the same temperature and different velocity. According to this figure, we cannot see more residual austenite. Just, XRD patterns broadening and shifting could be a little different each other.

If we compare each other, laser hardened sample has low broadening at the lowest velocity condition and from low laser beam velocity to high velocity the peaks broadening start to increase.

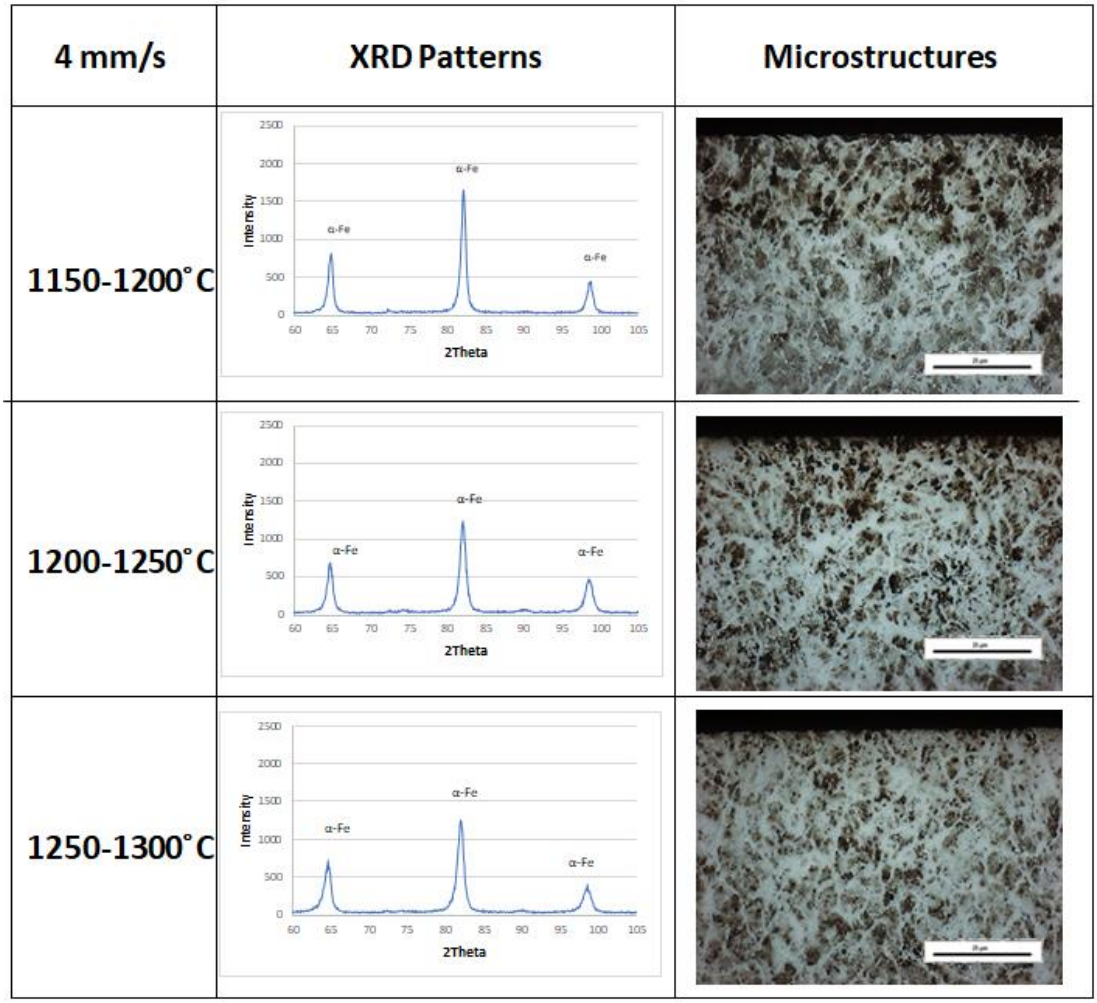


Figure 8.2: XRD patterns and microstructures of laser hardened samples at the same velocity(4 mm/s) and different temperature(1150-1200 ^{0}C, 1200-1250 ^{0}C and 1250-1300 ^{0}C).

Figure 8.2 shows that laser hardened samples XRD patterns and microstructures for their heat treatment conditions, which are the same laser beam velocity (4 mm/s) and different temperature. When the temperatures of laser beam start to increase, the

peaks broadening start to increase and 2theta value shift left side at the same velocity, which is 4 mm/s.

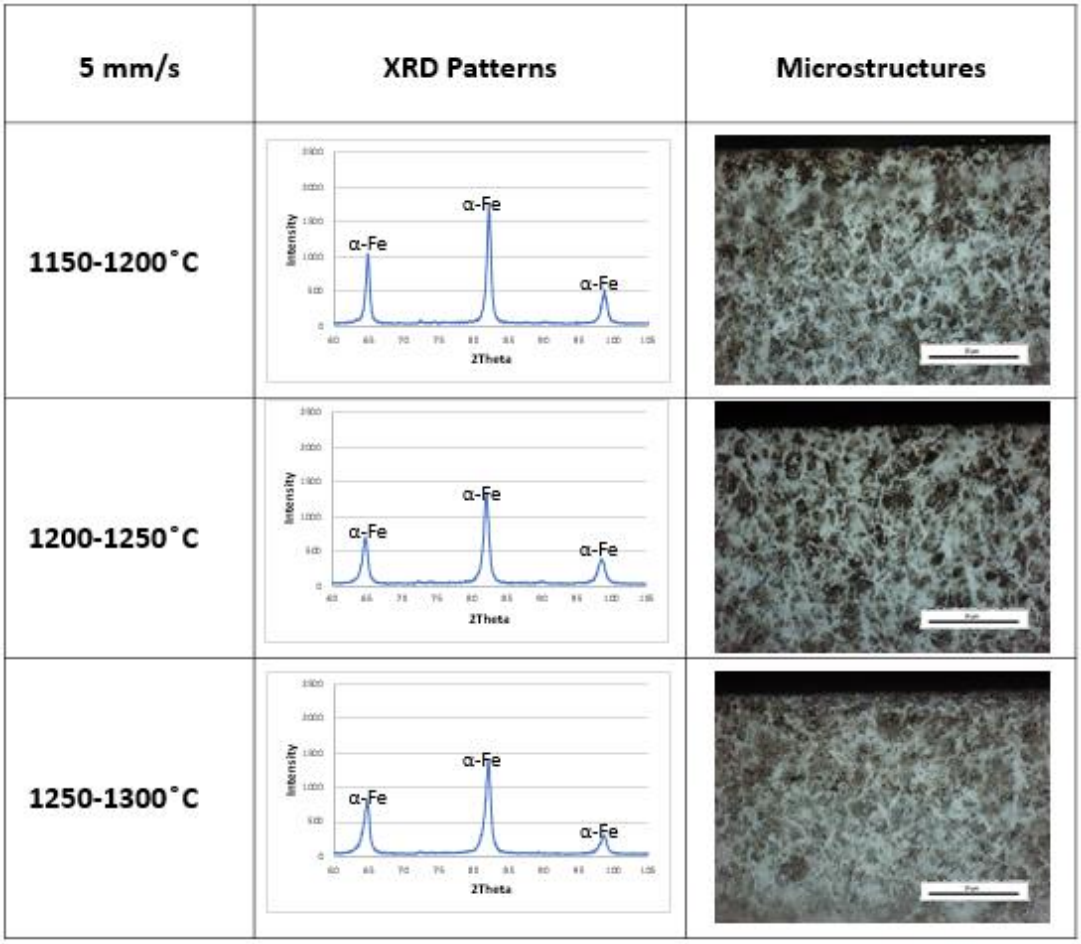


Figure 8.3: XRD patterns and microstructures of laser hardened samples at the same velocity(5 mm/s) and different temperature(1150-1200 ^{0}C, 1200-1250 ^{0}C and 1250-1300 ^{0}C).

Figure 8.3 indicates that XRD patterns and microstructures of laser hardened sample at constant 5 mm/s laser beam velocity and different temperatures. Increasing temperature causes increasing of the peaks broading and 2theta value start to shift left.

If we compare all XRD patterns, we can see the increasing temperature affects broadening and shifting of the peaks, the peaks broadening start to increase and 2theta values of the peaks shifts to left side. This situation could be originated from lattice strain or reduction in crystalline size in the microstructure.

Also, residual austenite is not observed in these XRD results of all laser hardened samples as general.

Additionally, we can see different microstructures for all laser hardened QR O90 samples. It could be originated from different laser surface hardening processes. Generally, these microstructures are not only martensite microstructure for hardening region as aspected. We can also see ferrite microstructures around the martensite formation grains.

8.2 Hardness Measurements

After laser surface hardening process of QR 90 samples, hardness results as below figures.

In this experiment the main variables are laser beam velocity and temperature. With these variables changing effect on hardness of samples was investigated at these figures (Figure 8.4, 8.5, 8.6, 8.8, 8.9 and 8.10).

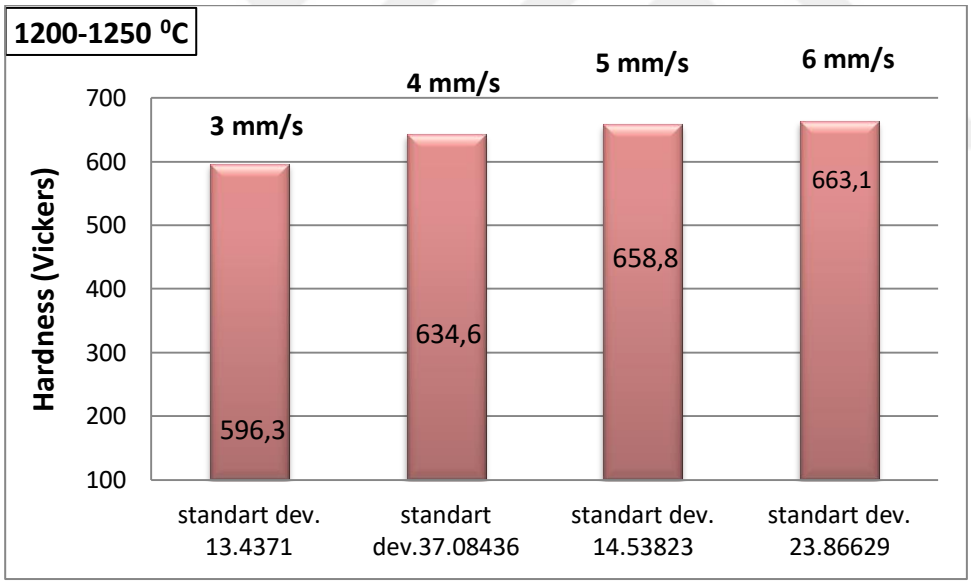


Figure 8.4: Laser beam velocity changing effects on hardness at 1200-1250 ^{0}C.

For hardness measurements, 200 gr. loading was applied. According to figure 8.4, increasing laser beam velocity values, we can observe the effect laser beam velocity on hardness of laser hardened samples. As general, increasing velocity causes increasing of hardness value except 5.sample,but this difference is not big.

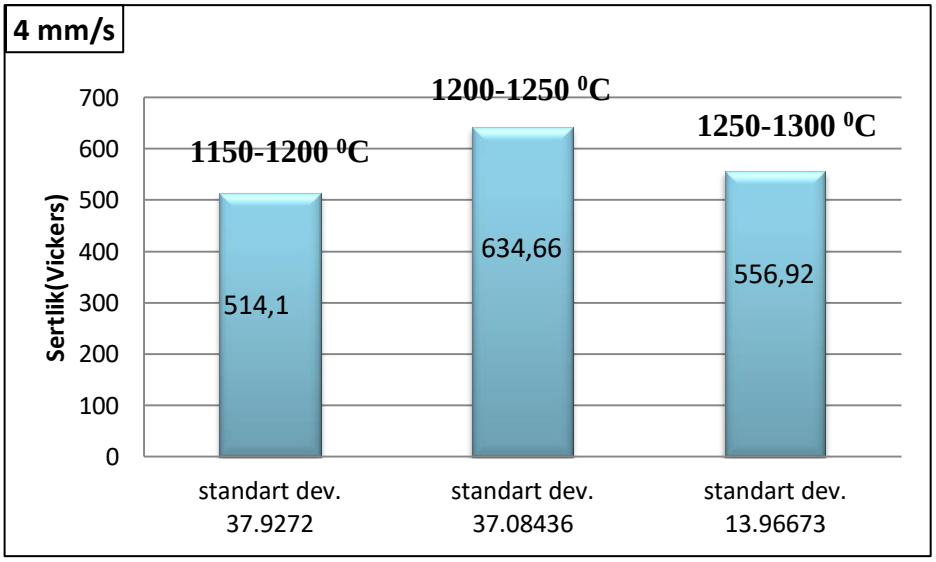


Figure 8.5: Different temperature effects on samples at constant 4 mm/s laser beam velocity.

According to figure 8.5, we can observe different temperature effect on samples at 4 mm/s laser beam velocity parameter. Temperature changes between 1150 and 1300 ^{0}C. The effective parameter in terms of hardness capability of samples is 1200-1250 ^{0}C temperature and 4 mm/s velocity, which is the average of hardness value of sample is 634 vickers.

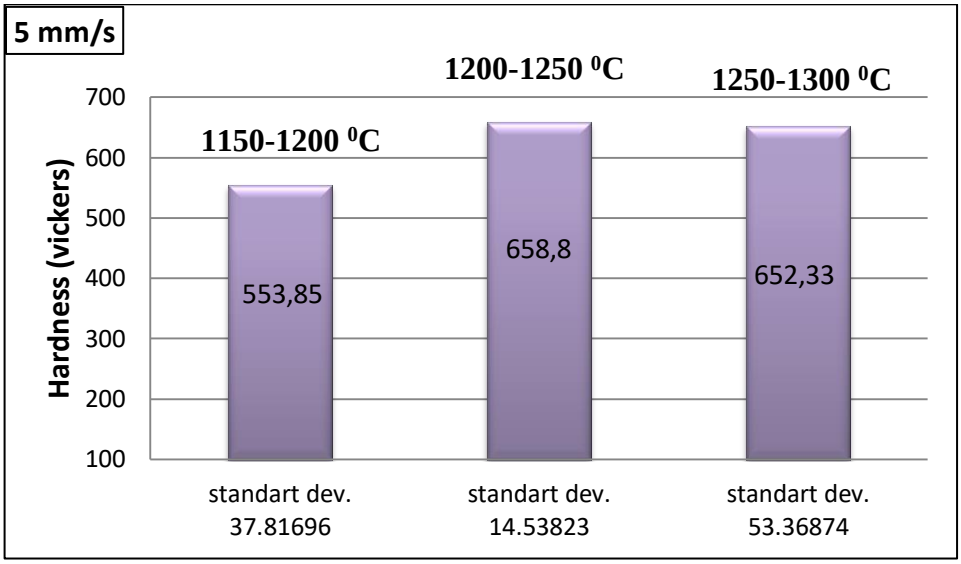


Figure 8.6: Different temperature effects on samples at constant 5 mm/s laser beam velocity.

At this figure 8.6, the effect of temperature changing at constant 5 mm/s laser beam velocity on samples. The effective parameter for this comparing, 1200-1250 ^{0}C and 5 mm/s velocity, which is the average of hardness value of sample is 655 vickers.

We can say that according to this resut, 1200-1250 ^{0}C tempature value and 6 mm/s velocity is suitable for handling higher hardness value for QR O90 samples.

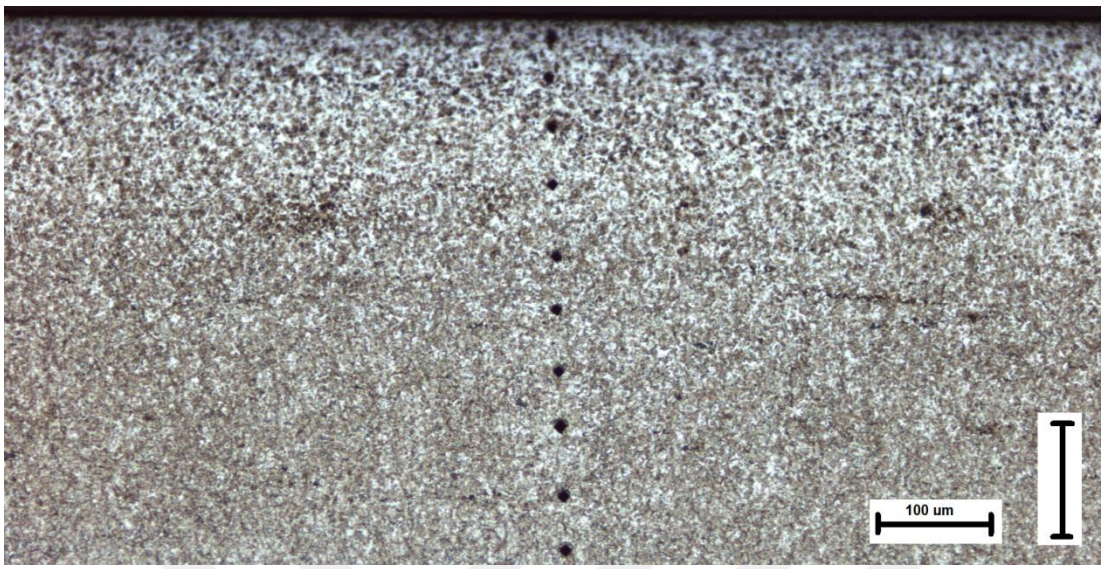


Figure 8.7: Optical microscope image of hardness depth vickers measurement as x100.

For hardness depth measurments, 25 gr. loading was used to determine the distance from maximum hardening place value to inner non-processing place value. Figure 8.7 shows us hardness depth measurements image of optical microscope for x100 magnification. Between the measurement point distance 50 micrometer as average.

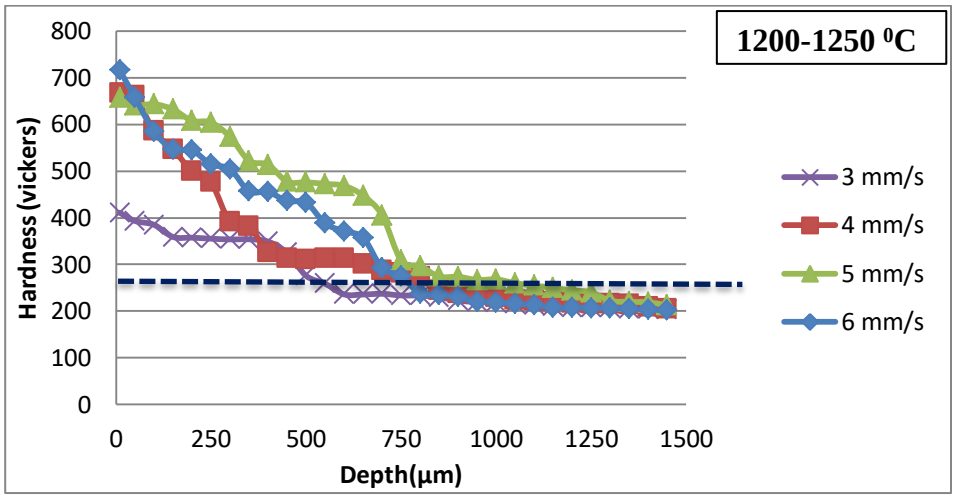


Figure 8.8: Hardness depth of laser hardened samples at constant temperature (1200-1250 ^{0}C) and different velocity(3 mm/s, 4 mm/s, 5 mm/s and 6 mm/s).

According to figure 8.8, we can see samples hardness depth results with vickers hardness experiment. This samples experiment conditions are 1200-1250 ^{0}C constant tempature and changing laser beam velocity between 3-6 mm/s.

The sample, which has 5 mm/s laser beam velocity, has highest hardess depth according to other laser beam velocities at the same temperature according to figure 8.8. Then, the hardness depth values from high to low respectively the samples, which have 4, 6 and 3 mm/s laser beam velocity.

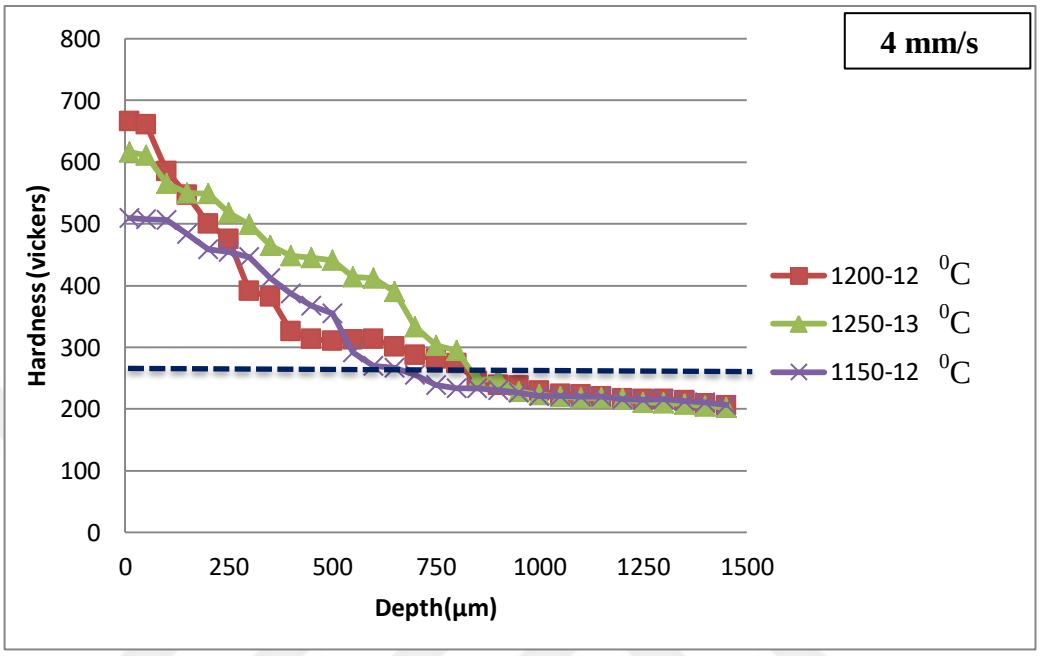


Figure 8.9: Hardness depth of laser hardened samples at constant laser beam velocity(4 mm/s) and different temperature(1150-1200 ^{0}C, 1200-1250 ^{0}C and 1250-1300 ^{0}C).

Figure 8.9 say that to us, the sample has higher hardness depth, which has 4 mm/s laser beam velocity and highest temperature as 1250-1300 ^{0}C. Hardness depth is respectively from high to low depth the samples, which have 1250-1300 ^{0}C, 1200-1250 ^{0}C and 1150-1200 ^{0}C temperature at constant 4 mm/s velocity.

We can say that lowest temperature causes lower hardness depth at constant 4 mm/s laser beam velocity.

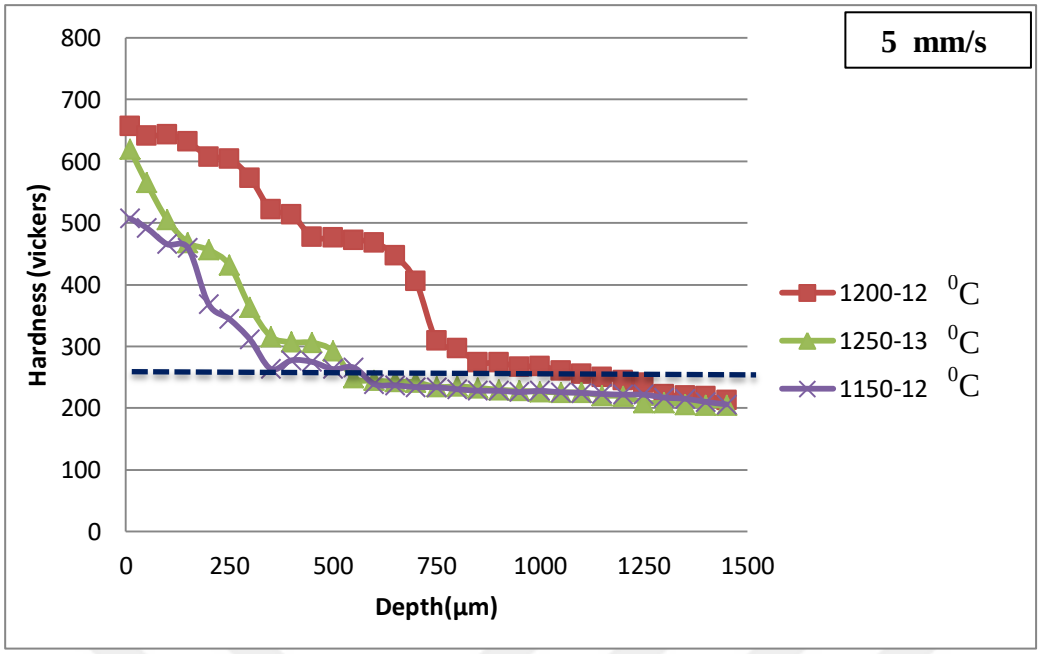


Figure 8.10: Hardness depth of laser hardened samples at constant laser beam velocity(5 mm/s and different temperature(1150-1200 ^{0}C, 1200-1250 ^{0}C and 1250-1300 ^{0}C).

According to figure 8.10, the sample has higher hardness depth, which has 1200-1250 ^{0}C temperature and respectively the samples, which have 1250-1300 ^{0}C and 1150-1200 ^{0}C temperature at constant 5 mm/s velocity.

We can see the same result like figure 8.9, lower temperature causes lower hardness depth on QR O90 samples at constant laser beam velocity, but changing of laser beam velocity value affects the hardness depth behavior of laser hardened samples for other temperature when we compare the figure 8.10 with figure 8.9.

8.3 Wear Experiment Results

After impact sliding tests of laser hardened samples were profiled as 2-D. 2-D profiles of laser hardened samples impact region are shown at figure 8.11, 8.12 and 8.13. With the help of the profilemeter, wear depth, width and area values were calculated.

Wear region is divided five parts. Fisrt part is called as impact region and it is 1 mm far away from wear start point. Other parts are called as sliding region and these are 2.5 mm, 3.5 mm, 5 mm and 6.5 mm far away from start point respectively.

At the result of the impact sliding test, the results were categorized as three groups according to temperature and laser beam velocity.

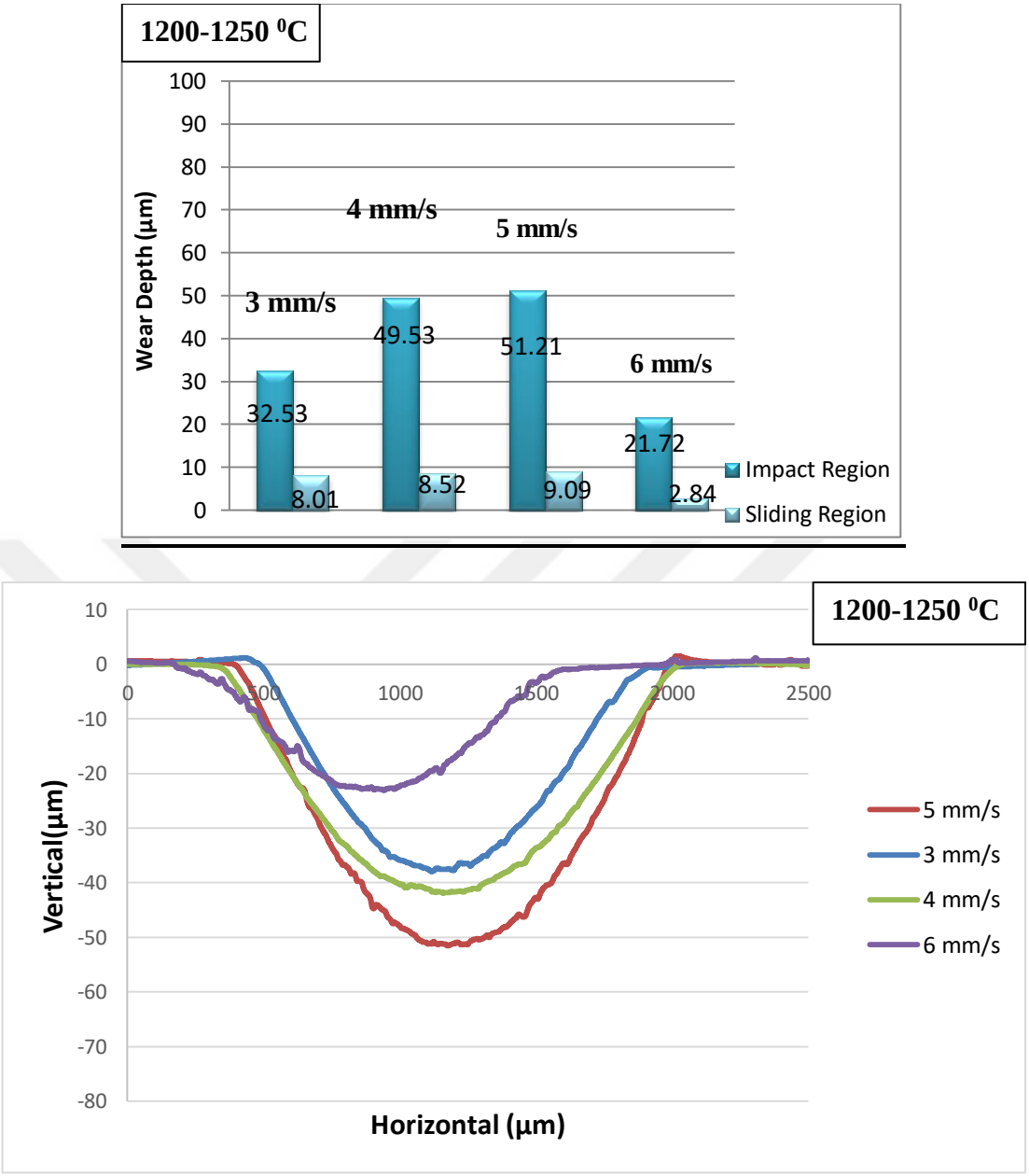


Figure 8.11: Wear depth of laser hardened samples at constant temperature (1200-1250 ^{0}C) and different velocity(3 mm/s, 4 mm/s, 5 mm/s and 6 mm/s) for impact region.

According to figure 8.11, the highest wear resistance belongs to sample, which has 6 mm/s laser beam velocity and also, it has 1200-1250 ^{0}C temperature. After that respectively the wear resistant samples, which have 3 mm/s, 4 mm/s and 5 mm/s velocity.

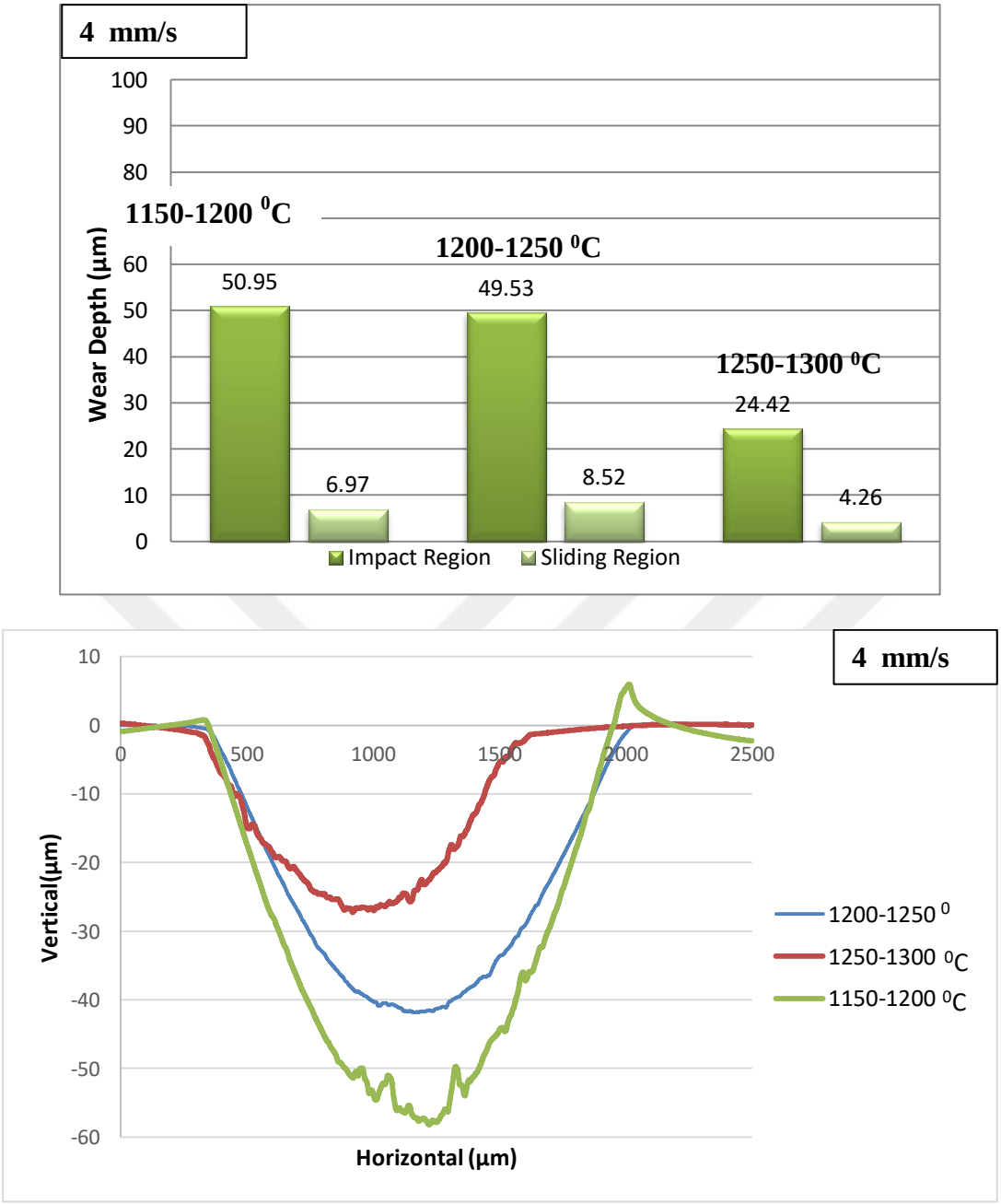


Figure 8.12: Wear depth of laser hardened samples at constant laser beam velocity(4 mm/s) and different temperature(1150-1200 ^{0}C, 1200-1250 ^{0}C and 1250-1300 ^{0}C) for impact region.

Figure 8.12 shows that the most wear resistant sample, which have 1250-1300 ^{0}C, and then respectively 1200-1250 ^{0}C, 1150-1200 ^{0}C temperatures. The temperature affect the wear resistance behaviour of samples at constant laser beam velocity. Higher temperature causes higher wear resistance.

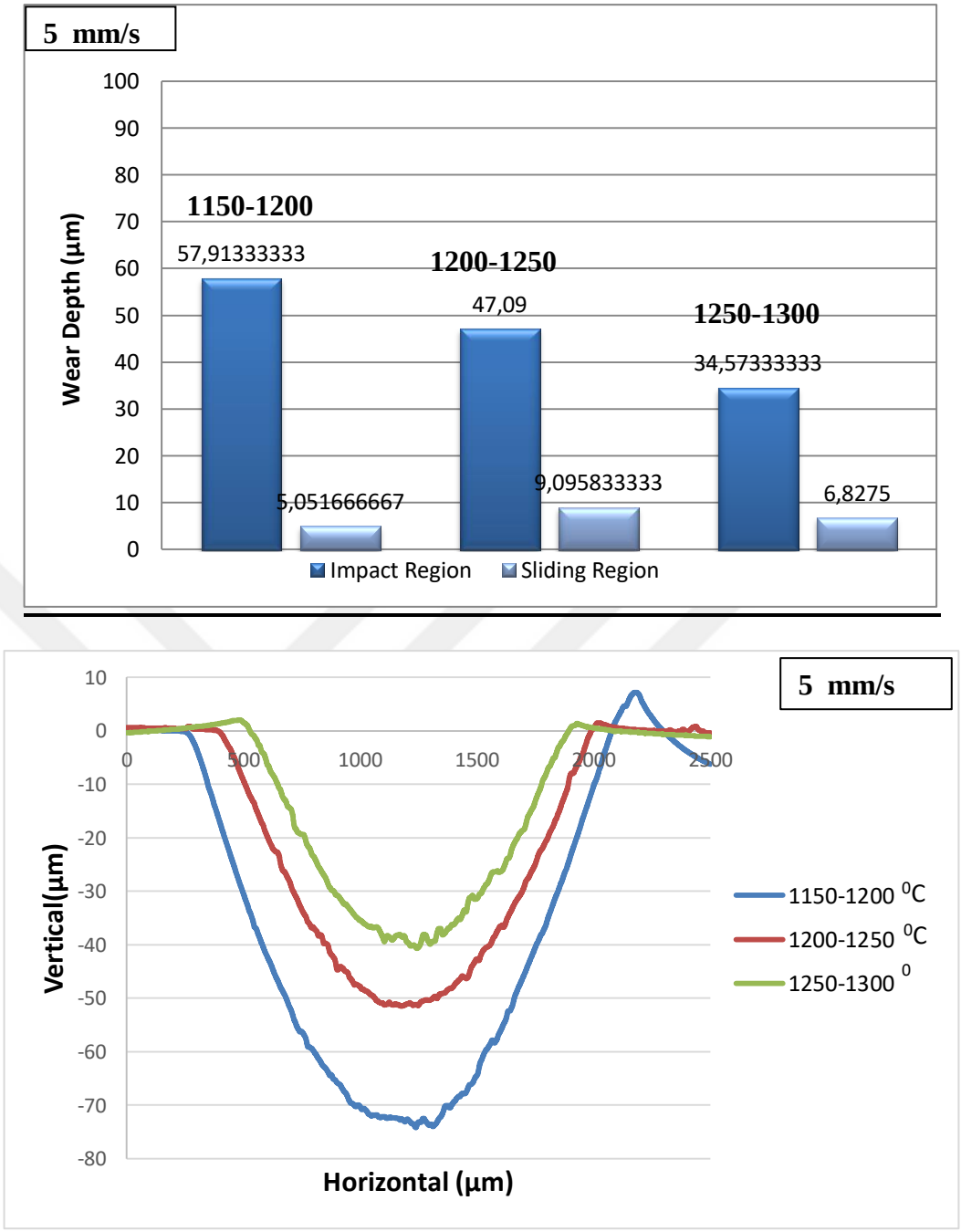


Figure 8.13: Wear depth of laser hardened samples at constant laser beam velocity(5 mm/s) and different temperature(1150-1200 ^{0}C, 1200-1250 ^{0}C and 1250-1300 ^{0}C) for impact region.

At constant laser beam velocity (5 mm/s), with the increasing operation temperature causes higher wear resistance. We can see at figure 8.13.

If we compare 4 and 5 mm/s laser beam velocity of laser hardened samples, the samples, which have 4 mm/s velocity has better wear resistance at different temperatures as general.

Table 8.1: Wear depth, width and area profilemeter measurements.

1.REGION		**Wear Depth (µm)**	**Wear Width (µm)**	**Wear Area ($µm^2$)**
QR O90	6. sample	32,53	1784	45556,3132
	1. sample	49,54	1928	74977,7992
	5. sample	47,09	1601	59182,00565
	8. sample	21,72	1601	27297,3702
QR O90	3. sample	50,95	1602	64073,1915
	1. sample	49,54	1928	74977,7992
	2. sample	24,42	1905	36518,2785
QR O90	4. sample	57,91	1811	82326,88285
	5. sample	47,09	1601	59182,00565
	7.sample	34,57	1371	37205,44395

2.REGION		**Wear Depth (µm)**	**Wear Width (µm)**	**Wear Area ($µm^2$)**
QR O90	6. sample	4,16	464	1515,2384
	1. sample	10,93	746	6400,7173
	5. sample	14,94	948	11118,0492
	8. sample	5,24	601	2472,1534
QR O90	3. sample	6,07	646	3078,1577
	1. sample	10,93	746	6400,7173
	2. sample	3,88	569	1733,0602
QR O90	4. sample	4,5	798	2818,935
	5. sample	14,94	948	11118,0492
	7.sample	4,79	480	1804,872

3.REGION		**Wear Depth (µm)**	**Wear Width (µm)**	**Wear Area ($µm^2$)**
QR O90	6. sample	5,45	570	2438,6025
	1. sample	9,46	766	5688,3926
	5. sample	6,67	679	3555,21005
	8. sample	2,77	581	1263,35545
QR O90	3. sample	8,75	669	4595,19375
	1. sample	9,46	766	5688,3926
	2. sample	3,92	455	1400,126
QR O90	4. sample	8,09	671	4261,28615
	5. sample	6,67	679	3555,21005
	7.sample	6,77	627	3332,16015

4.REGION		Wear Depth (µm)	Wear Width (µm)	Wear Area (µm^2)
QR O90	6. sample	7,89	705	4366,52325
	1. sample	7,49	655	3851,17075
	5. sample	7,52	676	3995632
	8. sample	2,13	381	637,05105
QR O90	3. sample	5,5	542	2340,085
	1. sample	7,49	655	3851,17075
	2. sample	4,02	686	2164,8102
QR O90	4. sample	4,65	551	2011,28775
	5. sample	7,52	676	3995632
	7.sample	6,98	628	3441,0004

5.REGION		Wear Depth (µm)	Wear Width (µm)	Wear Area (µm^2)
QR O90	6. sample	14,55	1051	12004,25925
	1. sample	6,23	633	3095,71815
	5. sample	7,26	802	4576782
	8. sample	1,22	328	314,1256
QR O90	3. sample	7,58	597	3552,3291
	1. sample	6,23	633	3095,71815
	2. sample	5,24	588	2418,6792
QR O90	4. sample	2,97	681	1587,71745
	5. sample	7,26	802	4576782
	7.sample	8,34	726	4753,0494

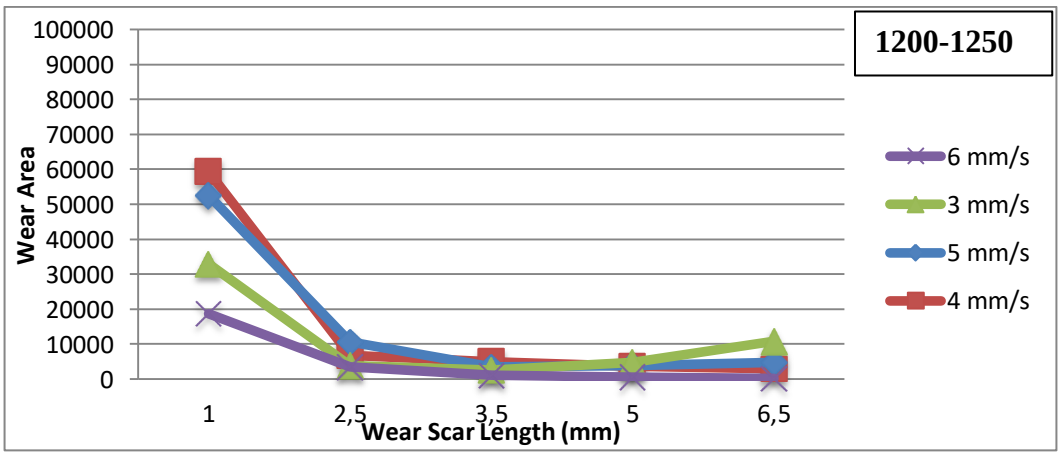


Figure 8.14: Wear area of laser hardened samples at constant temperature (1200-1250 ^{0}C) and different velocity(3 mm/s, 4 mm/s, 5 mm/s and 6 mm/s).

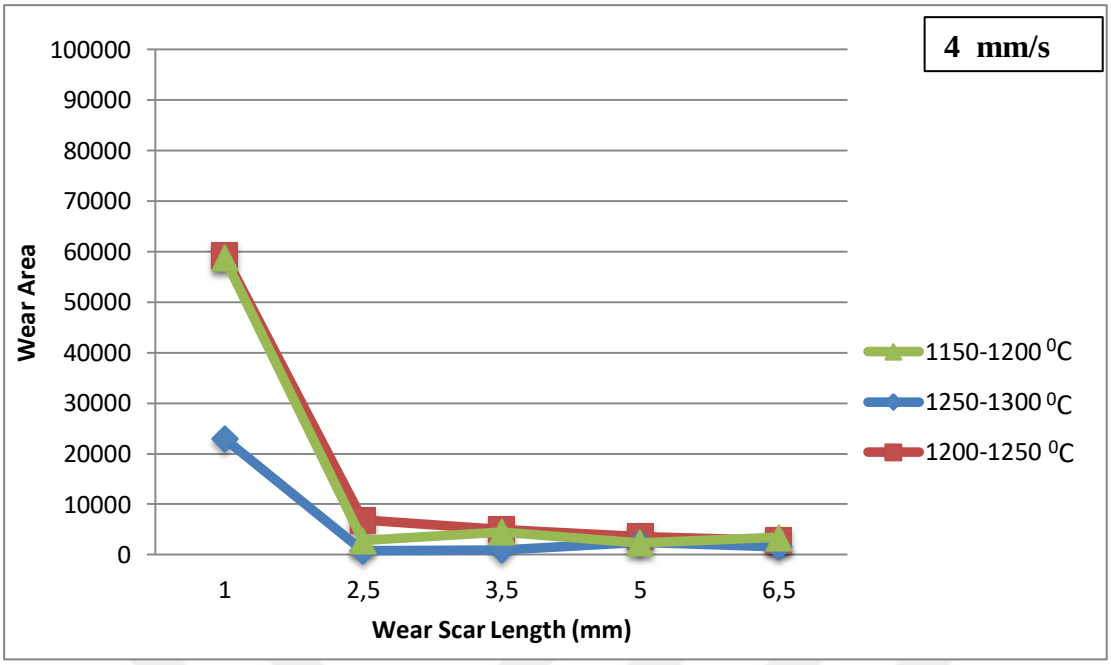


Figure 8.15: Wear area of laser hardened samples at constant laser beam velocity(4 mm/s) and different temperature(1150-1200 ^{0}C, 1200-1250 ^{0}C and 1250-1300 ^{0}C).

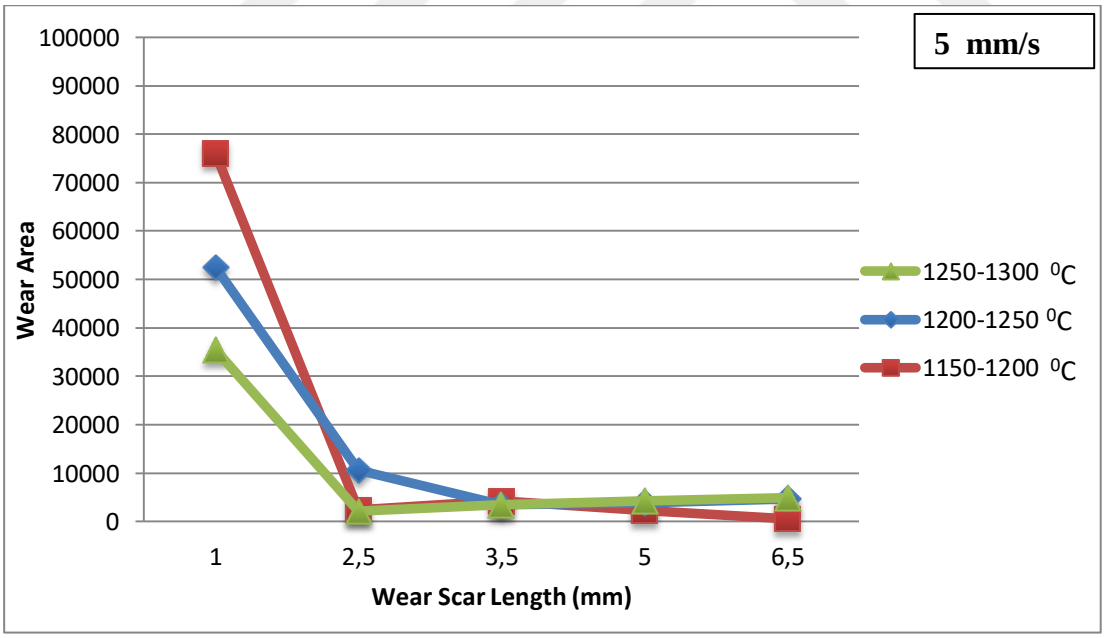


Figure 8.16: Wear area of laser hardened samples at constant laser beam velocity(5 mm/s) and different temperature(1150-1200 ^{0}C, 1200-1250 ^{0}C and 1250-1300 ^{0}C).

According to figure 8.14, 8.15 and 8.16, the result of the impact sliding test of laser hardened QR O90 samples wear area are shown. The results looks like wear depth results.

The higher wear resistant samples, which have 1250-1300 ^{0}C temperature, 4 mm/s velocity and 1250-1300 ^{0}C temperature, 6 mm/s velocity. They have lower wear area according to other samples.

9. GENERAL RESULTS AND CONSIDERATION

At the result of the impact sliding test and characterization experiments, we can observe some results;

XRD results of laser hardened samples change according to temperature especially. When the temperature increase, XRD patterns start to broaden and shifting left side as very low ratio. As general, this broaden and shifting left side of XRD patterns causes wear resistance property for some samples. This situation could be originated from lattice strain or reduction in crystalline size in the microstructure.

Hardness values of laser hardened samples change with according to temperature and laser beam velocity. The hardest sample, which has 1200-1250 ^{0}C and 6 mm/s. Not only temperature or velocity affect the hardness value of laser hardened samples. When we observe figure 8.5 and 8.6, 1200-1250 ^{0}C temperature range is suitable to handle higher hardness value for 4 and 5 mm/s velocity. Also, increasing laser beam velocity causes to higher hardness values, we can see at figure 8.4.

Hardness depth changes according to laser beam velocity and temperature. When the increasing laser beam velocity increases hardness value, but depth of hardness could be affected different from other parameters. For example, the sample, which has 6 mm/s velocity at 1200-1250 ^{0}C, has highest wear resistance, hardness value, but beside these properties, depth of hardness starts to decrease at higher laser beam velocity, we can observe this situation, when we compare 4 mm/s and 5 mm/s with 6 mm/s velocity. The laser hardened sample, which has 5 mm/s velocity and 1200-1250 ^{0}C temperature, has higher hardness depth according to other samples, which have different laser process parameters.

Wear resistance of QR O90 samples do not depend only hardness or depth of hardness. It is about also microstructure of material at the result of the different laser hardened process condition. When we observe optical microscope images of laser

hardened samples, ferrite microstructure is exist between the grains. Therefore, we cannot see only martensite structure for hardened regions of samples.

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APPENDICES

APPENDIX A : SEM Images of wear marks with different ratio for impact and sliding regions.

APPENDIX B : Sliding wear depth results for three categories according to temperature and velocity variables

APPENDIX C : Optical microscope images of laser hardened samples for 50x, 200x 500x and 1000x magnifications

APPENDIX A

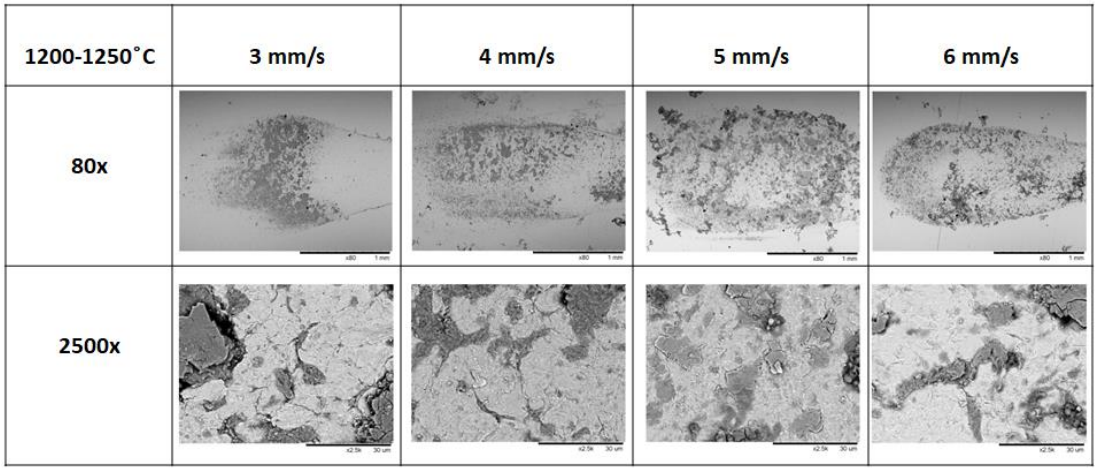


Figure A.1: SEM images with different magnifications of laser hardened QRO90 samples impact regions for different velocities at constant temperature.

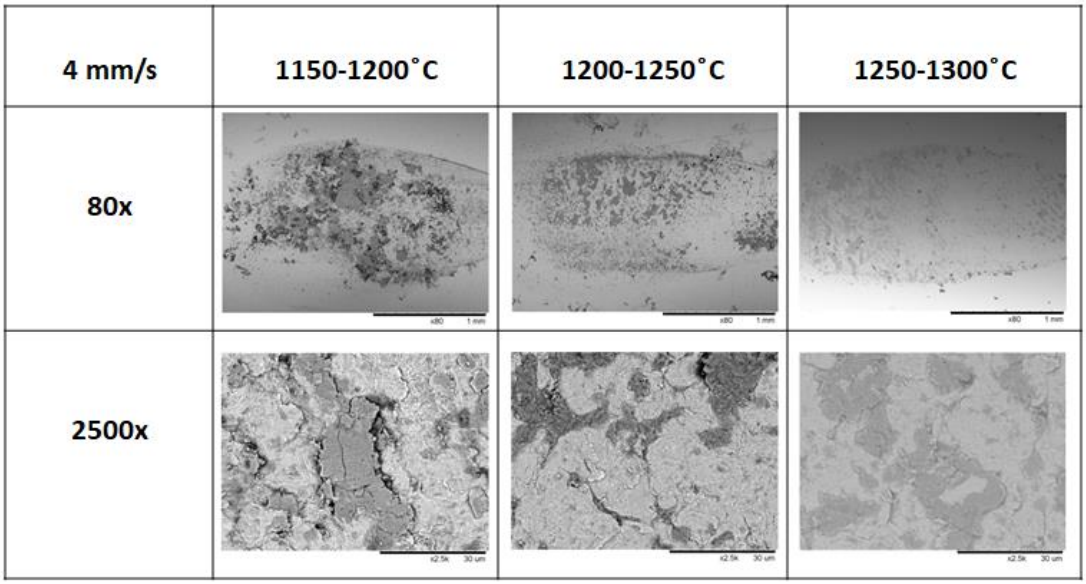


Figure A.2: SEM images with different magnifications of laser hardened QRO90 samples impact regions for different temperatures at constant laser beam velocity (4 mm/s).

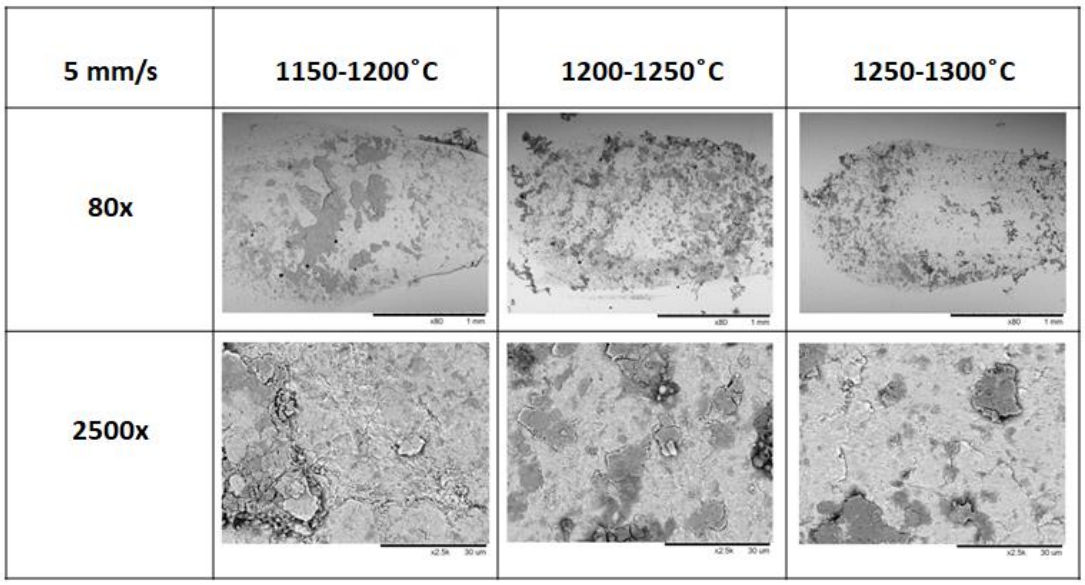


Figure A.3: SEM images with different magnifications of laser hardened QRO90 samples impact regions for different temperatures at constant laser beam velocity (5 mm/s).

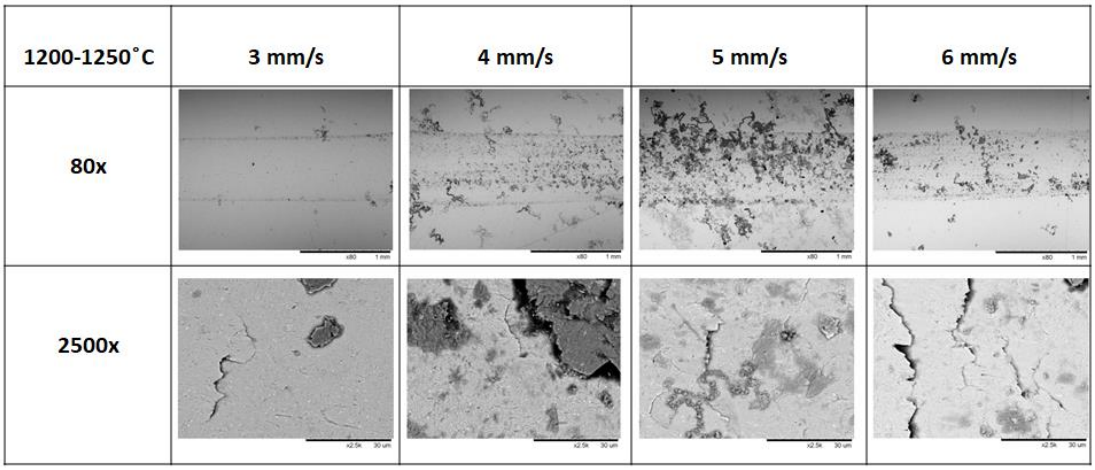


Figure A.4: SEM images with different magnifications of laser hardened QRO90 samples sliding regions for different velocities at constant temperature.

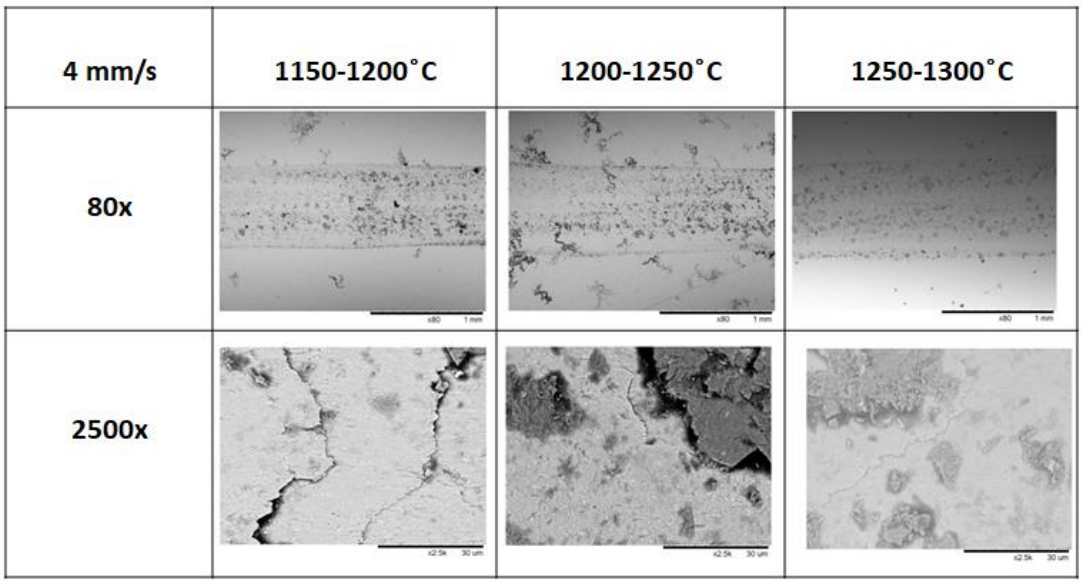


Figure A.5: SEM images with different magnifications of laser hardened QRO90 samples sliding regions for different temperatures at constant laser beam velocity (4 mm/s).

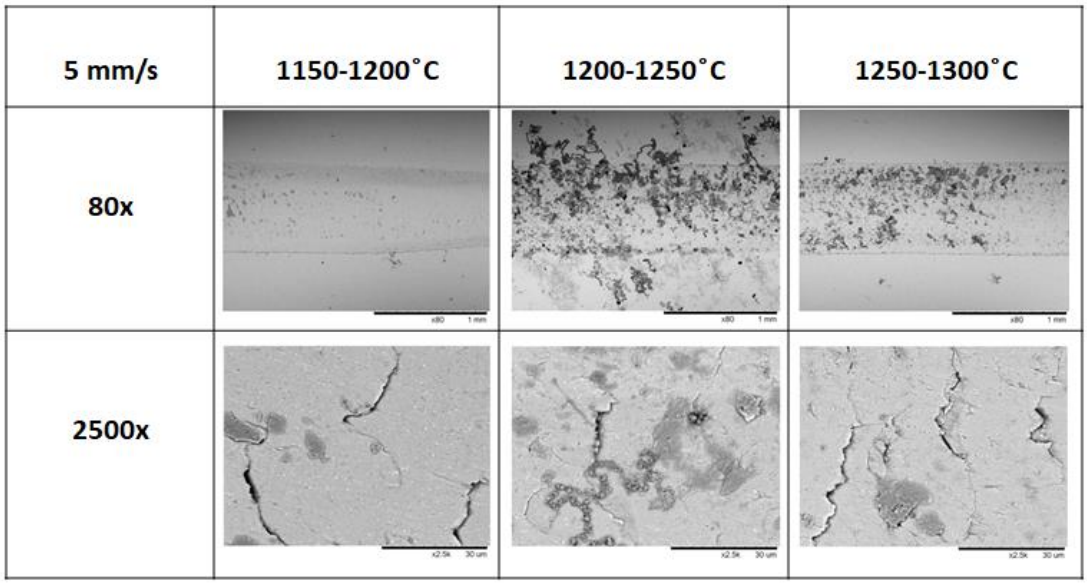
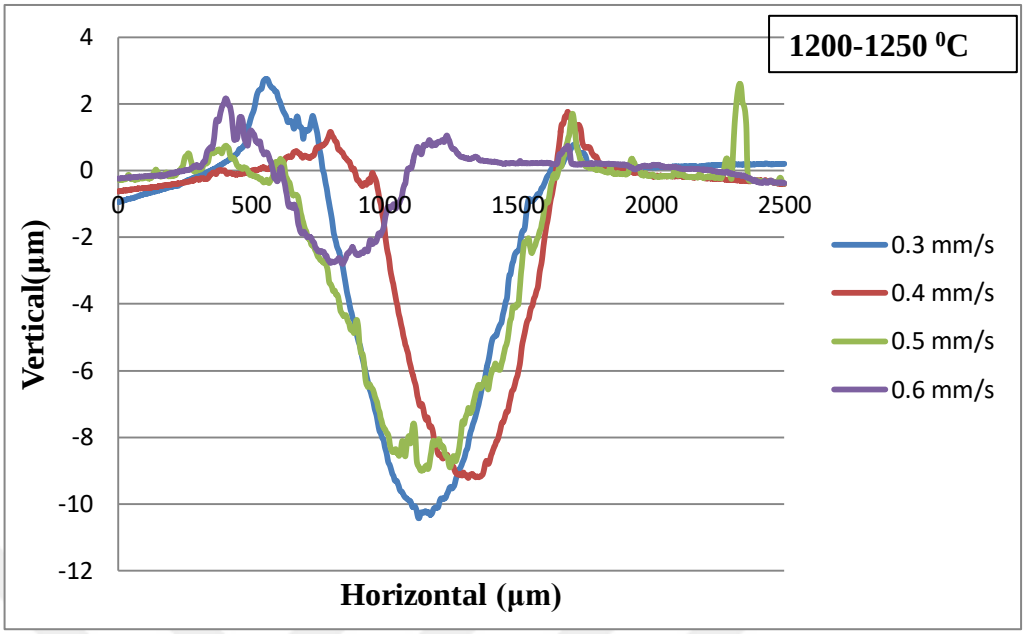
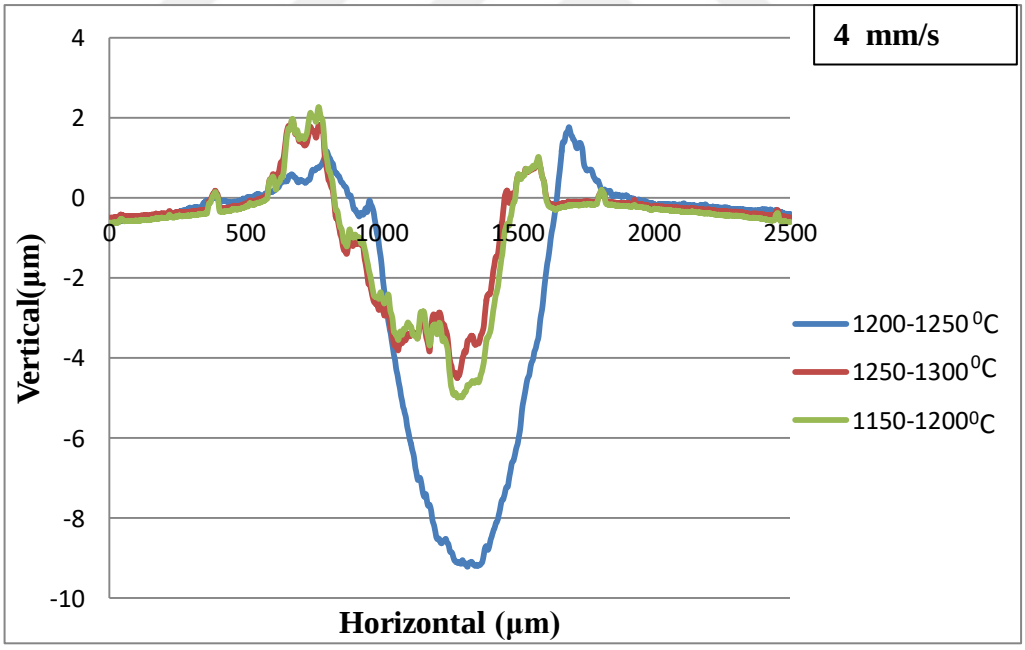


Figure A.6: SEM images with different magnifications of laser hardened QRO90 samples sliding regions for different temperatures at constant laser beam velocity (5 mm/s).

APPENDIX B


1200-1250 ⁰C
Vertical(µm)
Horizontal (µm)
0.3 mm/s
0.4 mm/s
0.5 mm/s
0.6 mm/s


4 mm/s
Vertical(µm)
Horizontal (µm)
1200-1250 ⁰C
1250-1300 ⁰C
1150-1200⁰C

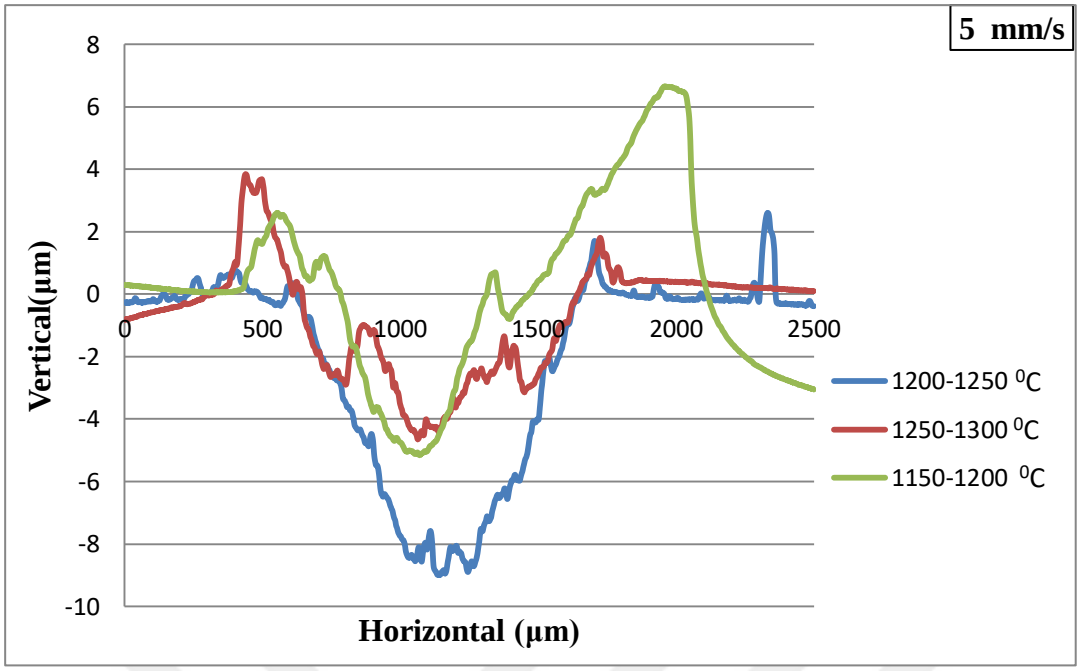


Figure B.1: 2-D profiles of laser hardened samples belongs to wear scars for average of sliding regions.

APPENDIX C

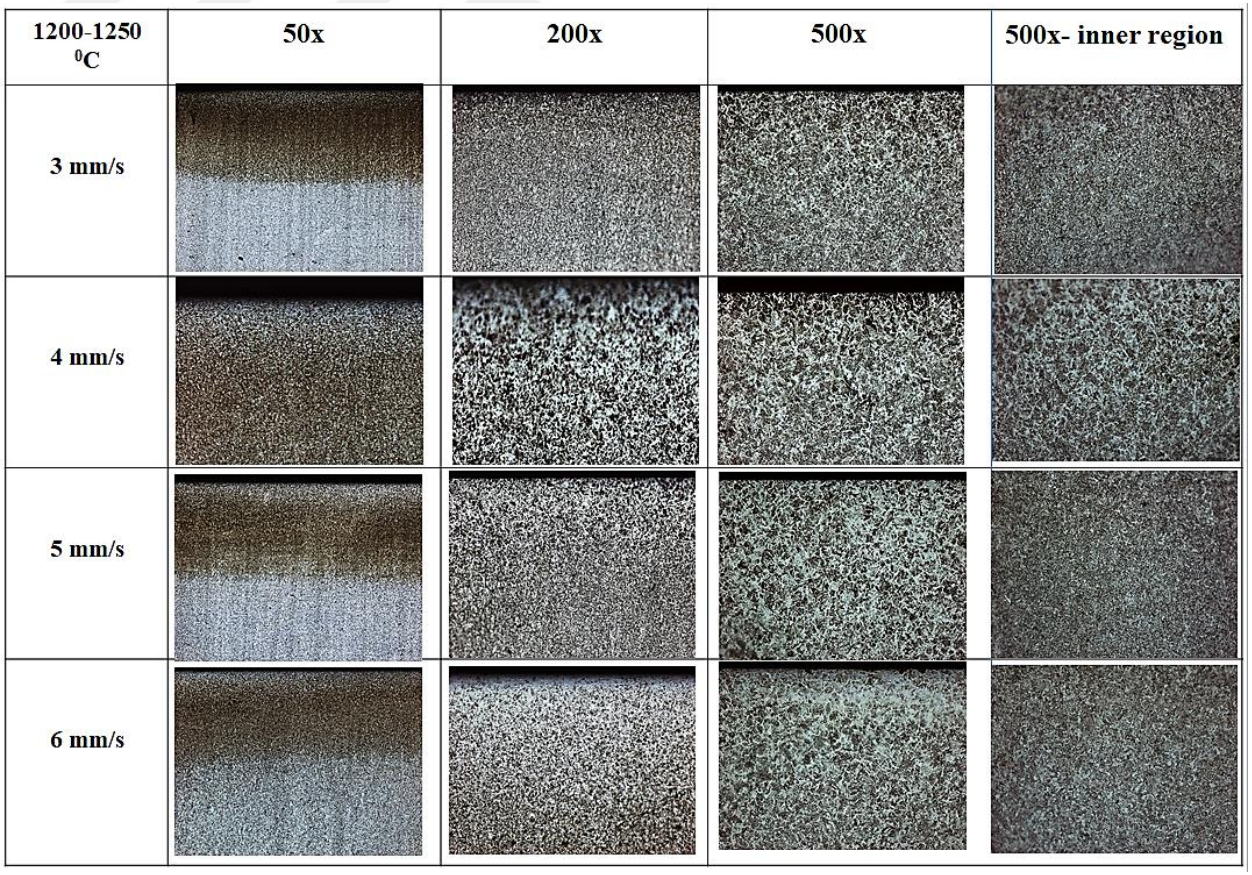


Figure C.1: Optic microscope images of laser hardened QR O90 samples for 50x, 200x and 500x magnifications at constant temperature and different laser beam velocity.

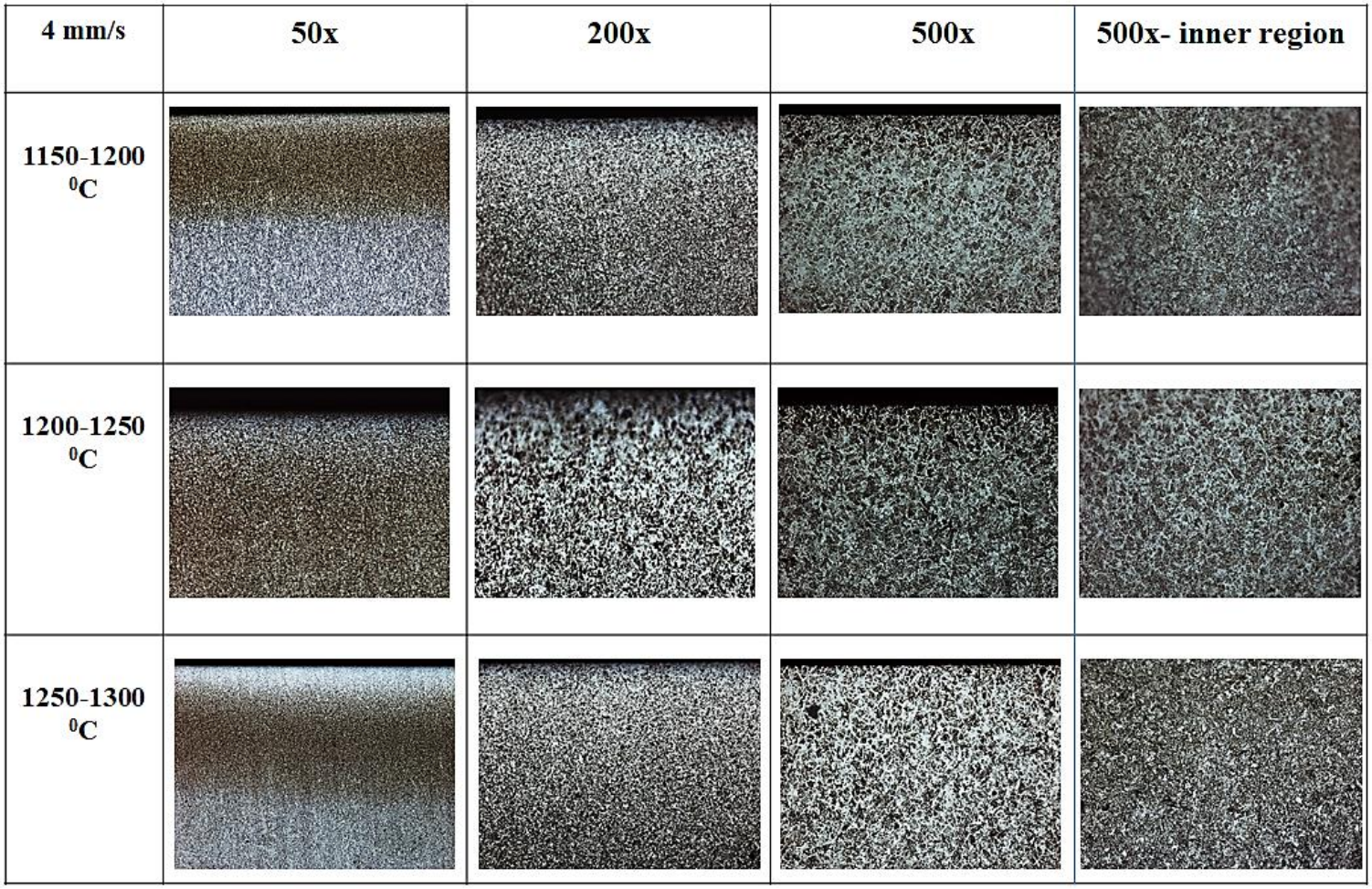


Figure C.2: Optic microscope images of laser hardened QR O90 samples for 50x, 200x and 500x magnifications at constant laser beam velocity (4 mm/s) and different temperature.

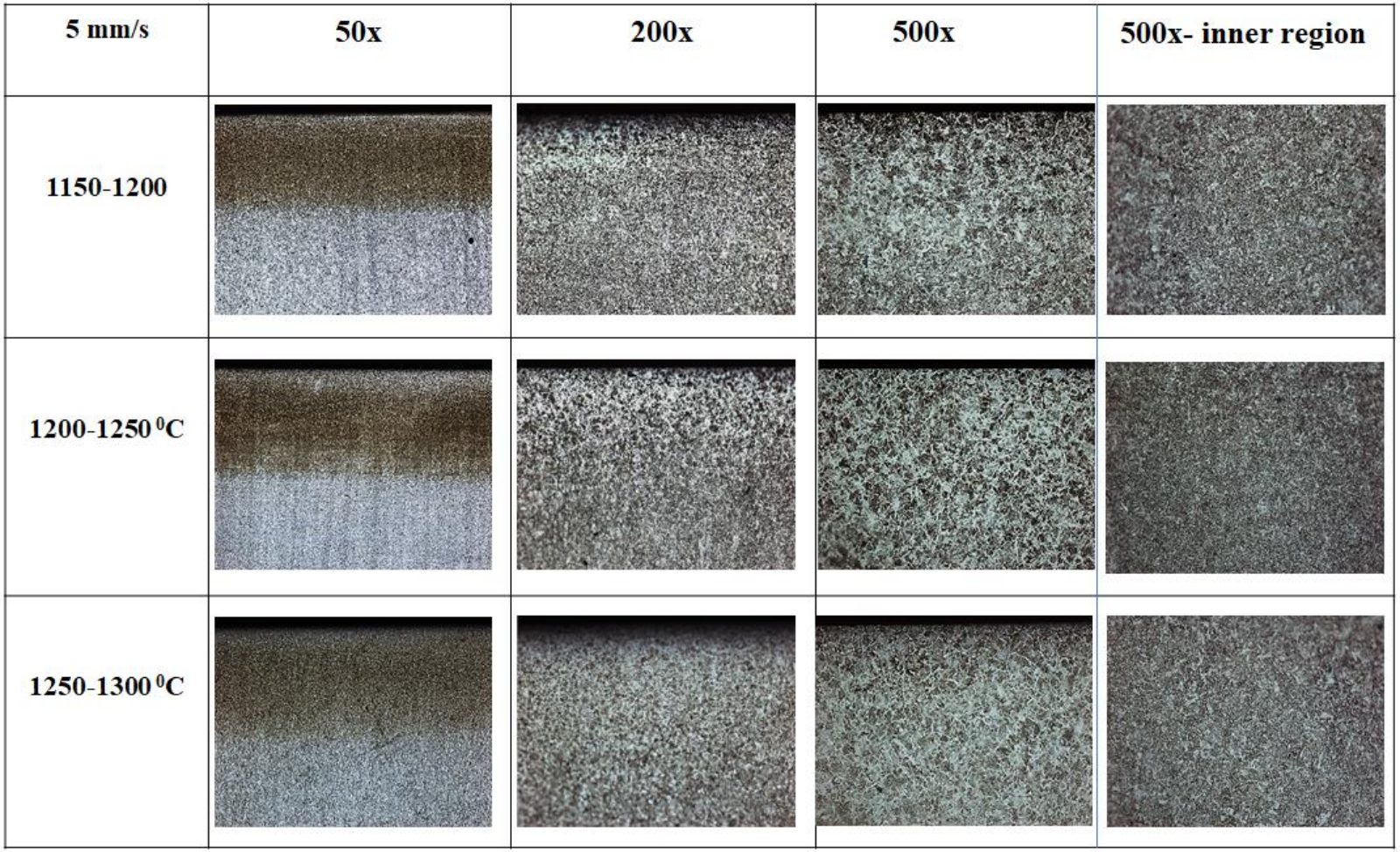


Figure C.3: Optic microscope images of laser hardened QR O90 samples for 50x, 200x and 500x magnifications at constant laser beam velocity (5 mm/s) and different temperature.

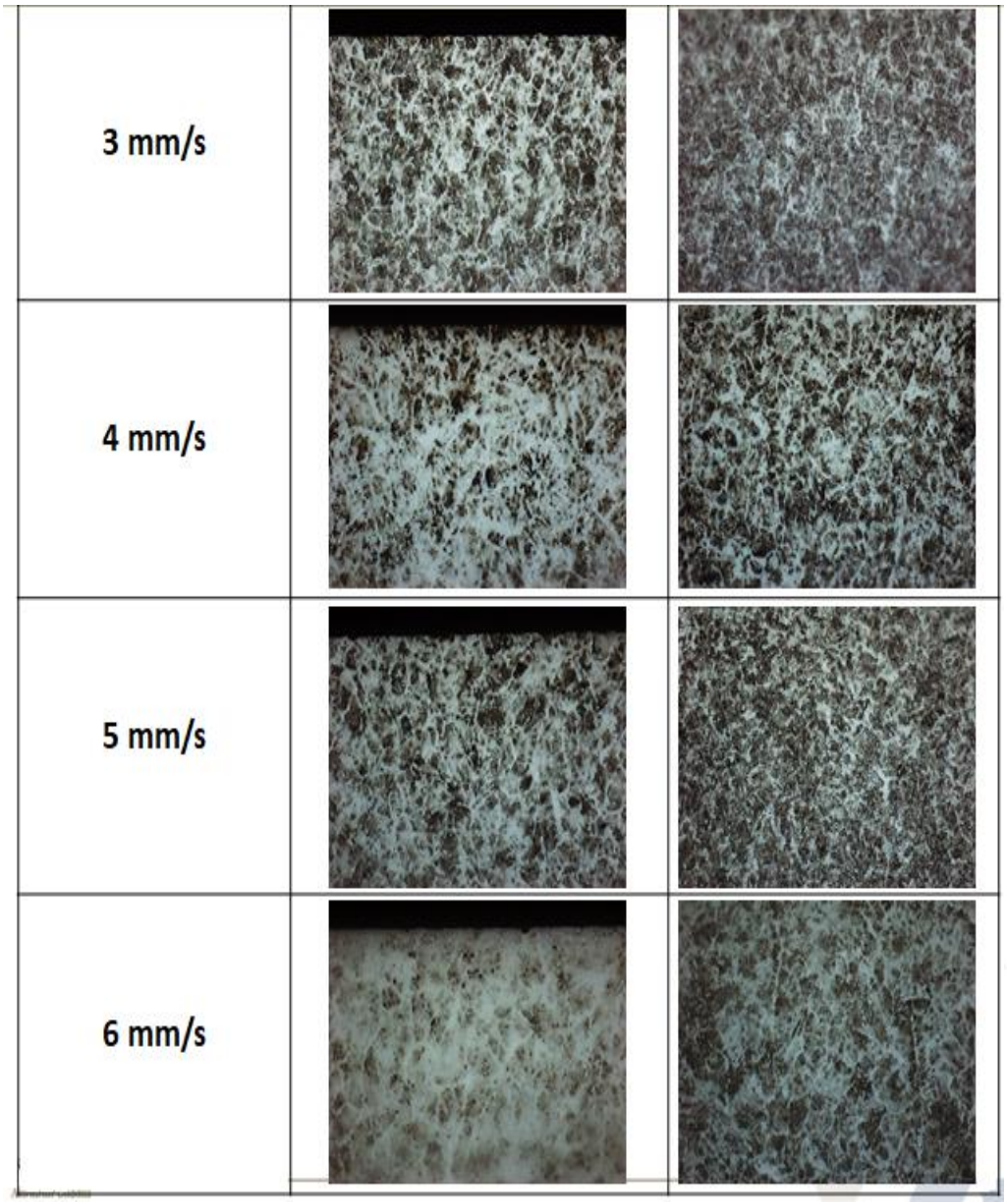


Figure C.4: Optical microscop images of laser hardened QR O90 samples at 1200-1250℃ constant temperature for different velocities as 1000x and 1000x inner region magnifications.

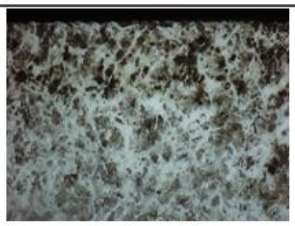
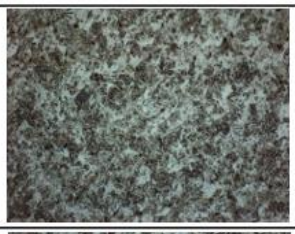
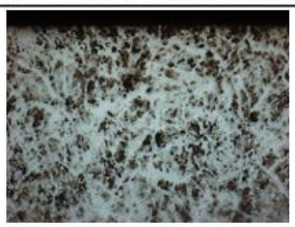
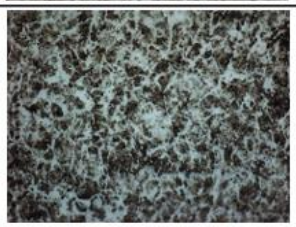
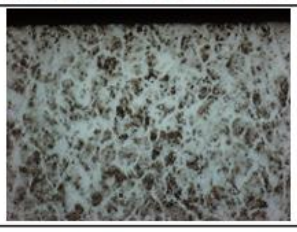
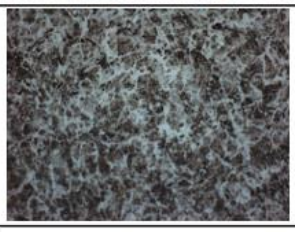
4 mm/s	1000x	1000x-inner region
1150-1200˚C		
1200-1250˚C		
1250-1300˚C		

Figure C.5: Optical microscop images of laser hardened QR O90 samples (1000x and 1000x inner region magnifications) at constant velocity (4 mm/s) for different temperatures.

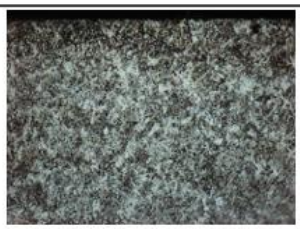
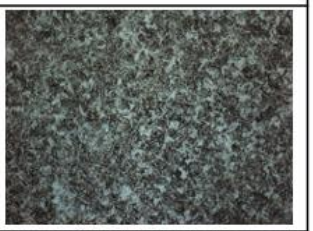
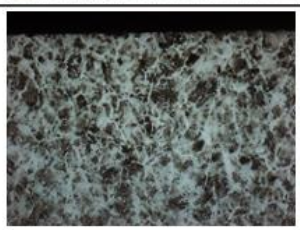
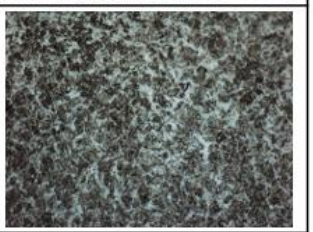
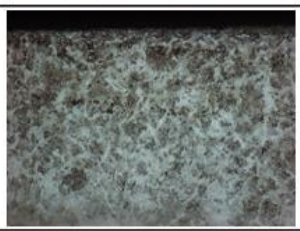
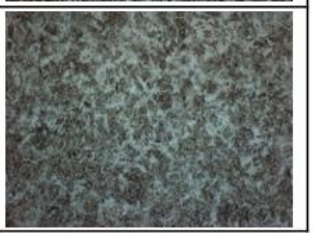
5 mm/s	1000x	1000x-inner region
1150-1200˚C		
1200-1250˚C		
1250-1300˚C		

Figure C.6: Optical microscop images of laser hardened QR O90 samples (1000x and 1000x inner region magnifications) at constant velocity (5 mm/s) for different temperatures.

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