ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE, ENGINEERING AND TECHNOLOGY

EFFECTS OF LOW TEMPERATURE CLEANING PROCESS ON LASER WELDING QUALITY OF INJECTION COMPONENTS

M.Sc. THESIS

Burçak Derya ÇAVLICA

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

DÜŞÜK SICAKLIKTA YIKAMA PROSESİNİN ENJEKTÖRDEKİ LAZER KAYNAK KALİTESİNE ETKİLERİ

YÜKSEK LİSANS TEZİ

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FOREWORD

First, I particularly thank to honourable my thesis advisor Prof. Dr. Hüseyin ÇİMENOĞLU for his guiding and giving chance to me perform my master thesis at RBTR and dear Research Assistant Faiz MUHAFFEL to help all my analysis studies in ITU.

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ABBREVIATION

AV	**:** Average
ASS	**:** Anschlussstuck
Bu	**:** Bursa
CON	**:** Concentration
EDX	**:** Energy Dispersive X-ray
ET	**:** Melt pool width
FIR	**:** Far Infrared
HDEV	**:** Hochdruckeinspritzventil- high injector valve
IR	**:** Infrared
ITU	**:** Istanbul Technical University
LBW	**:** Laser Beam Welding
M	**:** Martensitic structure
MIR	**:** Middle Infrared
NB	**:** Width of welded surface
NC 3300	**:** Neutrocare 3300 chemical
Nd: YAG	**:** Neodymium-doped yttrium aluminum garnet
NIR	**:** Near Infrared
RBTR	**:** Robert Bosch Turkey
SEM	**:** Scanning Electron Microscope
ST	**:** Station
STD	**:** Standard
T.Par.	**:** Trial Parameter
V	**:** Vacuum

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Ø	**:** Contact angle
δ-	**:** Hydrophobic part
δ+	**:** Hydrophilic part

EFFECTS OF LOW TEMPERATURE CLEANING ON LASER WELDING QUALITY OF INJECTION COMPONENTS

SUMMARY

Stainless steel is a ferrous alloy with a minimum 11 % chromium element content by mass. They are important materials for especially automotive industry because of high corrosion resistant, mechanical properties at low and high temperature condition, machinability and low cost properties. Low cost, high-speed mass production and low fault proportion in production are significant factors at the assembly process of manufacturing line. High speed and feasibility of laser welding technology are increased usage area in manufacturing system.

Cleanliness and quality of work piece surface are assumed to play important role at laser welding quality. Cleanliness of work piece surface provided by cleaning process can be defined as pre-process. Cleaning process consists of two main steps, which are cleaning and drying. Machined parts are cleaned in cleaning baths with chemical solution and this process can be done particular or splith type. Temperatures of cleaning baths are approximately 65 °C and drying section's approximately 110 °C. Heating elements provide high temperature that increases cost of process due to spent high electricity.

Present study was initiated with the aim to reduce the cost of cleaning by lowering the temperetaure of the bath. In this respect, instead of conventional cleaning temperature of 65°C parts were cleaned at 35 °C.. Experimental cleaning baths were prepared with 1,93 and 8 vol% concentration of different chemical solutions. Cleanliness tests of cleaned parts made according to BOSCH cleanliness standard.

Nd: YAG laser welding as an assembly process with variable parameters was applied after cleaning step. Due to fact that pre-process of samples (cleaning) and laser welding parameters affect the final quality of parts, effects of both process is investigated simultaneously. Laser welding parameters are shielding gas rate and vacuum condition. Minimum, average and maximum of shielding gas rate and vacuum power were applied at laser welding process after standard cleaning of samples at 35 and 65 ºC with two different and standard concentration of cleaning agent respectively.

Particulate measurement was done for evaluating effect of pre-process variables on clearness of samples. Metallographic studies were done by using optical and stereo microscopy for investigating of laser welding factors on final quality of coupons.

For evaluating mechanical properties and bonding strength of welded samples tensile and hardness test were conducted on prepared specimens.

Consequent of all cleaning and laser welding trials; different parameters of cleaning process such as temperature or chemical concentration, were not effective above the laser welding quality as opposite to belief. Observing of the cleaning process indicates that increasing temperature is more effective than increasing chemical concentration on cleanliness of parts. In the literature sputering is reported as the

welding defect arising from poor cleaing process before the welding process. However, experimental results of the study revealed that cleaning process does not affect on formation of sputtering fault. In addition, after cleaning in high concentration bath the laser welding quality does not change. As the results, laser welding parameters are more effective on welding quality comparing with the effect of pre-process parameters.

All laser-welding processes were completed at BOSCH Bursa Injector Factory and analyzing experiments were done in mechanical metallurgy laboratories at Istanbul Technical University.

DÜŞÜK SICAKLIKTA YIKAMA PROSESİNİN ENJEKTÖRDEKİ LAZER KAYNAK KALİTESİNE ETKİLERİ

ÖZET

Paslanmaz çelikler, çeliklere en düşük %11 krom elementi eklenerek elde edilen alaşımlardır. Korozyona karşı direnç özelliğinin yanında yüksek ve düşük sıcaklıklardaki mekanik özellikleri, ısıl işleme olan uygunluğu ve imalat sırasındaki işlenebilirliği göz önüne alınınca özellikle otomotiv endüstrisi için çok önemli malzemelerdendir. İmalat sırasındaki montaj sürecinde düşük maliyet, hızlı üretim ve hata oranı düşük ürünün eldesine dikkat edilmektedir. Lazer kaynak hızı ve uygulama alanı genişliği sayesinde günümüz montaj teknolojisinde yaygın kullanıma ulaşmaktadır.

Lazer kaynak montaj kalitesi kaynak yapılacak olan yüzeyin kalitesi ile doğrudan ilgili olduğu düşünülmektedir. Ön işlem olarak temizleyici görev üstlenen yıkama prosesi gerçekleştirilmektedir. Yıkama prosesleri lazer kaynak montaj işleminden önce şekillendirilmiş paslanmaz çaliklerin tekil veya topluca yıkanıp kurutulmalarını içeren bir proses olarak tanımlanabilir. Sıralı, büyük banyo hazneleri ve büyük kurutma bölümlerinden oluşmaktadır. Yıkama işleminin amacı talaşlı imalat işlemi görerek şeklini almış olan parçaların partikül ve yağlarından arındırılmasıdır. Bunun için yıkama banyolarında alkali bazlı kimyasallar kullanılmaktadır. Yıkama prosesinde banyo haznelerini sabit 65 °C’ ta tutan ısıtıcılar, kurutma bölümlerinde sıcak hava oluşumunu sağlayan ısıtıcılar ve vakum kurutma bölümlerinde vakumlu ortamın gerçekleşmesini sağlayan vakum pompası düzenekleri bulunmkatadır. Bu yüzden maliyeti yüksek bir ön prosestir.

Bu çalışmada yıkama makinelerindeki maliyeti azaltmak adına yıkama proseslerini 35 °C farklı kimyasal kullanarak gerçekleştirildi. Oluşturulan yıkama banyolarının kimyasal konsantrasyonu hacimce %1,93 ve %8 konsantrasyon seviyesi olarak ayarlandı. Yıkama denemeleri boyunca mekanik etki olan ultrasonik ve eksensel hareketlerden yararlanıldı. Gerçekleştirilen yıkamaların parça üzeri partikül miktarına bağlı temizlik analizleri BOSCH standartlarına uygun olarak incelendi.

Yıkama sonrasında Nd:YAG lazer kaynak montaj işlemi keyhole modu kaynak eriyik havuzunu gerçekleştirerek uygulandı. Yıkamanın yüzey işlemi olduğu göz önünde bulundurularak, lazer kaynak prosesinde yüzey özelliklerini doğrudan etkileyen kaynak proses parametreleri saptanarak yeni lazer kaynak montaj deneme işlemleri gerçekleştirildi. Bu parametreler proses vakum koşulu ve koruyucu akış hızıdır. Gerçekleştirilen yeni lazer kaynak montaj denemelerinde vakum koşulu ve koruyucu gaz akışı minimum, ortalama ve maximum güçlerde çeşitli koralasyonlarda 35 °C şartında yıkanan tüm parçalara uygulanmıştır ve sonuçları incelenmiştir.

Yıkama sonrası yapılan partikül analizi temizlik kontrolü için yapılırken, metalografik ve mekanik incelemeler ise laser kaynak proses parametrelerinin kaliteye etkisni anlamak için yapılmıştır.

Yapılan farklı konsantrasyonlu yıkama banyolarından çıkan parçaların temizlik sonuçları, banyoların kimyasal konsantrasyonun artışından temizlik kalitesinin etkilenmediğini göstermektedir. Yıkama temizlik sonuçlarında sıcaklık artışının daha etkin olduğu söylenebilir. Ayrıca yapılan düşük sıcaklıktaki yıkama denemeleri temizlik sonuçları deneme amaçlı kullanılan parça tiplerinde partikül sonuçlarının limit değerlerinden düşük olduğunu göstermiştir. Bu sonuç yıkama prosesinin düşük sıcaklıkta gerçekleştirilebileceğinin bir göstergesidir.

Kaynak prosesi sonrası ilk yapılan kontrol incelemesidir ve stereo mikroskop kullanılarak çeşitli büyütmelerde görüntüler elde edilmiştir. Bu sayede kaynak dikiş özellikleri ve proses parametresi korolasyonlarına bağlı olarak ortaya çıkan özellikler tanımlanmıştır.

Sonrasında metalografik çalışmalar yapılmıştır ve kaynaklı parçaların iç yapılarını incelemek amaçlı olmuştur. Bu incelemelerde kaynak havuzu derinlikleri ve kaynak yüzey genişlikleri ölçülmüş ve bu sonuçlar yapılan koruyucu gaz akış hızı ve vakum koşulu koraslasyon denemelerine göre değerlendirilmiştir.

Kaynaklı parçalara yapılan çekme testi ile tüm parçalarda kaynak bölgesinden kopma gerçekleşmiştir. Çekme testi sonuçlarına göre ergime havuz derinliği az olan parçaların kopma yükleri düşüktür. Yüzeyi yanmış olan kaynak denemleri ise ortamalama bir kaynak derinliği dolayısı ile çok düşük olmayan kopma yükü sonucu vermişlerdir. 14 gün, 35 °C’ ta ve sabit debide yapılan tuz testi sonucunda, ysnık ksynsk bölgeli parçalarda mikroskop altında yapılan göz kontrolü ile korozif bölgeler saptanmıştır. Bu korozif bölgeler EDX kullanılarak kaynak dikişindeki rastgele seçilen iki noktada Cl iyonu saptanması ile ispat edilmiştir.

Kaynak hatası olarak tanımlanan sıçrama ile yüzeyde yıkama sonrası kalan kimyasal tabaka arasında bir bağlantı gözlenememiştir. Bunun yanında yüksek konsantrasyonlu yıkama işleminden sonra lazer kaynak kaliesinde önemli değişimler gözlenmemiştir. Ayrıca yıkanmamış parçalarla yapılan kaynak işlemi kalite sonuçları deneme parçalarının seri şartlardaki kalite durumuna çok yakın çıkmıştır. Sonuç olarak seri şartlarda yıkanmış parçalar, yıkanmamış parçalar, %1,93 ve %8 ile düşük sıcaklıkta yıkanmış olan parçaların kaynak kalite sonuçları birbirlerine çok benzer nitelikte ve kabul edilebilir BOSCH limitleri düzeyindedirler.

Lazer kaynak prosesinin kendi parametrelerinin kaynak kalitesi üzerinde daha etkili olduğu düşünülmektedir. Koruyucu gaz akış hızına bağlı olarak, kaynak dış yüzeyi bağlanma noktası (kaynak dikişi) genişiliği değişmektedir. Koruyucu gaz etkisinin aktif olduğu şartlarda bu değer istenilen ölçüde ve geniştir. Fakat koruyucu gazın etkin olmadığı şartlarda bu değeri küçülmesi ve kayanak dikişinin yanarak karaması gözlenmiştir. Etkin vakum koşulunun istenilen kaynak modunda prosesi gerçekleştirebilmek için önemli olduğu düşünülmektedir. Bu durum eriyik havuz derinliğini doğrudan etkilemektedir. Vakum parametresine bağlı olarak ise, doğru orantılı biçimde değişen bir etki saptanmamış fakat ergime havuzu derinliği etkilenme oranının daha fazla olduğu gözlenmiştir. Ancak ergime havuz derinliği oluşumunda koruyucu gazın etkinliğinin de önemli olduğu görülmüştür. Bu durumda ortaya çıkan iki farklı parça yüzeyini etkileyen parametrenin oransan ve birbirlerinin etkilerini azaltmayacak şekilde proses sırasında var olmaları hata oranını azaltmaktadır.

Denemeler yalnızca belirli kişiler tarafında ve kendini tekrar eder şekilde yapılmıştır.

Yapılan bütün yıkama denemeleri laboratuvar ölçekli yıkama makinesinde ve lazer kaynak denemeleri ise lazer kaynak montaj hattında bir istayonda BOSCH Bursa DS/GS Enjektör Fabrikası'nda gerçekleşmiştir. Denemelerin analizleri ise İstanbul Teknik Üniversitesi mekanik laboratuvarlarında yapılmıştır.

1. INTRODUCTION

Stainless steel is the most preferred materials especially automotive industry due to its corrosion resistance, machinability and high mechanical properties. Gasoline injector is produced by using several stainless steel materials.

Production of gasoline injector contains three basic steps: cleaning, laser welding assembly and laser welding quality tests. Especially for the gasoline, injector laser welding assembly is an important. Cleaning is a pre-process for the laser welding assembly. Cleaning process is high cost process caused by spent electricity. Aim of the study decrease total production costs changing cleaning type and protecting status of laser welding quality.

Beside investigation of cleaning process affects to laser welding quality, changing of laser parameters research too.

1.1 Purpose of Thesis

Purpose of this study is to provide low temperature cleaning process before critical assembly as laser welding and investigation laser welding quality. Beside this investigation of own laser parameters changing during laser welding process which parameters affect the surface of work piece as shielding gas and vacuum power.

Aim of trials will occurred correlation between cleaning process (its concentration parameters) and laser welding quality in addition between laser welding parameters and laser welding quality.

In according to this, during the trials, the characterizations of the cleaned and welded parts were carried out by analysis methods, which are metallurgical, microscopy, mechanical tests, etc).

1.2 Background

Laser welding is developing technology for welding process. Laser welding is preferred technique to industry at current production due to its speed, ability of welding difficult geometries and high automatic level.

Moreover, studies, the subject of laser welding of stainless steels has still problems to solve. This problem caused by preprocess of laser welding or laser welding process parameters changing. Although laser welding create low cost to production, pre-process of laser welding increases production total cost.

This thesis important point is researching of changing pre-process condition at the laser welding process, in addition, investigation of changing laser welding process parameters at laser welding quality.

As a result, investigation of this changing creates defect on laser-welded zone or not.

1.3 Hypothesis

This research studies two main subjects. In the first step, effect of temperature of cleaning baths on clearness of samples is investigated. In next step, the effect of variable laser welding parameters on microstructure, mechanical properties and corrosion behavior of cleaned samples is studied.

2. GASOLINE SYSTEM in RBTR

Robert Bosch Turkey (RBTR) is produced two types of injector system at Bursa organized industry. One type of injector is Common rail system, which produces at Bu1 and Bu2 factories; another type is Gasoline system produces at Bu4 factory. Gasoline system includes different two type's injector, which are HDEV4 and HDEV5. HDEV is consisted of 'Hoch Durck Einspritz Ventil'initial letter

Figure 2.1 : RBTR factory at Bursa organized industry [1].

2.1 Gasoline Injector Types

HDEV family contains five members are HDEV1, HDEV5.1, HDEV5.2, HDEV long, and HDEV4.

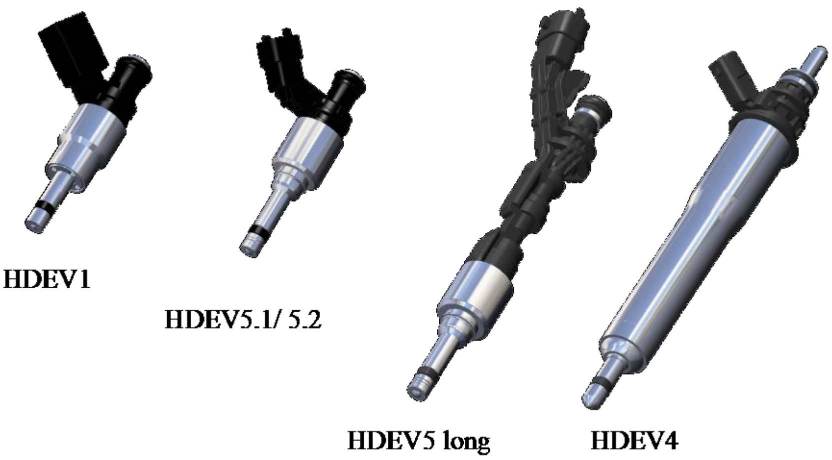


Figure 2.2 : HDEV family [2].

HDEV5 works range between 150-200 bars. It works inducing of magnetic wound inductor. Pulverization of injector starts after magnetic wound work. This family, HDEV5 is new generation in the all gasoline system contrary to HDEV4 family. HDEV5.1 and 5.2 types include development researches so improved day by day. The shorter long and spatter sections properties are important evidence for improvement properties since a few years ago.

3. CLEANING TECHNOLOGY

Technology is developing and devices are getting smaller, so cleanliness of the object used in these devices becomes more important. Products expected a long term to perform without a breakdown. Small amounts of any kind of contamination can irreversibly damage the product. As a result, cleaning technologies keep very critical situation at production.

Cleaning aim is create degreasing and removal of contaminations from surface before assembly operation due to generate high quality assembly at automotive industry. Metal cleaning remove dirt, lubricants, particulates and fluids that accumulate on metal parts during the metalworking processes. Rinsing meaning is, removal of unwanted materials diluted in cleaning agent. Drying meaning is also removal of dilute or pure cleaning agent [4].

Cleaning system includes cleaning operation part and drying part. Cleaning part is formed by aqueous baths. Aqueous baths constitute cleaning steps and rinsing steps. Drying part generally includes vacuum drying technology and hot air drying system. Recently vacuum drying technology contains infrared drying as an assistive power.

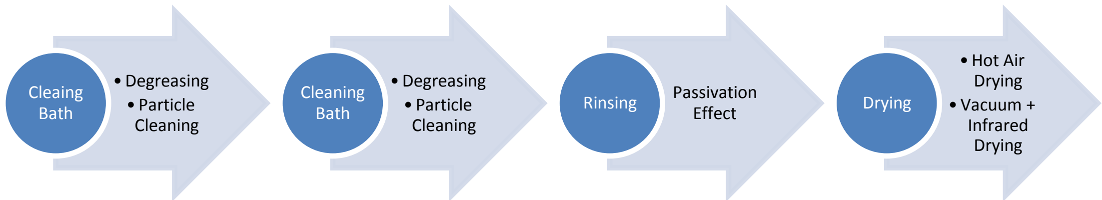


Figure 3.1 : Cleaning system.

There are different cleaning types regard to parts geometry and efficient cleaning process. Immersion and spray cleaning are constituted cleaning machine operation properties. In addition, spilt and singular cleaning techniques are relevant parts geometry size and cleaning baths volume.

3.1 Aqueous Cleaning

An aqueous cleaner is a blend of ingredients designed to enhance the cleaning ability of water. Typically, an aqueous cleaner contains a surface-active agent (surfactant) and builders to help the surfactant.

Surfactants:

It is an organic molecule with a hydrophobic (water-hating/oil-loving) end and a hydrophilic (water-loving) end. The surfactant acts as a wetting agent to allow the cleaning solutions to penetrate into crevices and around and under soils. Chemicals with surfactants, compounds that penetrate and loosen soil by low-erring surface and interfacial tension, are typically the most effective. The alkyl benzene portion of the molecule is the hydrophobic/oleophilic end of this surfactant and the negatively charged sulfonate molecule is the hydrophilic end of the molecule. Surfactants classify as anionic, nonionic, and cationic [5].

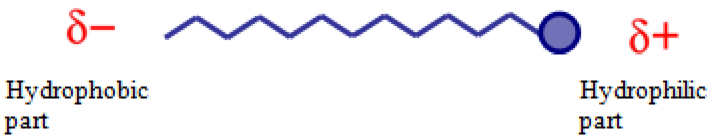


Figure 3.2 : Two points of surfactant.

Anionic surfactants, negatively charged end of the molecule that gives it the hydrophilic part of the molecule. Anionic surfactants are formed by the reaction of an organic compound with an inorganic compound.

Nonionic surfactants are surfactants that have no ions. They derive their polarity from having an oxygen-rich portion of the molecule at one end and a large organic molecule at the other end.

Cationic surfactants are positively charged molecules usually derived from nitrogen compounds. They do not much use as cleaning agents in hard-surface cleaners because of the tendency of the cationic positively charged molecule to be attracted to hard surfaces (that usually have a net-negative charge). Cationic or positively charged surfactants are water-soluble and are commonly used in immersion cleaning.

Inhibitors:

Inhibitors, compounds that reduce corrosion of metal parts, and emulsifiers, compounds that keep oil and grease in suspension to prevent their re-adsorption onto parts, may be included in the cleaning chemical and may enhance cleaning performance [5].

Aqueous cleaners are classified according to pH value as being neutral, acidic, or alkaline on a scale of zero to 14, with a pH of 7 being neutral. Thus, a pH value of less than seven is considered acidic, and higher than seven, alkaline [6].

Table 3.1 : Cleaner types [6].

Type of Cleaner	pH Range	Soils Removed
Mild Alkaline	8 ½-11	Oils, particles, films
Alkaline	11-12½	Oils, fats, proteins
Corrosive Alkaline	12½-14	Heavy grease-soils

Advantages over solvent degreasing in the removal of certain types in contaminants include soaps and salts. The cleaning action is based on the saponifying and emulsifying effects of aqueous alkalis, often reinforced by sequestrating, complexion and surface-active agents. The ingredients are usually selected from sodium hydroxide, sodium carbonate, sodium metasilicates, trisodium phosphate, sodium pyrophosphate, sodium borates, and complexing agents. They may be used hot or cold and with or without applied current which may be either anodic or cathodic [4].

Cleaning of metal parts is done by alkaline chemical. Detergents use both chemical and physical action to clean, which are affected in turn by temperature, time, type of mechanical action, cleaner concentration, and additives. Mechanical action is provided by immersion, spray, or ultrasonic [7].

Cleaning quality effects of aqueous system;

-Concentration of chemical

-Time of cleaning time

-Temperature of cleaning baths

-Mechanical effects intensity

3.2 Mechanism of Cleaning

Oils, greases, waxes, polymers, paints, adhesives, or coatings are organics and hydrophobic. Organic contaminants are removed by two primary mechanisms. The first is solublization in an organic solvent. The second is by displacement with a surfactant film followed by encapsulation and dispersion. The mechanism of removal of organic contaminants by detergent involves wetting both contaminant and substrate. According to Young's equation, wetting increases the contact angle (θ) between the contaminant and the surface, thus decreasing the surface area wetted with the hydrophobe, and reducing the scrubbing energy needed for removal [8].

$$\cos\emptyset = \frac{\gamma SB - \gamma SO}{\gamma OB} \quad \textbf{(2.1)}$$

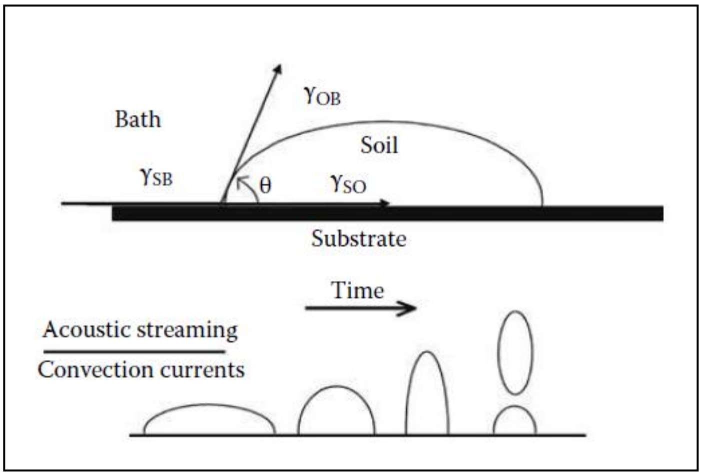


Figure 3.3 : Liquid soil removal [8].

3.2.1 Ultrasonic cleaning

There are two mechanical effects during aqueous cleaning system, which are arising from machine design and water mechanical power.

Cleaning machine design change to their mechanical behavior properties during cleaning process. Immersion and spray cleaning design are created two different mechanical effects. Immersion mechanical effect means, parts move two dimension seesaw and three-dimensional rotation in cleaning, rinsing vessel. Spray effect is different from immersion. Spray effect is used water spray power through parts during cleaning process. Besides all these, ultrasonic power is also extra mechanical effect for aqueous cleaning process. That is water mechanical power.

Ultrasonic cleaning is a technology that uses high frequency sound waves (ultrasonic: above the range of human hearing) to agitate an aqueous or organic medium (cleaning chemistry) that in turn acts on contaminants adhering to substrates like metals, plastics, glass, rubber and ceramics. Contaminants can be dust, dirt, oil, pigments, grease, polishing compounds, flux agents, fingerprints, soot wax and mold release agents, biological soil like blood, and so on. Ultrasonic effect is based on two principles, which are cavitations and acoustic streaming. Cavitations are a process where the constructive interference of sonic energy causes the formation of rarefiable bubbles in the cleaning liquid. When these microscopic bubbles implode, they produce microscopic jets of liquid that can impinge on the surface of parts to be cleaned. These high-velocity jets remove particles from surfaces and convey cleaning chemicals to organic and inorganic chemical contamination on the surface [8].

An ultrasonic cleaner consists of an ultrasound generator along with special transducers mounted on the bottom of a liquid-filled stainless steel bath. The generator and transducer combo create alternating waves of compression and expansion in the liquid at extremely high speeds [9]. Sound waves are composed of two actions: an expansion cycle during which liquid molecules are being pulled apart (A), and a compression cycle (B), during which the molecules are being compressed. If the expansion cycle has enough energy to overcome the forces, which hold the molecules of liquid together, a bubble or cavity is produced. The compression cycle immediately follows the expansion cycle, rapidly compressing the bubbles created (C) until implosion, takes place (D).

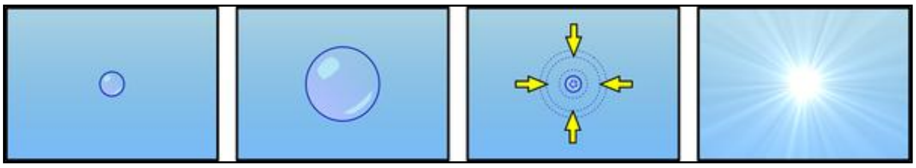


Figure 3.4 : Cavitations and implosion [9].

The size of the cavitations bubble determines the amount of energy released at implosion. This is governed by the frequency of the ultrasonic generator. Higher frequencies generate smaller-sized bubbles. A larger cavitations bubble releases more energy on implosion resulting in a more intense cleansing action. A smaller bubble has a gentler impact. As a general rule of thumb, high frequency is good for fine particles and cleaning of very small features on substrates while the lower frequency is suitable for heavy and coarse contaminants [10].

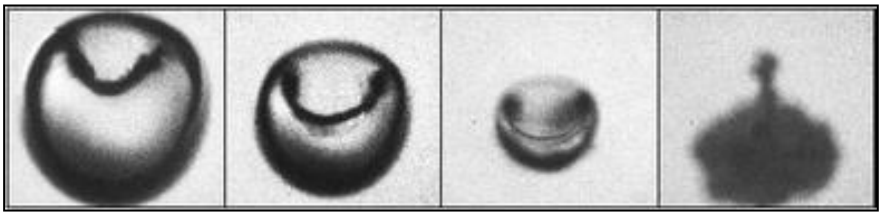


Figure 3.5 : Cavitations bubble [11].

Cavitations bubble image depicts an imploding bubble or cavity. Notice that the top of the bubble folds inward and produced a jet of liquid which can be seen at the centre of the cavity. It indicates that the compression cycle has begun in the bubble. Depending on the type of cleaning requirement and the substrate that needs cleaning a detergent solution or a similar aqueous medium can dramatically increase the cavitations. Lowering the surface tension of the liquid reduces the energy required to form the bubbles, and when combined with the inherent cleaning property of the solution results in superior micro cleansing of the soiled surface. The choice of the cleaning medium is critical. The nature of the substrate and contamination are the key factors in selecting the cleaning chemistry, which is typically aqueous or semi-aqueous.

Temperature also plays a crucial role in the cleaning process. The number of cavitations bubbles increases proportionally to temperature increase. This happens up to about 60°C beyond which cavitations begins to decline and stops completely when the liquid's boiling point is reached. However, as the temperature and vapor pressure increase the cavitations energy decreases. Thus, each cleaning chemistry provides maximum cleaning efficacy at an optimum temperature setting.

3.3 Drying Technology

Drying is final part before aqueous cleaning process is completed. Efficient drying is important to prevent passivation of metal parts before assembly. Drying part of cleaning system has critical important for welding assembly to prevent humidity fault in welding zone as hydrogen embrittlemet.

Moisture in a solid may be either unbound or bound. There are two methods of removing unbound moisture: evaporation and vaporization. Evaporation occurs when the vapor pressure of the moisture on the solid surface is equal to the atmospheric pressure. This is done by raising the temperature of the moisture to the boiling point. This kind of phenomenon occurs in roller dryers. In vaporization, drying is carried out by convection, that is, by passing warm air over the product [12].

There are two main classes for drying technique of aqueous cleaning systems, which is consisted of hot air drying system and vacuum drying system with infrared drying.

Hot Air Drying:

This system is based on heat up air with resistance and spray warm air through parts during mechanical motion in empty vessel. It is an airflow system directly on to components to make a force to remove liquid from components the critical point during process warm air temperature. The temperature is not high as burn to passivation layer on metal parts. Temperature range is between 100 °C – 120 °C.

Vacuum drying is after step than hot air drying section. Hot air drying system cannot be affected on complex part uniformly [13].

Vacuum and Infrared Drying:

Vacuum drying principle is low temperature vaporization. At vacuum condition, water vaporization temperature decreases and as a layer thickness water ruins can be vaporized. As vacuum drying is known, cold drying. At vacuum drying vacuum range generally 1000 mbar. This technique is made an advantage on complex shape. Vacuum drying is not rinse the temperature of vacuum chamber.

Infrared technology is an additional power for vacuum drying to rinse the parts surface temperature. IR radiation is the part of the electromagnetic spectrum that is predominantly responsible for the heating effect of the sun. The wavelength spectrum of the radiation depends on the nature and temperature of the heat source. Everybody emits radiation due to its temperature level, which is called ‘‘thermal radiation’’ because it generates heat. The wavelength range of thermal radiation is 0.1–100 mm within the spectrum. IR radiation can be divided into three categories and is conventionally classified as (Sandu, 1986): near IR (0.75–3.00 mm NIR), medium IR (3.00–25mm MIR), and far IR (25–100 mm FIR) [14, 15].

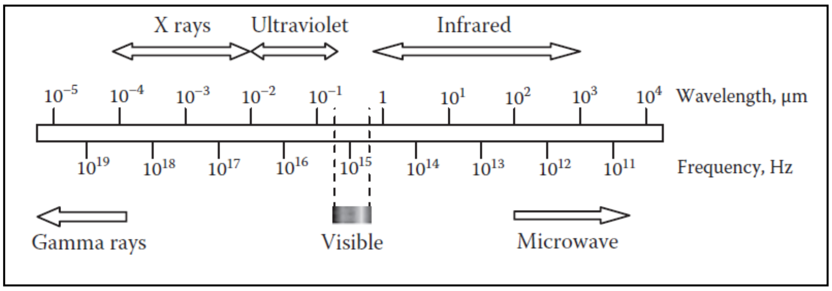


Figure 3.6 : Electromagnetic wave spectrum [14].

Middle wavelength is absorbed well by water layer on surface. The principle of infrared drying is based on absorption capability of water. Emissivity, absorptivity, reflectivity, and transmissivity are the key radiation properties.

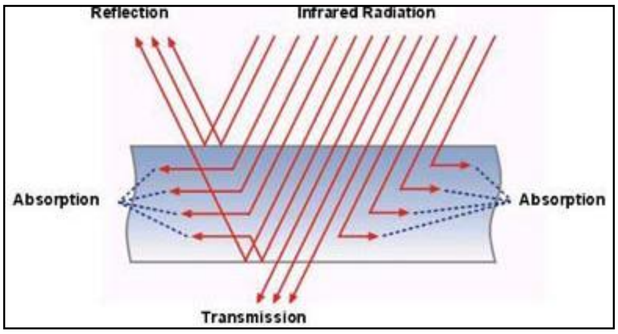


Figure 3.7 : Infrared absorption, radiation, reflection and transmission [16].

Three-wavelength classification of infrared technology and incident radiation absorption ability of water create vaporization from substrate. Thus drying is come trued on the wet parts surface. The importance of infrared drying is direct effect of metal surface neither rinse the condition temperature since therefore rapid drying and low energy consumption during drying.

4. LASER WELDING

4.1 Laser Welding Types

Laser welding represents a new process to be applied to an old industrial technique. It is a fusion welding process requiring no filler material, where parts are joined by melting the interface between them and allowing it to solidify [17]. The laser may be used as a welding heat source and consists of a high-energy coherent beam of light of an essentially constant wavelength. LASER is an acronym for Light Amplification by Stimulated Emission of Radiation and the medium in which it is generated may be solid, liquid or gaseous.

Helium/neon and CO_2 are commonly used as a basis of gaseous systems whilst ruby and neodymium doped yttrium aluminum garnet (Nd:YAG) are used in solid state lasers [18]. Energy source (pump), lasing medium (solid, liquid, gas) and optical resonator are necessary to produce laser light.

Laser welding is not alternative to conventional welding process in industry, but rather it offers flexibility and speed for mass production. The main features of laser welding which make it alternative compared to conventional process are simply;

- High process speed
- The low heat input into the material obviates the need for complex jigging
- Allows distortion-free welding of thick to thin section
- A small heat-affected zone reduces metallurgical damage and allows welds to be made to heat –sensitive components.
- Deep welds can be made with high metallurgical quality
- Continuous joints

There are five types of lasers, which are used in industry and suitable for welding:

1. CO_2 lasers: type of gas laser, commonly used in industry Nd:YAG lasers: type of solid state lasers, especially for welding C-Mn steels, coated steels, stainless steels, Al alloys, Ti alloys,
2. Diode lasers: for plastic welding and smaller applications
3. Yb Fiber laser: suitable for cutting as well as welding
4. Disc laser [19].

4.2 Laser Welding Modes

When a laser beam comes on the surface of material, it can heat, melt and/or evaporate the metal due to the absorbed energy. Laser welding is performed by two mechanisms which are 'conduction welding' and 'keyhole welding'.

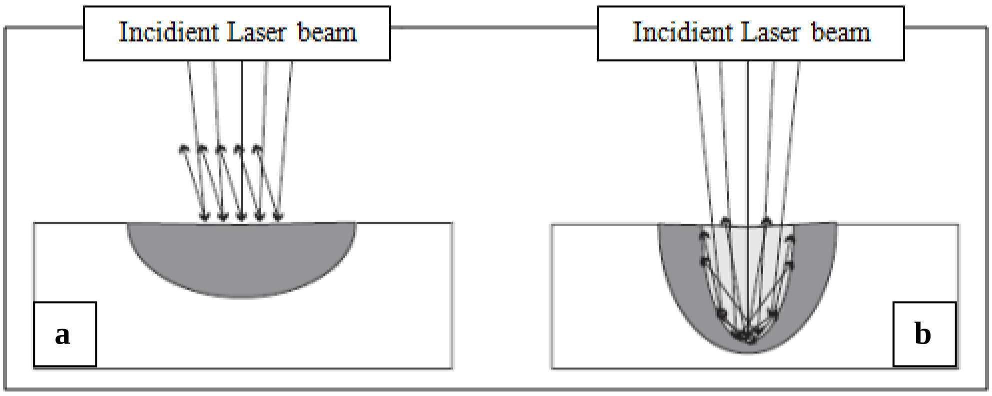


Figure 4.1 : Typical two laser welding modes [20].
a) Conduction mode
b) Keyhole mode

Conduction mode:
Conduction limited welding occurs when the power density at a given welding speed is insufficient to cause boiling and therefore to generate a keyhole.

In conduction, welding, overlapping spots from a pulsed laser or from the beam of a continuous laser is absorbed by the surface of the material and the volume below the surface is heated by thermal conduction producing. High intensity level the rapid removal of metal by vaporization from the surface leads to the formation of a small keyhole into the work piece. The keyhole grows in depth because of increased coupling of radiation into the work piece, through multiple reflections of the laser beam off the keyhole walls, and material vaporization. The balance between the hydrostatic forces of the liquid metal surrounding it governs its existence and the pressure of vaporized and ionized material or plasma within it.

Plasma is ejected from the keyhole, forming a cloud above the work piece. This plasma cloud can have a deleterious effect on the welding process because it can shield the work piece from the laser beam leading to wider [19].

Keyhole:

The weld pool has strong stirring forces driven by Marangoni-type forces resulting from the variation in surface tension with temperature. Weld pool is unbroken on the material surface and energy transfer to the deep into the material happens by conduction. The other mode is “keyhole” welding, in which there is sufficient energy per unit length to cause evaporation and hence a hole in the melt pool. The pressure from the vapor is generated stabilizes this hole. In some high-powered plasma welds, there is an apparent hole, but this is mainly due to gas pressures from the plasma rather than from evaporation. The “keyhole” behaves like an optical black body in that the radiation enters the hole and nearly all the beam is absorbed.

There are two principal areas of interest in the mechanism of keyhole welding. The first is the flow structure since this directly affects the wave formation on the weld pool and hence the final frozen weld bead geometry. This geometry is a measure of weld quality. The second is the mechanism for absorption within the keyhole, which may affect both this flow stability and entrapped porosity. The absorption of the beam is by Fresnel absorption (absorption during reflection from a surface) and inverse bremsstrahlung leading to plasma re-radiation. The calculation must allow for the slope of the face, the mode structure of the original incident beam, polarization effects and focal position. The plasma effects vary with polarization and speed.

Some ingenious experiments have been shown a roughly circular hole, with the dimensions of the focused beam diameter, very rapidly fluctuating in shape, pulsing in size and flapping from side to side. They also show that the plasma coming from the keyhole has two components. One is the metallic plasma from the boiling material, which fluctuates as directed by the shape of the keyhole, but tends to be directed backwards at slow speeds and more vertically at higher speeds. The other is the shroud gas plasma, which forms by interaction with the metal plasma. It is almost stationary relative to the laser beam but varies in intensity with the laser power and welding speed. These experiments come from high-speed videos of the keyhole entrance have been made – carefully illuminated by an argon laser [19].

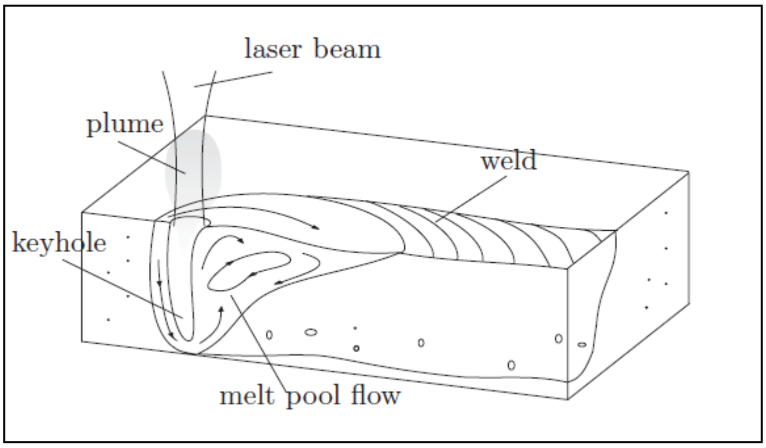


Figure 4.2 : Keyhole with surrounding melt pool [20].

4.3 Laser Welding Parameters

Laser welding requires the control of a number of operating parameters like other process as power, mode, shielding gas and travel speed. The main process parameters related with beam, material, shielding gas and transport properties.

- Beam is classified (based on laser) : power, pulse or continuous, polarization and wavelength
- Material process parameters (based on material): composition, surface condition
- Shielding gas parameter (based on welding parameters): velocity of shielding gas, type of shielding gas
- Transport properties: speed, focal position, joint geometry

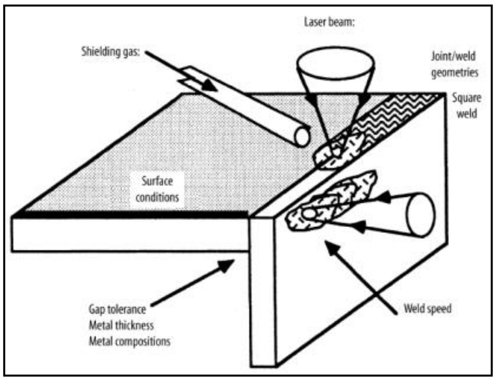


Figure 4.3 : The main process parameters [21].

4.3.1 Based on laser technology

Wavelength:

Wavelength means, distance between top of wave at visible lights basically, the greater energy creates larger frequency and short wavelength. Short wavelength more energetic than long wavelength. At shorter wavelengths, the more energetic photons can be absorbed by a greater number of bound electrons and so the reflectivity falls and the absorptivity of the surface is increased [19, 21].

At the conduction or keyhole, welding surface reflectivity becomes paramount and the lower reflectivity with the shorter wavelengths gives a distinct advantage to excimer at laser welding process. However, there is another factor affecting absorption and that is the plasma formed owing to the very hot gases coming from the keyhole. Shorter wavelengths there will be less absorption and hence cooler and less absorbing plasma as found. This gives a significant advantage to shorter-wavelength lasers for welding.

Pulse Energy:

Pulse energy is the amount of energy transferred by individual pulses to material. Pulse energy is changed due to the rate of current to the flash lamps and changes in pulse time.

Power:

Power and power density are related each other. When the power density is too low, energy coupling of laser beam to work piece and penetration can be lost. If the power density is too high, this can cause welding defects such as spatter, undercut, under fill [22, 23].

Penetration is a function of power and hence if the peak power is raised by pulsing or modulating the beam, as in super pulsing or hyper pulsing, there can be greater penetration for a given average power.

4.3.2 Based on material

Composition of materials:

Not all materials can be welded with equal ease due to widely differing thermo physical properties. Laser welding can be able to apply metallic materials, ceramic materials, composites and polymers materials.

The main material problems with laser welding, in common with most welding methods, are crack sensitivity, porosity, HAZ embrittlement and poor absorption of the radiation. For welds of dissimilar metals, there is the additional problem of the possible formation of brittle intermetallics. Crack sensitivity refers to centerline cracking, hot cracking or liquation cracking. The weld pool-cooling rate and the post solidification solid-state cooling rate during laser welding greatly influence the microstructure in the weld. Depending on the rapid solidification characteristics and the composition of the steel, the microstructure may be fully austenitic, ferritic, or duplex austenitic. Laser welding of stainless steel may be associated with the changes in the composition of the weld metal due to the pronounced vaporization of the alloying elements from the weld pool. The pronounced effect of laser welding on the decrease in manganese content in the weld pool has been reported. Furthermore, the effect of manganese vaporization was observed to be more pronounced at low powers. Welding speed and shielding gas flow rates did not significantly influence the composition changes.

The important considerations during the laser welding of titanium are the attainment of desired tolerances without welding defects and the minimization of welding defects [23].

Thickness and joint configuration:

Thickness and weld speed are effected each other to determine laser parameter. Thickness of the work piece increases, the welding speed for producing deep welds decreases.

Laser welding can be used with a variety of joint configurations such as butt weld, lap weld, edge weld, T-weld, fillet weld, the important consideration here is the achievement of tight tolerances by minimizing air gaps between the overlapping work pieces [24].

Surface Condition:

The surface condition of the material is directly effective on energy absorption of the incident laser beam and the required energy for keyhole welding. There can be oxide layers, coatings or special film layers on the material surface that come from the pre-process as cleaning process that has been discussed previous chapter. On the other hand, material can be welded as-received condition. Quality of the weld and the rate of defects such as spatter and porosity changes in every case due to different reflectivity, absorptivity and vaporization level of the each surface [22, 23, 24].

4.3.3 Based on welding process

Weld speed:

Thickness of the work piece determines the welding speed for producing deep welds. In general, as the thickness of the work piece increases, the welding speed for producing deep welds decreases. Similarly, the depth of penetration decreases with increasing welding speed [25].

Welding position:

What one should consider where is the need to have sufficient power density to generate a ‘keyhole’ or ‘conduction mode’ and then for that power to stay together increase the penetration. Thus, the main parameters to consider would be the depth of focus, the minimum spot size and optimum eccentricity at the laser welded work piece surface [24, 25].

When part is close the laser source, there is small spot and thin adhesion surface, deep depth properties at the parts. Positioning of nozzle is a part of welding position parameter. The required welding gas flow rate depends on nozzle design, nozzle diameter, type of laser, and laser power. The flow rate should be neither too low nor too high. A low flow rate will not provide adequate shielding of the weld pool. A high welding gas flow rate affects the melt flow direction and results in a poor quality of weld, like, for example, an uneven weld bead and undercut. In addition, the welding gas stream should be laminar and even. Turbulence caused by an excessively high flow rate and barriers in the flow direction results in air being mixed with the welding gas, thereby impairing shielding.

Shielding Gas:

The welding gas is flushed onto the work piece through a nozzle system in order to protect molten and heated metal from the atmosphere. However, the welding gas has other functions, too. It protects the focusing optics against fumes and spatters and, in the case of CO_2 lasers controls plasma cloud formation. The welding gas often plays an active role in the welding process, such as increasing the welding speed and improving the mechanical properties of the joint. Gases have different chemical reactions and physical properties, which affect their suitability as assist gases for different welding tasks. At least three important points must be considered: tendency to form a plasma, influence on mechanical properties, blanketing/shielding effect [24].

During laser welding with sufficiently higher powers, the surface of the work piece undergoes rapid vaporization. The subsequent ionization of the vapors creates a standing ionization cloud (plasma) above the work piece surface. This standing ionization cloud absorbs and scatters the laser radiation. For effective welding, it is necessary to remove the cloud. Various shielding gases such as argon, helium, CO_2 can be used for this purpose. Two common configurations of assist gases can be used. In one, the assist gas is directed at the laser–material interaction point; while, in the other, the assist gas is directed slightly offset from the work piece [22, 25].

Vacuum:

Vacuum is applied at laser chamber during laser welding process, because creating without contaminations condition during process time and sum up shielding gas. Hence providing optimum shielding gas balance.

5. EXPERIMENTAL STUDIES

Main object was investigation of work piece surface condition effects on laser welding quality. Surface condition consisted of work piece cleanliness, cleaning chemical contamination on work piece, laser welding process parameters, which affected work piece surface as shielding gas, vacuum.

Aim of the experiments, considering effects of low temperature cleaning process at laser welding quality. This low temperature cleaning was constituted by Neutrocare 3300 (NC3300) chemical and its different concentration at cleaning bath from serial. Thereby, NC3300 cleaning sufficiency for laser welding assembly process and different concentration of NC3300 trial provided to understand effects of chemical contamination on work piece surface on laser welding assembly process.

Trials were planned according to use Minitab experiment design programmer. Experiments included two different concentrations cleaning experiment, seven different parameters welding experiments. Total 2 cleaning and 16 laser welding experiments were done.

All cleaning and laser welding experiments were done at Robert Bosch Turkey – Diesel and Gasoline Factory at Bursa.

Experiment Plan:

1. Step → Cleaning Experiment & Cleanliness analysis

    1,93% NC3300 concentration cleaning experiment

    8% NC3300 concentration cleaning experiment

2. Step→ Laser Welding Experiment & Welding quality analyses

    Laser welding with average value (serial) process parameter of shielding gas rate & vacuum power

        Unclean Parts

        Cleaned with serial standard

    1,93% NC 3300 concentration cleaned parts

8% NC 3300 concentration cleaned parts

Laser welding with different process parameter of shielding gas rate & vacuum power

1,93% NC 3300 concentration cleaned parts

8% NC 3300 concentration cleaned parts

5.1 Preparation of Cleaning System

Cleaning process aim is removing the particles and grease from the work piece surface before assembly process. This cleanliness importance is different according to assembly type such as laser welding assembly more critical than force fitting reassembly. Besides this, cleanliness includes chemical surface layer on work piece after cleaning process.

Cleaning process is formed cleaning baths and drying parts at cleaning machine.

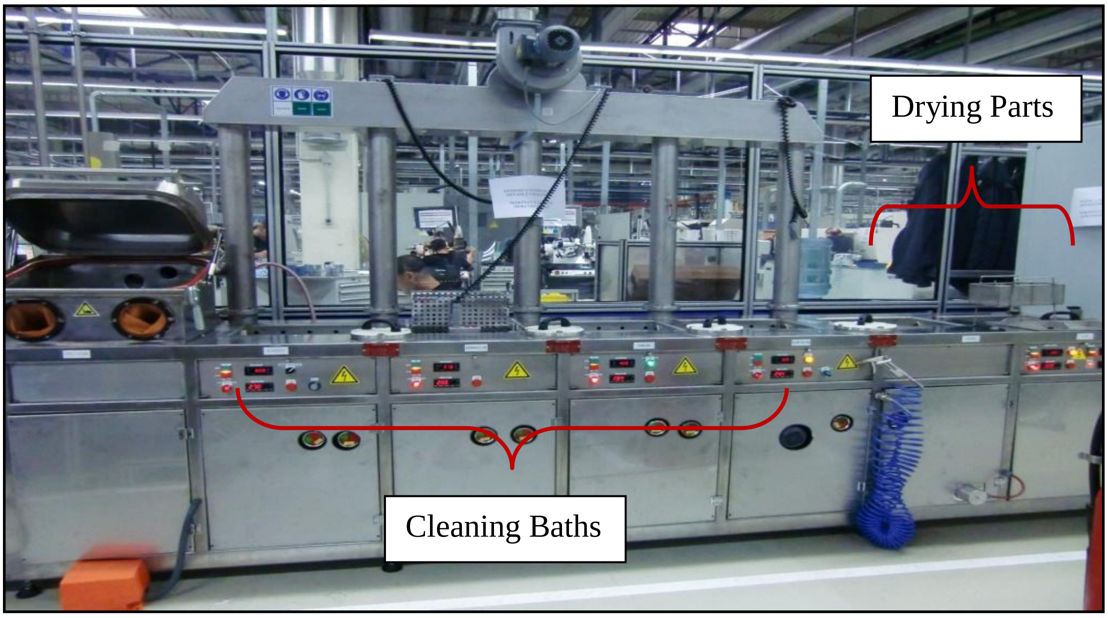


Figure 5.1 : Cleaning Machine.

All cleaning baths were 30lt at the cleaning machine (Figure 5.1). On the left side of figure 5.1 was 1st cleaning bath and there were four baths. Right side of the 1st bath was second bath and last bath was before the drying parts of cleaning machine. This machine had vessel to clean hereby immersion-cleaning type. Ever there had not been vessel, cleaning was made by nozzle. This type was spray cleaning.

Subsequently all bath concentration measurements, particle cleanliness analyzes was made at the cleaning machine filters. Filter cleanliness analyze was made before all trial beginning at 1st cleaning bath and last cleaning bath (last rinsing). Aim of that was ensuring cleaning machine cleanliness.

There were two cleaning style, which were particular, and spilth. Since therefore tambour design changed to cleaning style for effective cleaning. Before the cleaning trial, cleaning style was decided according to work piece properties. Trial parts of experiment were anschlussstück, which were cleaned splith and aktorgehause and cleaned particles.

5.2 Experimental Flowchart

- Baths set-up for immersion cleaning at 1,93% concentration and 8% concentration
- Cleaning of anschlussstück & aktorgehause parts with passivation chemical (Neutrocare 3300)
- 10 parts were chosen from 60 parts on anschlussstück and aktorgehause for cleanliness analysis from 1,93%, 8% cleaning trial & unclean parts.
- Enter to assembly
    - Laser welding at station 425
- Visual & Stereo microscopy control to all welded parts of each trial group, serial and unclean parts
    - Changing of color on welding
    - Changing of welding structure
- Metallographic analysis for 2 welded parts of each trial group, serial and unclean parts
    - Measurement of welding depth and welding surface thickness
- Tensile test for 10 welded parts of each trial group, serial and unclean parts
- Salt spray test for 1 parts of each trial group, serial and unclean parts.

5.2.1 Experiments of parts cleaning and cleanliness analysis

There were two style of work piece which anschlusstück and aktorhegause.

Figure 5.2 : a) Anschlussstück **b)** Aktorgehause

Anschlusstück is a 415 M stainless steel, which is improved weld ability. Aktorgehause is a 304 Cr-Ni austenitic stainless steel.

Was of different design of work piece trial parts, two cleaning styles were applied to immersion cleaning process. Anchlusstück was cleaned by spilth style and aktorgehause was cleaned by particle.

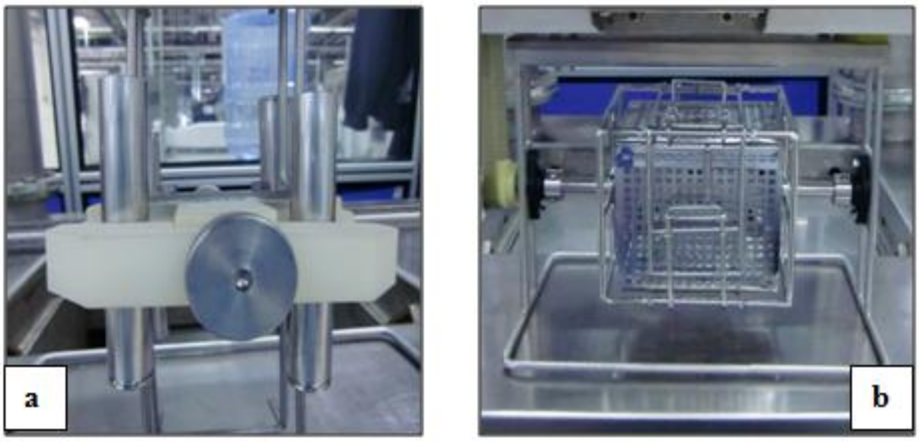


Figure 5.3 : a) Particle cleaning style. **b)** Spilth cleaning style.

Cleaning bath preparation was started at bath concentration measurement from the technical user worksheet about chemical information. Two different concentration baths were prepared which were 1,93% cleaning and 8% cleaning series.

This 1,93% cleaning series was 1st cleaning bath was 1,93% chemical concentration, 2nd bath was half of 1st bath concentration - %1 chemical concentration, 3rd bath was %0,5 chemical concentration and finally last bath was %0,325 chemical concentration.

8 %cleaning serial was 1st cleaning bath was 8% chemical concentration, 2nd bath was 4% chemical concentration, 3rd bath was 1,93% chemical concentration and last bath had ¾ proportion with 3rd bath- 0,43% chemical concentration.

1st and 2nd cleaning baths called ‘cleaning’, 3rd and final baths called ‘rinsing’.

Table 5.1 : Cleaning and rinsing baths time-temperature information of 1,93% and 8% concentration.

Operation	Time[sec.]	Temperature[°C]	Concentration[%]
1st cleaning	240	35±5	1,93
2nd cleaning	150	35±5	0,965
3rd cleaning	150	35±5	0,5
4th cleaning	150	35±5	0,3
1st cleaning	240	35±5	8
2nd cleaning	150	35±5	4
3rd cleaning	150	35±5	2
4th cleaning	150	35±5	0,43

All cleaning baths had ultrasonic cleaning effect and turbination. Thereby, only concentration property was different all of cleaning baths.

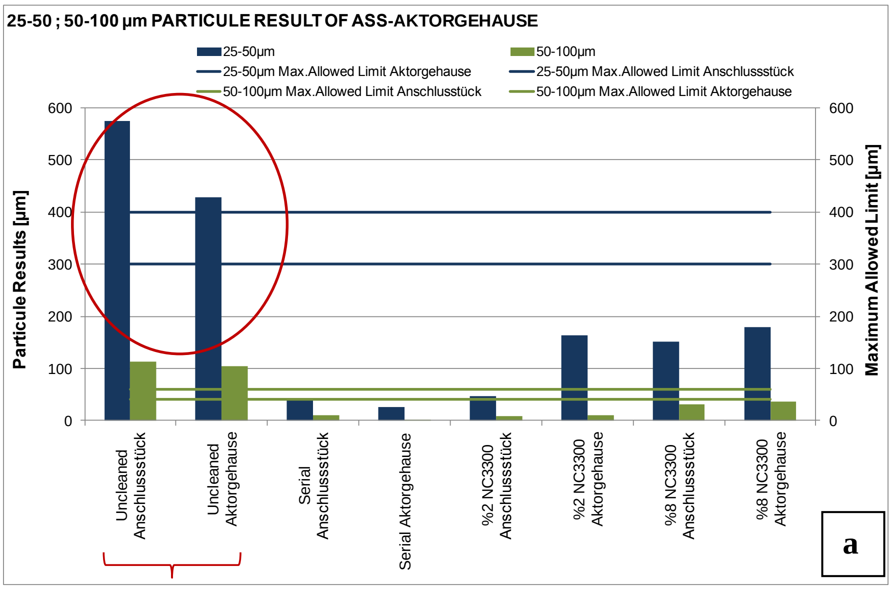
After the cleaning steps, parts were continuing drying step to complete the cleaning process. Drying steps properties were same as one another to 1,93% and 8% concentration cleaning trial. Hot air drying was 90 °C – 110 °C ranges and 200 sec. Vacuum drying was 153 sec. infrared drying was not applied during all cleaning trial.

After cleaning process completed, parts cleanliness analysis was applied to 10 parts from 1,93% concentration aktorgehause and anschlusstück cleaning trial and 10 parts from 8% concentration aktorgehause and anschlussstück cleaning trial. In addition, this parts cleanliness analysis was applied also 10 unclean aktorgehause and anchlussstück parts and 10 parts aktorgehause and anschlussstück from cleaned with serial standard.

Cleanliness analysis is a kind of particle counting method that is used to determine the size and quantity of the particles on the parts. The basic principle of this method is light absorption and/or light scattering from surface. Because small particles scatter less light, device is able to find out the quantity and size of the particles.

First, potential contaminants are removed from cleaning liquid or on the part surface. Injector parts are washed in a cabin and contaminants are taken in a filter. Important point at cleanliness analysis, there should be no external effect on parts surface after cleaning process is completed.

Particles counting were made based on particle’s sizes. Particles divided five groups which were 25 – 50µm, 50 – 100µm, 100 – 200µm, 200 – 400µm and >400µm. Both aktorgehause and anschlussstück parts, 200 – 400µm and >400µm particles size had not to be on counting result to okay cleanliness result.



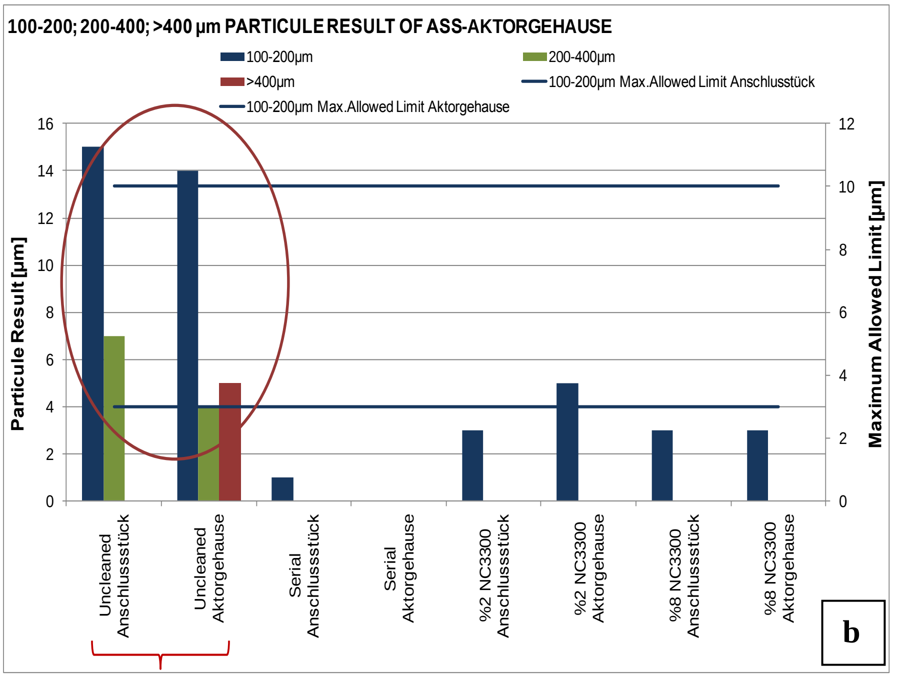


Figure 5.4 : Cleanliness particle results of 1,93% & 8% concentration, serial and unclean aktorgehause and anschlussstück parts,
a) 20 – 50µm; 50 – 100µm particle results,
b) 100 – 200µm; 200 – 400µm; >400µm particle results.

Figure 5.4 are showed unclean aktorgehause and anschlussstück particle results were exceed the allowed max limit. Serial cleaning that means Surtec chemical was more effective cleaners than NC3300. Seeing that particle results were less than NC3300 chemical results. Addition, 8% NC3300 aktorgehause 25-50µm, 50-100µm cleaning particle results were more than 1,93% NC3300 cleaning particle results. Consequently, this general comment was not true, high concentration chemical provided more effective cleaning. When increase the chemical amount, increase the cleanliness property. Only one comment could say, high temperature increases cleanliness of parts. Temperature was more effective than chemical concentration at cleanliness.

5.2.2 Experiments of laser welding and metallographic analysis

At station, 425 assembly line, aktorgehause and anschlussstück parts are compounded by laser welding. At serial process, firstly aktormodul and anschlussstück parts are compounded each other after aktorgehaouse is added. However, during trials aktormodul part is not used because its price. Only aktorgehause and anschlussstück laser welded surfaces are enough to understand the low temperature cleaning process effects.

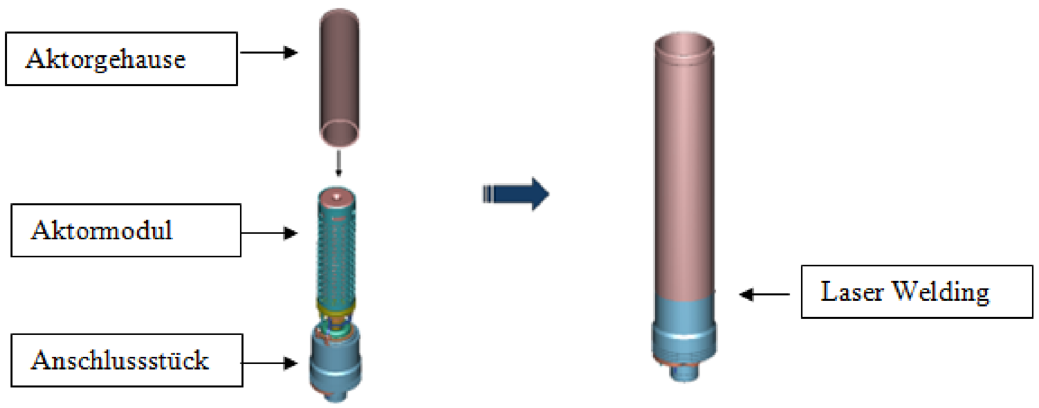


Figure 5.5 : Compounding of Anschlussstück – Aktorgehause and Aktormodul parts at station 425.

Serial parameters at station 425 of shielding gas is N_2, 12 l/ min and vacuum value is 11,5 m^3/h. This shielding gas and vacuum parameters are affected directly on surface properties of cleaned parts alongside of cleaning process. Laser welding quality changes with these reasons. Therefore, shielding gas and vacuum parameters were chosen to trials.

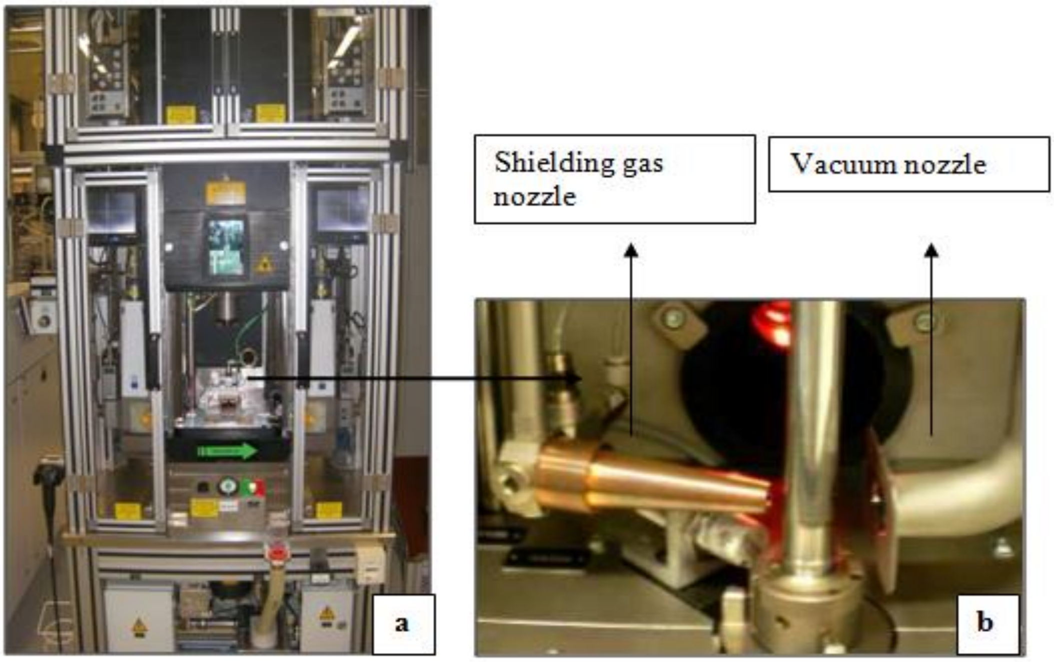


Figure 5.6 : Laser welding station 425,
a) Main machine chamber
b) Vacuum nozzle and shielding gas nozzle

Laser welding trial contains changing of station 425 vacuum values and shielding gas velocity parameters. Two parameters of laser welding were changed: the rate of vacuum and the rate of the shielding gas. Changes were done at every tray. Vacuum value and shielding gas rate were used at three levels, which were minimum, maximum and as serial.

Table 5.2 : Parameters table of welding process and cleaning process for welding trial.

Trial Parameter	Trial Description	Concentration[%]	Laser Parameters
1	NC 3300	1,93	Av.
2	NC 3300	1,93	0 Gas – Av. V
3	NC 3300	1,93	Av. Gas – 0 V
4	NC 3300	1,93	0 Gas – 0 V
5	NC 3300	1,93	Av. Gas – Max V
6	NC 3300	1,93	Max Gas – Max. V
7	NC 3300	1,93	Max. Gas – Av. V
8	NC 3300	8	Av.
9	NC 3300	8	0 Gas – Av. V
10	NC 3300	8	Av. Gas – 0 V
11	NC 3300	8	0 Gas – 0 V
12	NC 3300	8	Av. Gs – Max. V
13	NC 3300	8	Max Gas – Max V
14	NC 3300	8	Max Gas – Av.V

15	Serial Surtec 533+89	2±0,5	Av.
16	Unclean	-	Av.

Table 5.3 : Values of vacuum condition and shielding gas rate at experiments.

Value of Laser Welding Process Parameters	Vacuum Condition [-bar]	Shielding Gas Rate [l/min]
Minimum	1	0
Average	5	6,10
Maximum	28	11,6

Laser welding is different than traditional welding technology according to heat affected one structure, process time, suitability of process chain and knowledge to constitute process.

Laser welding is high speed thereby suitable to mass production assembly. Speed is coming from high effective laser technology. Addition force as vacuum and shielding gas should be used during laser welding process to invent optimum laser quality.

When the laser beam reaches on work piece surface at process, melting of steel is began so it is created melt pool, plume is started from melt pool and surface layer of work piece. The work piece revolve 360° whirl around during reaching the laser beam on it.

Parameters of vacuum and shielding gas are caused some fault at laser welding as spatter (ejection), insufficient depth on keyhole, false color on welded surface, porosity both surface and melted zone structure.

Based on literature information and experimental observation, shielding gas and vacuum parameters affect the plasma/plume and spatter formation.

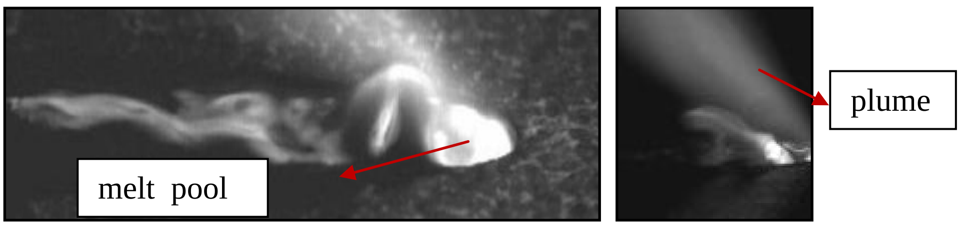


Figure 5.7 : Characteristic image of melt pool and plume deviation [26].

These images were achieved by using high-speed video camera during laser welding. Plasma/plume formation can be prevented by used vacuum technology. Shielding gas is additional force for the vacuum to prevent the plume. Plume is unwanted because it is prevent to reach whole laser beam on work piece. It forms obstacle between laser beam and melted surface. Hereby, total melted zone cannot be procured at the concretion point. This situation prevents the keyhole mode at laser welding process, because total arriving laser beams require forming enough depth for keyhole mode. More interaction laser beam at melted zone is formed high depth.

Vacuum optimum value is important to formation of optimum concretion point. Less vacuum value provides high amount plume around melted zone. Shielding gas rate also affective on decrease plume amount. High speed shielding gas rate decreases plume amount.

However, shielding gas main role prevents oxidation during welding. Because shielding gas is inert gas, it ruptures the air with melted zone relation. Only, high-speed rate of shielding gas can create spatter formation from melting zone. High blast rate above the melted zone can create spatter from melted material. Ejection term is the same meaning with spatter formation.

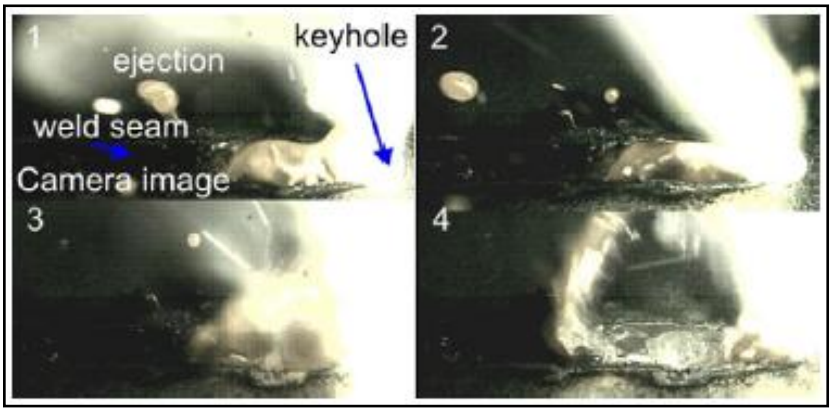


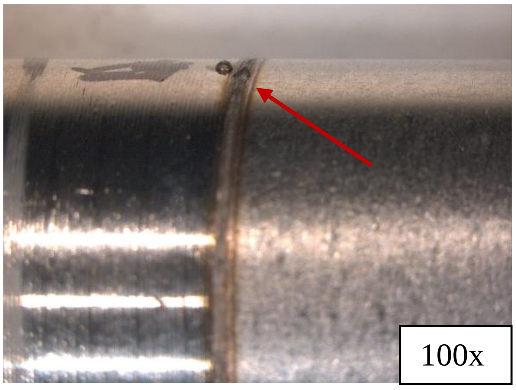
Figure 5.8 : Image of spatter (ejection) formation [22].

In addition, based on thesis the spatter formation was caused this clause “faster vaporization of cleaning chemical components than material components itself and higher cleaning chemical amount on the surface results in denser plasma formation these two phenomena are responsible for spatter formation” [22].

Based on trials, 105 parts welded which cleaned with 1,93% concentration NC 3300 and 105 parts welded which cleaned with 8% concentration NC 3300. Further, 15 parts welded, which were unclean parts, and 15 parts welded, which were cleaned with serial standard. 1,93% concentration and 8% concentration cleaning baths constituted difference cleaning chemical amount on the work piece surface for laser welded surface. 8% concentration cleaning bath formed higher chemical amount on the surface than 1,93% concentration cleaning bath. There was no observed spatter formation at the serial shielding gas rate and vacuum value after cleaning at 1,93% and 8% concentration. Contrary to thesis working, there was only one spatter formation after the 1,93% concentration cleaning bath. It was T.Par.5, which had these parameters; standard shielding gas rate and maximum vacuum value. Can be said that laser welding parameters, as vacuum value and shielding gas rate were more effective than chemical amount on the work piece surface to formation of spatter fault. Based on the thesis hypothesis, 8% concentration cleaning bath could spawn more spatter fault at laser-welded surface but there was not observed spatter formation at parts, which cleaned with 8% concentration cleaning bath.

After all trials obligation it can be said that, vacuum power above melt pool, shielding gas flow rate above melt pool and whirl rate of the pats during welding process caused to centrifugal power were main reason to formation spatter fault.

Figure 5.12 images were procured by Keyence stereo microscopy at 200x Leica stereo microscopy at 100x extension.



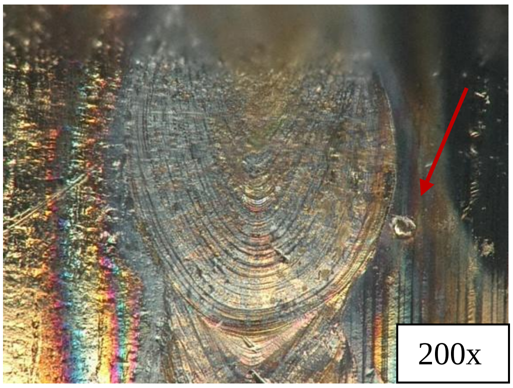


Figure 5.9 : Spatter formation images of T.Par.5 at 1,93% concentration cleaning bath.

Based on experiments obligations, these parameters affect sufficient depth of concretion point, width of welded surface, welded color and pores on welded zone and pore in welded structure.

Depth of concretion point at the length mould is described as ‘ET’ and width of welded surface is described as ‘NB’ at optic microscopy image.

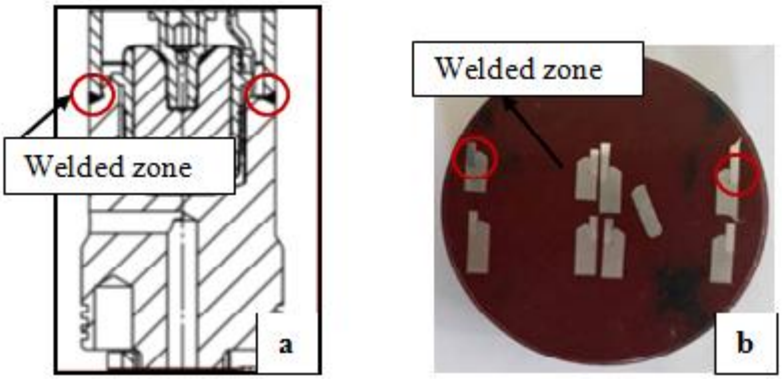


Figure 5.10 : a) Length mould description, **b)** Mould image.

Occurring of length mould description was part cut red arrow direction. Flat surface molded. Welded zone was at flat surface at mould.

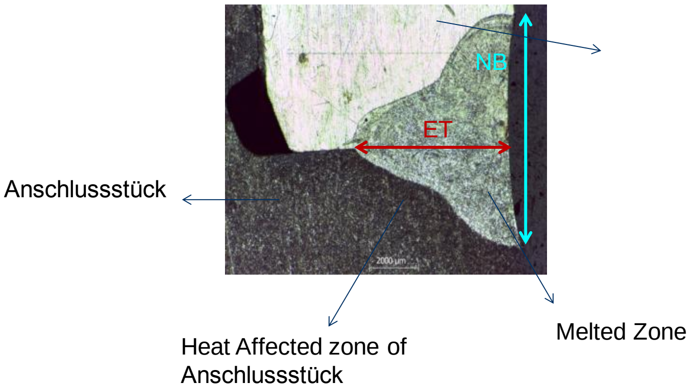
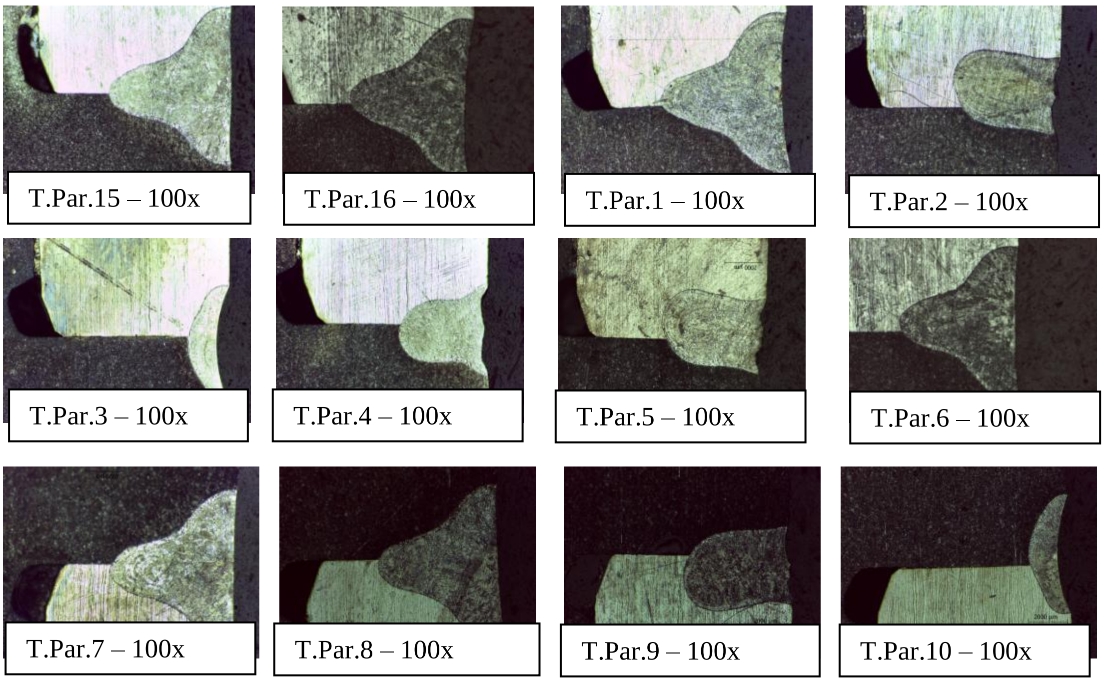


Figure 5.11 : Description of ‘ET’ and ‘NB’ term.



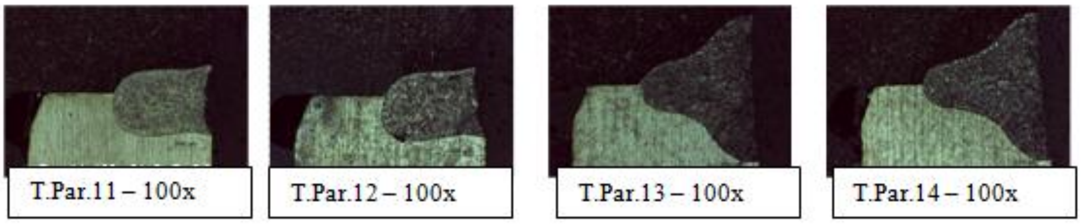


Figure 5.12 : ET and NB optic microscopy images from T.Par.1 to T.Par.16.

Two welded parts of each trial were investigated that 32 parts dropt forging at the length position later all mould images took by optic microscopy. Totally, 64 optic microscopy images were measured that every one forging created 2 NB and 2 ET values which were NB left – NB right and ET left – ET right.

Figure 5.12 shows laser welded microstructure and its measurement different at vacuum value variable and shielding gas rate variable. Influence of shielding gas zero or low, microstructure of welded zone has blunt point, short ET and NB value. This situation occurs at shielding gas rate equal to zero like in T.Par.2 – T.Par.4 – T.Par.9 – T.Par.11 or applied vacuum pulls the shielding gas like T.Par.12.

The same situation about short ET value forms vacuum value equal to zero like T.Par.3 and T.Par.10. Not only shielding gas rate equal to zero but also vacuum value equal o zero ET value is short. Difference between when vacuum value and shielding gas rate equals zero, NB value. When only situation of vacuum value equals zero NB value is longer than only shielding gas rate equals zero. T.Par.3 and T.Par.10 shows this difference. Mentioned all differences same with 1,93% concentration of cleaning bath and 8% concentration of cleaning bath. From experiment this comment can be made, chemical concentration difference of cleaning bath is not affecting laser-welded microstructure. Parameters of laser welding process are the most important to constitute the microstructure.

Maximum and standard shielding gas rate and vacuum value of laser welding parameters create optimum weld microstructure according to welding shape, ET and NB measurements.

At the low temperature about 35 ± 5 °C, cleaning process and its chemical effectiveness is not critical point to welding quality. Even the same comment applies to unclean parts of welded surface. Figure 5.12 shows T.Par.16 is unclean welded microstructure image and its NB and ET values in limit according to serial standard.

In addition, cleaned with 1,93% chemical concentration, 8% chemical concentration and at serial standard parts are the same welding microstructure at serial vacuum and shielding gas parameters.

General effects of laser welding process parameters can be summarized according to experiments results.

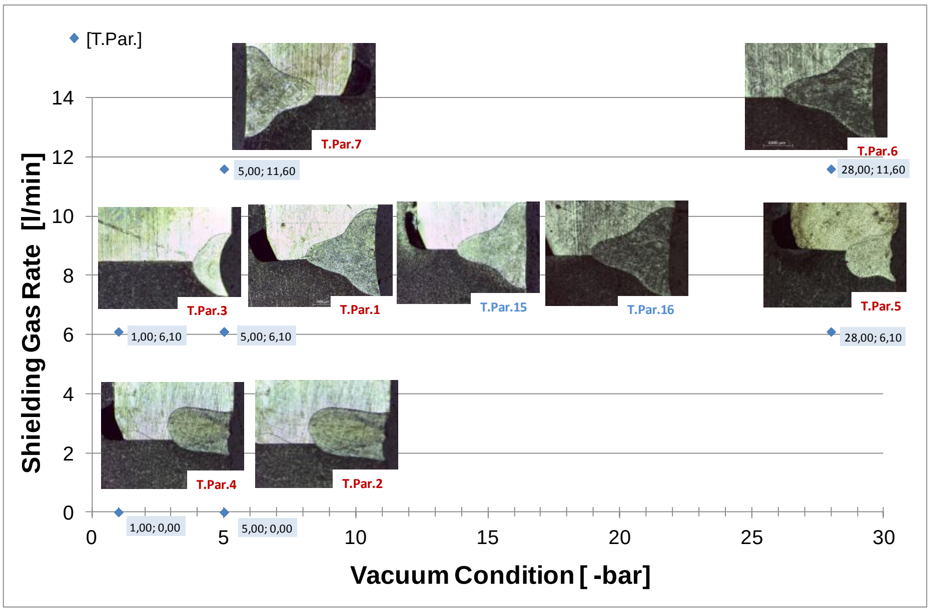


Figure 5.13 : Conversion of microstructure according to shielding gas and vacuum parameters which were cleaned at 1,93% concentration.

The type of experiments is referred by red, dark blue and light blue colors. Red color indicates 1,93% concentration of cleaning condition, dark blue is 8% concentration and light blue is cleaning condition of serial and unclean parts respectively.

At Figure 5.13, left number on blue rectangle indentifies vacuum condition and right number is shielding gas rate. There is three main microstructure images which are low ET melt pool at no vacuum with average shielding gas rate. Medium melt pool, which are T.Par.2 -4 and T.Par.5, which are under vacuum effect, but there is no shielding gas. In addition, the perfect keyhole mode which is made by optimum vacuum condition and shielding gas rate.

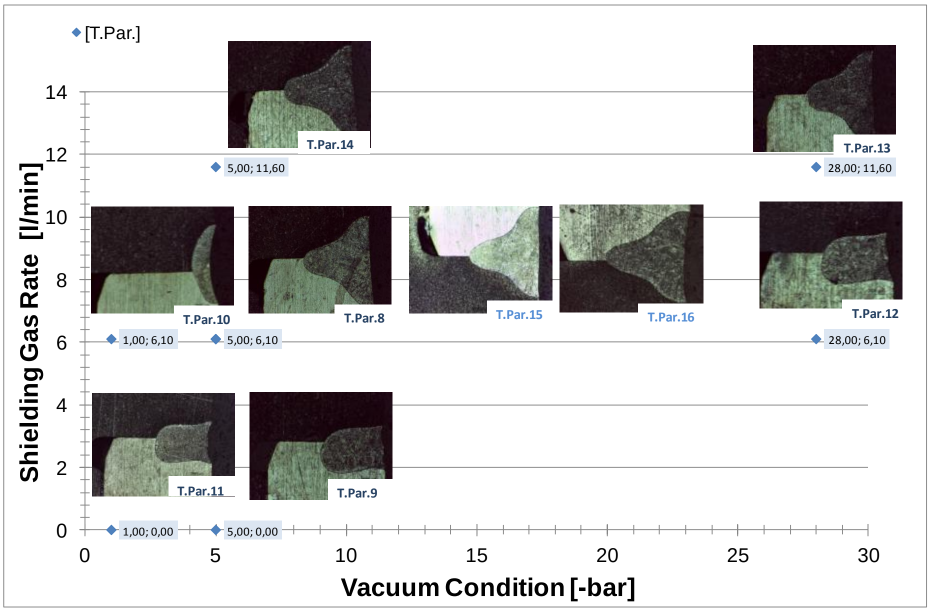


Figure 5.14 : Conversion of microstructure according to shielding gas and vacuum parameters which were cleaned at 8% concentration.

The all results of three images of 1,93% concentration experiments are the same with 8% concentration cleaning.

Figure 5.14 shows increasing of vacuum condition at the constant shielding gas rate, penetration of laser increase which means ET value increase. Addition, form of welded zone is sharply by the time about -20 bar vacuum value. After -20 bar vacuum value, vacuum power pulls the shielding gas. Consequently, penetration of laser decreases so ET value decreases and microstructure of welded zone' form started roundly.

At serial constant vacuum, it was -5 bar, shielding gas increased laser penetration increase so laser penetration increase and formation of microstructure started sharply. T.Par.2 – T.Par.1 – T.Par.7 had standard vacuum condition (-5 bar) and showed us welding microstructure formation changing. At minimum constant vacuum, it was – 1 bar, while shielding gas rate increased ET value so laser penetration ability decreased. Because plasma/plume formation above welds, pool could not be prevented. At this situation, vacuum power was not enough to pull plasma above melt pool so laser beam could not arrive the work piece zone during process and 'keyhole mode' could not complete. T.Par.4 and T.Par.3 images explain this situation. At maximum constant vacuum value, it was – 28 bars, while shielding gas rate increased ET value so laser penetration ability increased. Because plasma/plume formations above weld, pool could be prevented. At this situation, vacuum power was enough to pull plasma above melt pool. Keyhole mode could be completed. T.Par.5 and T.Par.6 images explain this situation.

Explained all steps of 1,93% concentration cleaned experiments were the same with 8% concentration cleaned. Figure 5.13 and Figure 5.14 tendencies were same at that topic was different concentration chemical cleaning parts welding result. That means, concentration difference of cleaning process was not affected at ‘ET’ value on laser welding area.

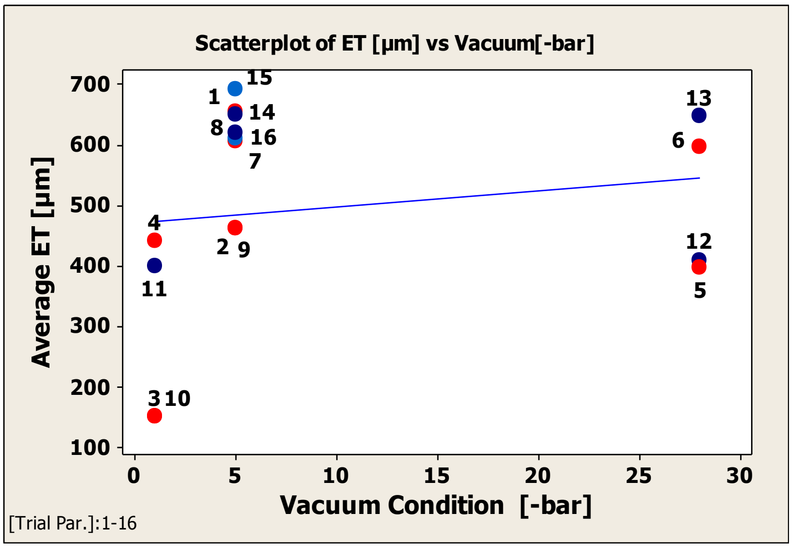


Figure 5.15 : Graph of vacuum condition via average ET value in order to interpret changing of ET value.

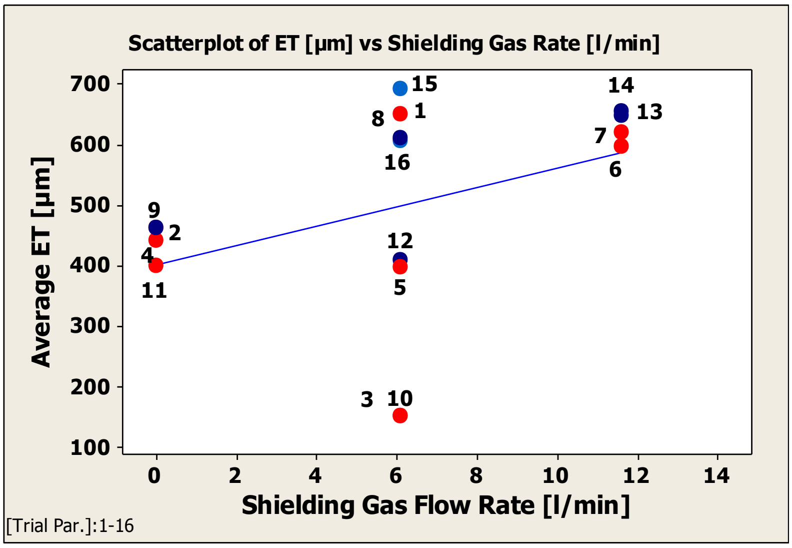


Figure 5.16 : Graph of shielding gas rate value via average ET value in order to interpret changing of ET value.

Graph of Vacuum Condition via Av.ET (Figure 5.15) and Shielding Gas Rate via ET (Figure 5.16) shows that, when vacuum was applied at max. or efficient level, applying of shielding gas rate was not important to ET result. That means vacuum is more efficient parameter than shielding gas rate in order to create deeper ET result.

When vacuum and shielding gas rate levels were zero, average ET result was ensured. In addition, without vacuum level, efficient shielding gas level was created minimum ET result.

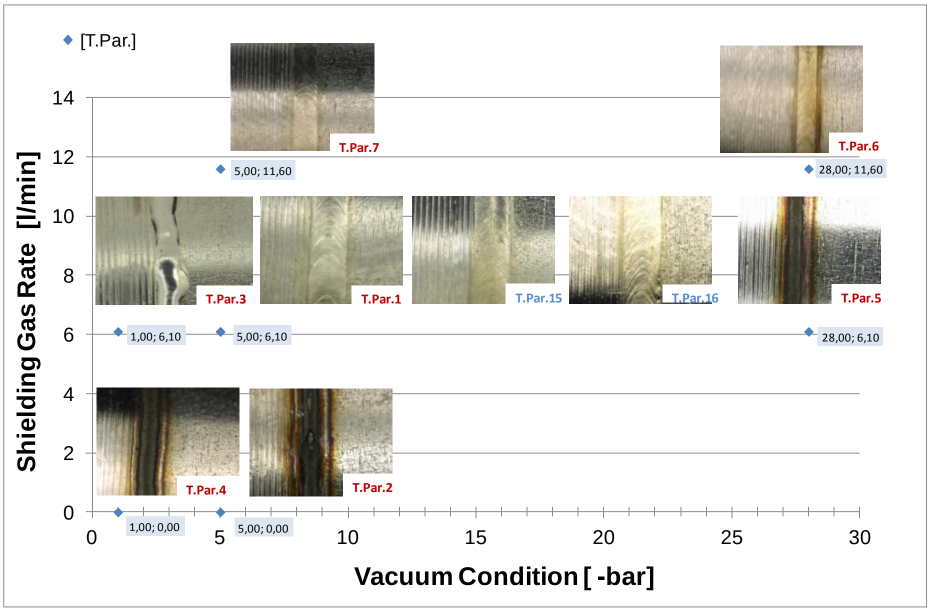


Figure 5.17 : Conversion of welded surfaces according to shielding gas and vacuum parameters which were cleaned at 1,93% concentration.

The same colors of referring microstructure were used at identifying of Figure 5.17 and Figure 5.18. Red color indicates 1,93% concentration of cleaning condition, dark blue is 8% concentration and light blue is cleaning condition of serial and unclean parts respectively.

Similar with microstructure images, surface of welding experiments have three main group which are shinny and straight, dark brown and burned, eruption and shinny structure.

Cleaning condition of 1,93% and %8 concentration are not showed differences on the surface images of welded zone according to change parameters of laser welding process. Results of all properties at the same condition of 1,93% concentration repeat for 8% concentration results.

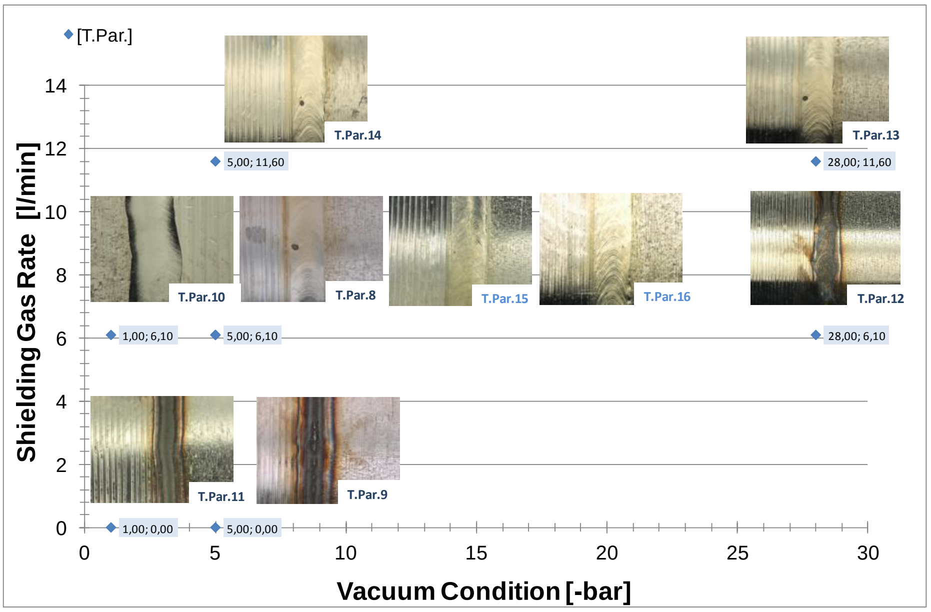


Figure 5.18 : Conversion of welded surfaces according to shielding gas and vacuum parameters which were cleaned at 8% concentration.

An addition, not only welded microstructure but also welded surface of part affected changing of vacuum value and shielding gas rate at the process. Low shielding gas rate constituted burned surface as T.Par.11 and T.Par.9. Because shielding gas is an inert gas, main function of shielding gas restrains oxidation during welding process. However, low gas rate was not sufficient to prevent oxidation formation at process.

Additively, low shielding gas rate realized low NB value on both microstructure and welded surface. Generally, when shielding gas increase, NB value increase and welded surface of work piece formed unburned, shiny appearance. Except T.Par.3 and T.Par.10, NB value was not increase with shielding gas rate because at these experiments vacuum and shielding gas rate interaction was not sufficient to annihilate plume/plasma formation. On the other hand, the keyhole mode also turned into limited mode due to insufficient laser beam because of flowing inert shielding gas. The mode of laser welding could not be maintained. At that point, vacuum condition can be understudied why important to generate depth melt pool during process.

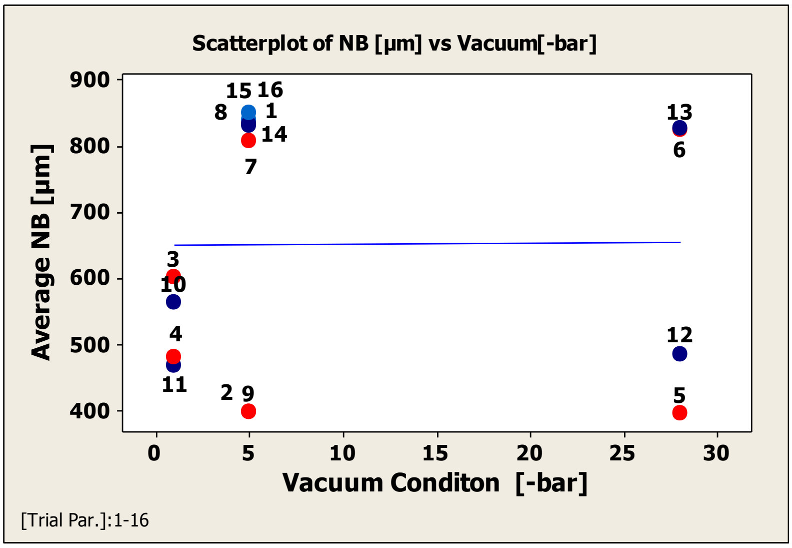


Figure 5.19 : Graph of vacuum value via average NB value in order to interpret changing of NB value.

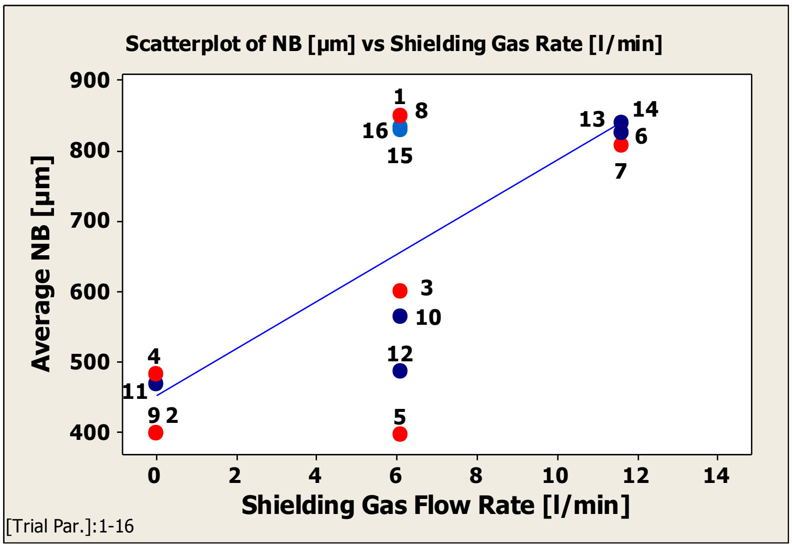


Figure 5.20 : Graph of shielding gas rate value via average NB value in order to interpret changing of NB value.

The NB results were a little different from ET results because, the effective parameter could be indicated itself at the graphs. Figure 5.19 and Figure 5.20 shows that, when shielding gas rate increased, NB value increased. Moreover, only if vacuum had increased; NB result would have not increased. The minimum NB value was created by vacuum less condition or high vacuum level, which was destroyed shielding gas effect to laser welding process. As a result, low temperature cleaning process and high concentration chemical bath were not important properties to laser welding quality to procure good quality welding result.

6. TESTS AND ANALYSES

Experiment results can be commented by tests and their analyses to true decision. Systematic changing of experiments can be recognized by test results and their analyses.

Analysis of 16 trials divided two subtitles. Cleanliness analysis realized after cleaning trial and microscopy analyses realized after laser welding. These analyses mentioned at 5.1 and 5.2 titles. Tensile test and salt spray test require attaching perspective at the results.

Tensile tests were done at Materials Engineering Department of Chemical – Metallurgical Faculty at Istanbul Technical University. Salt spray test was done at Robert Bosch Turkey – Gasoline Factory at Bursa.

6.1 Tensile Test and Analysis

The tensile test is probably the simplest and most widely used test to characterize the mechanical properties of a material. Tensile properties indicate how the material will react to forces being applied in tension. A tensile test is a fundamental mechanical test where a carefully prepared specimen is loaded in a very controlled manner while measuring the applied load and the elongation of the specimen over some distance. The main product of a tensile test is a load versus elongation curve, which is then converted into a stress versus strain curve.

Tensile tests are used to determine the modulus of elasticity, elastic limit, elongation, proportional limit, and reduction in area, tensile strength, yield point, yield strength and other tensile properties.

After laser, welding experiments tensile test was applied to 10 parts for each trial. Total 160 parts were used for the tensile test. Tensile test machine was DARTEC and its load capacity was 10 kN. Strain rate of tensile test was 1 mm/ min. It was slow pulling rate of the tensile test at this situation.

Figure 6.1 : Tensile test machine at ITU.

Tensile test specimens prepared distinctively. It has two shoulders and a section in between. The shoulders are large, whereas the section has a smaller cross-section so that the deformation and failure can occur in this area. Merely, specimens of tensile test can be different at mass production.

After aktorgehause and anschlussstück parts assembled with laser welded, this combined injector part had to use at tensile test machine. Therefore, this combined belongs to a mass production so some modification was made on it. Anschlussstück and aktorgehause welded part was unsuitability as test specimen so additional part which was 10 mm length and 15 mm diameter used to create tensile test specimen. Figure 6.2 (b) shows, this additional part smashed into the tip of aktorgehause after the welding process. Figure 6.3 shows, welded part could settle at chin of tensile machine to do test.

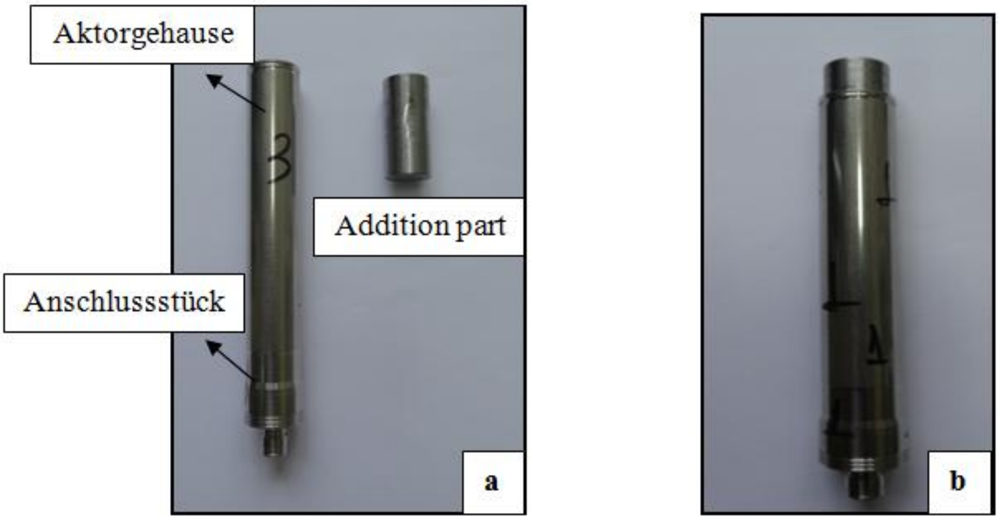


Figure 6.2 : Anschlusstück – Altorgehause combined part and addition part
a) Tensile specimen,
b) Modified combined part – tensile test specimen.

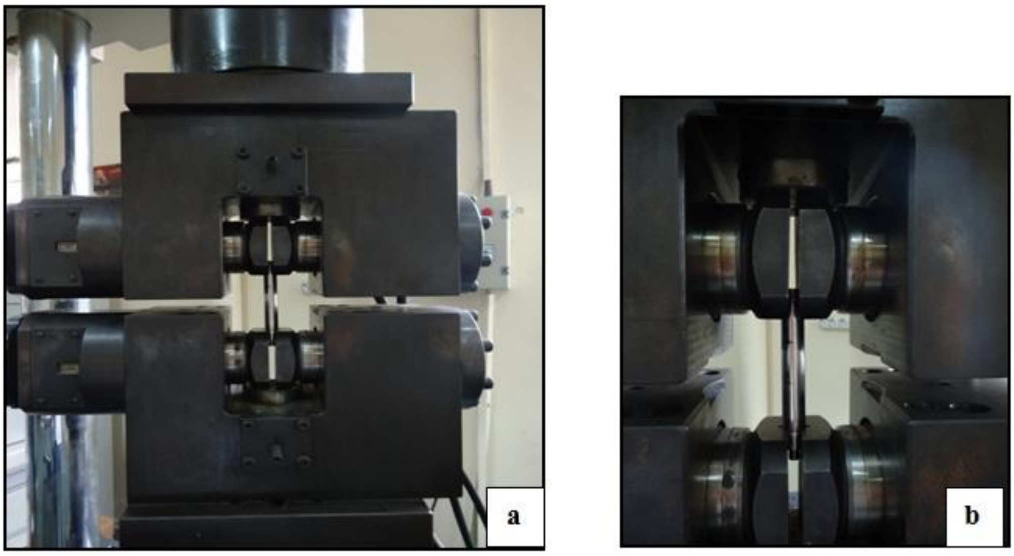


Figure 6.3 : Image of test specimen at tensile test,
a) Tensile test specimen,
b) Chin of tensile test.

Tensile test results divided two subgroup which were 1,93% concentration cleaned parts and 8% concentration cleaned parts. Thus, cleaning bath concentration effects distinguished from the tensile test results of 16 experiments.

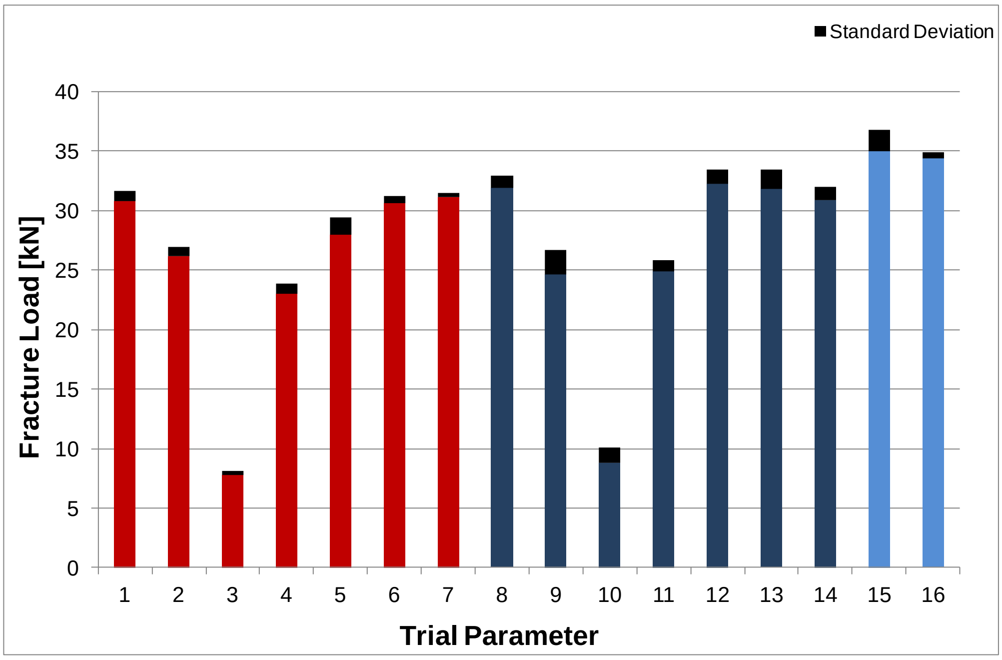


Figure 6.4 : Welded parts tensile test results of cleaned with 8% and 1,93% concentration cleaning bath.

The same colors refer to the same meaning through the experiments. Red belongs to 1,93%, dark blue 8% cleaning concentration and light blue refers serial standard and unclean parts respectively.

Fracture starts from discontinuity or deformation at microstructure or surface. Tensile test informed pore numbers of microstructure or surface, NB values effectiveness at welded zone.

Figure 6.4 got same tendency of tensile test results. Cleaned with serial standard, which was Surtec 89 + 533 chemical and 1, 93%, concentration-cleaning bath, T.Par.15 got the most high load results. This score range was between 30kN -35kN and exceeded the 35kN. T.Par.16 referred the unclean parts, their score range were close the cleaned with serial standard parts. The main investigation was T.Par.1 and T.Par.8 results. Both of them load ranges were same. That mean was concentration difference of cleaning bath did not affect laser-welding microstructure so laser welding quality. T.Par.5-T.Par.6-T.Par.7 and T.Par.12-T.Par.13-T.Par.14 had same load range it was about 30kN. Especially, T.Par.6-T.Par.7 and T.Par.12-T.Par.13 results indicated to remove plasma formation by shielding gas was more effective to laser welding quality. Their tensile test results were similar to T.Par.1, T.Par.8, T.Par.15 and T.Par.16. Except T.Par.5 and T.Par.12 all high load score results of experiments had same microstructure with serial so T.Par.15. That means, they had good laser penetration so high ET values. It can be said that, when ET value increases tensile load to fracture increases. In addition, their welded surfaces were unburned and good NB value.

T.Par.3 and T.Par.10 had minimum load score, which was between 5kN – 10kN. When reviewing their microstructure, they had minimum ET value. However their welded surface was the most shiny and good NB value but discontinues at the welded surface was more than other experiments.

T.Par.9 and T.Par.11 had middle ET value and NB value. Their microstructures were completely different from T.Par.1 and T.Par.8. Their welded zone was burned appearance. They had low NB values. Because during their welding process, shielding gas effect was zero.

Left measurement results of mould used for tensile test to ET and NB graphs. Dispersion of right measurement and left measurement on mould was same each other. This chose was made by irregular decision.

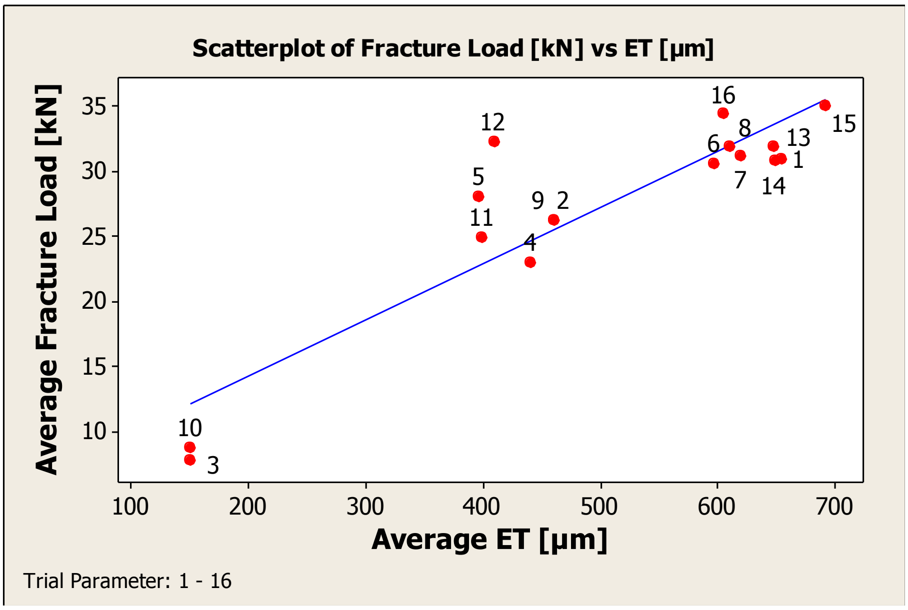


Figure 6.5 : Determine tendency at ET and tensile test load from Minitab.

Figure 6.5 shows that, when ET value increased, rupture delayed, load capacity increased of the tensile test. Laser penetration effectiveness increases ET value. If plasma/plume formation prevented, laser penetration ability would be increase.

T.Par.15 had the highest ET and load level. T.Par.8 was second range and T.Par.1 was the laser range among these. T.Par.15 identified serial standard which was cleaned with 1,93% concentration Surtec 533+89 chemical at 65 °C. Parts of T.Par.1 and T.Par.8 cleaned with NC3300 chemical at 35 °C. T.Par.1 was 1,93% concentration and T.Par.8 was 8% concentration at trial cleaning bath. Hence, this situation shows, while cleanliness increases, ET value and load capacity increase. However, this rise was not sufficient to affect welding quality.

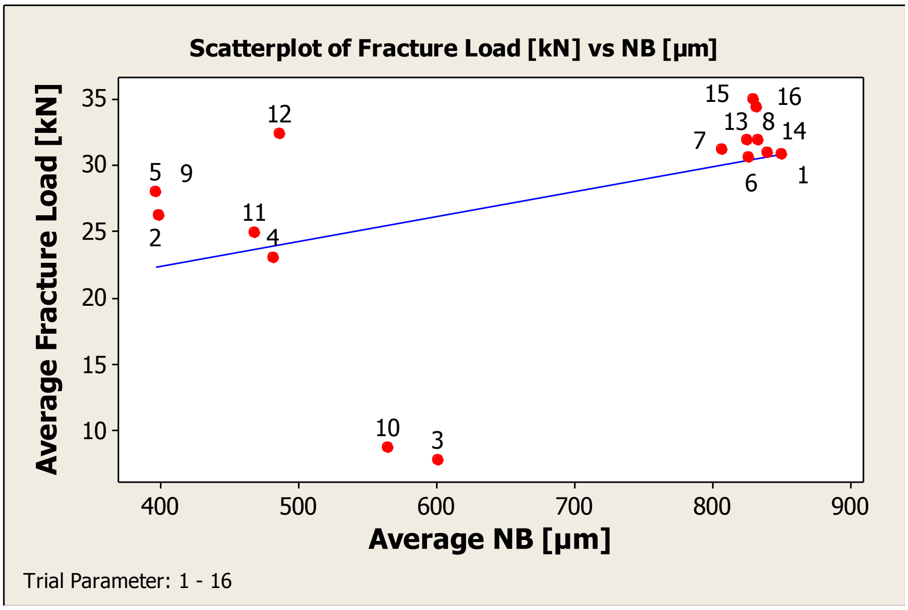


Figure 6.6 : Determine tendency at NB and tensile test load from Minitab.

T.Par.1 and T.Par.8, T.Par.6 and T.Par.1, T.Par.7 and T.Par.14 were the same shielding gas rate and vacuum value parameters during laser welding process. T.Par.8, T.Par.13 and T.Par.14 cleaned in 8% concentration bath, which were high concentration layer on the parts surface. They are more than 800µm NB value but, T.Par.1, T.Par.7 and T.Par.6 800µm or less NB value. 8% concentration cleaned parts had got more plasma formation during laser welding. This situation decreased ET value but increase NB values. Seeing that, laser beam could not penetrate toward plasma totally. When increase the plasma formation during welding, decrease the penetration property of laser beam. Thus, laser beams affected at surface of work piece during welding, NB value increased.

T.Par.3 and T.Par.10 shown similar situation about plasma formation and laser penetration relation. Their NB value sufficient good but ET values were not enough.

Only shielding gas applied during process but it was not affect to prevent the plasma formation.

Other Experiment types welded at low or zero shielding gas effect. Surface of laser welding burned so brown color. NB values were too low. Especially T.Par.2 and T.Par.9 had the minimum NB value. Their process parameters were same which standard vacuum power and 0 shielding gas rate. Thus, shielding gas rate was as same as effect with vacuum to prevent plasma formation. In addition, shielding gas rate was more effective than vacuum for NB formation.

Therefore, all graphs about ET and NB via Average Fracture Load shows, if ET increases, fracture load to rupture increases, otherwise; NB value does not effective on tensile strength.

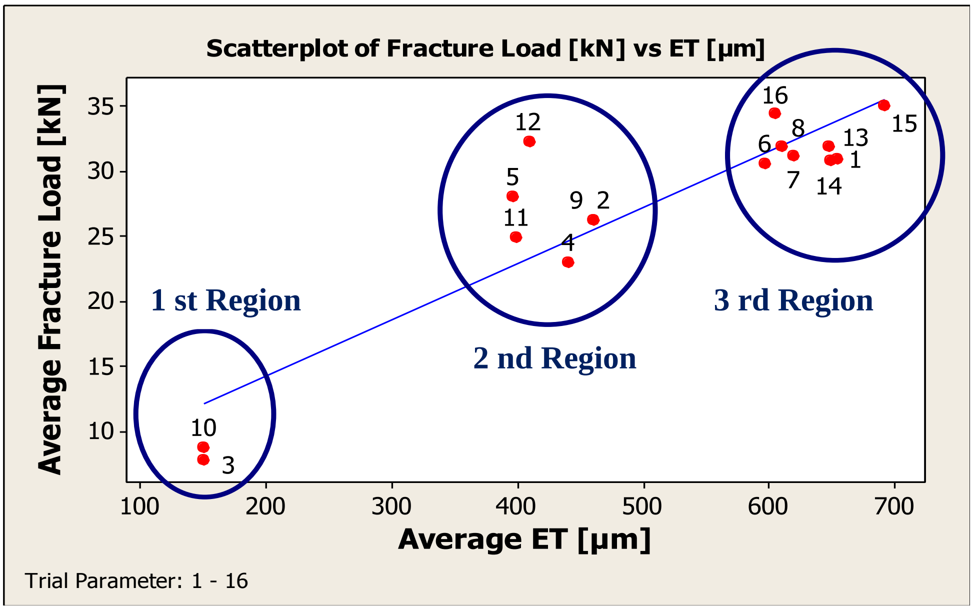


Figure 6.7 : General graph of average fracture load via ET.

At the first region, parts' ET was high and NB values were low. Thus, fracture load capacity was low and the surface of laser-welded region was shinny. Second region, ET result of part was average and low NB value. Thereby, average fracture load at second region was average result. In addition, laser surface of part was burned. Final region was third; part had high ET and NB result. Hence, fracture load level of part was high. Laser welded surface as it with first region, shinny.

There are some trial parameters tensile test graphs, which are T.Par.1, and 8, their concentration 1,93% and 8% respectively in addition, vacuum power 5 bar, shielding gas rate 6,10 l/min for both tensile test result of trial parameters. In addition, at the same laser welding parameters but different cleanliness condition tensile test results of trials, which are T.Part.15 and T.Part.16, were shown. The main differences were cleanliness results due to cleaning process's of trials. Consequently, 4 graphs were cleaned at 1,93% and 8% concentration; unclean and cleaned at serial standard were shown at the same laser welding parameters.

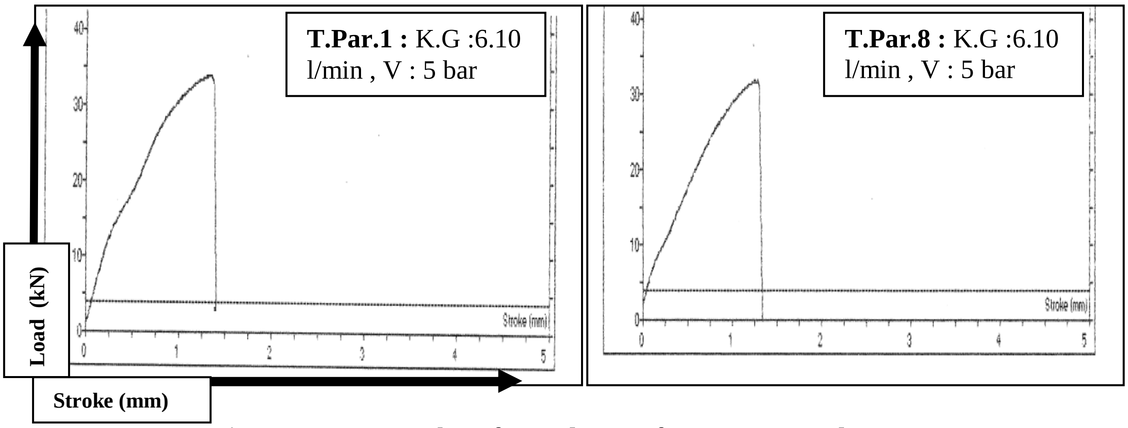


Figure 6.8 : Graphs of tensile test for T.Par.1 and T.Par.8

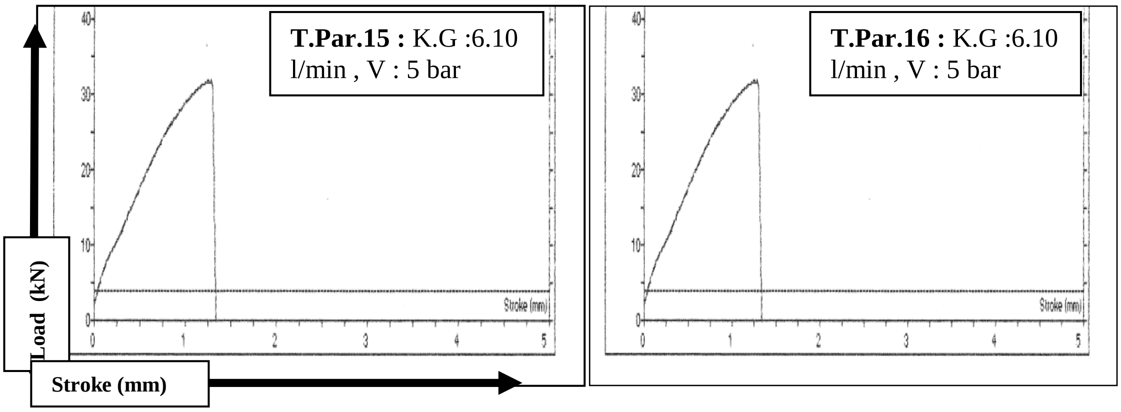


Figure 6.9 : Graphs of tensile test for T.Par.15 and T.Par.16

Whatever their cleanliness result and cleaning process condition, the results of tensile test were almost same, slightly bigger than 30kN for all T.Par. The result was indicated fracture at about 32 -33kN range. In addition, near 10kN, there was a curve was different from elastic limit range at strain-stress graph. This curve was evaluated as a welding zone fracture behavior because of different kind of stainless steel welded each other.

For instance, 1.93% and 8% concentration cleaning but different welding condition trials which T.Par.3 and T.Par.10 were shown completely different result. Vacuum power was 1 bar; shielding gas was 6,10 l/min during trials. These trials have the minimum ‘ET’ value throughout all trials so they were chosen to be experiment for the tensile tests graph at different parameter condition during laser welding.

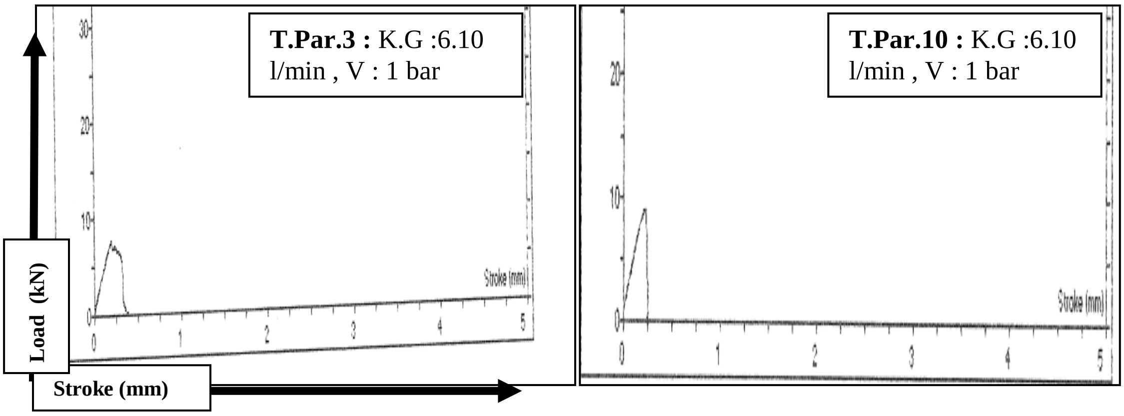


Figure 6.10 : Graphs of tensile test for T.Par.3 and T.Par.10

The fracture was shown at below 10kN for both of T.Par. types. These results considerably different from other T.Par. experiments that have bigger ‘ET’ value than T.Par.3 and T.Par.10. The other parameter correlations of trials have not formed as much as lower T.Par.3 and 10 conditions so the fracture range of tensile tests did not be as a Figure 6.9. This was happened by lower ‘ET’ value after welding.

The ‘ET’ effectiveness can be shown at these images, which belong fracture surface of welded parts after tensile test.

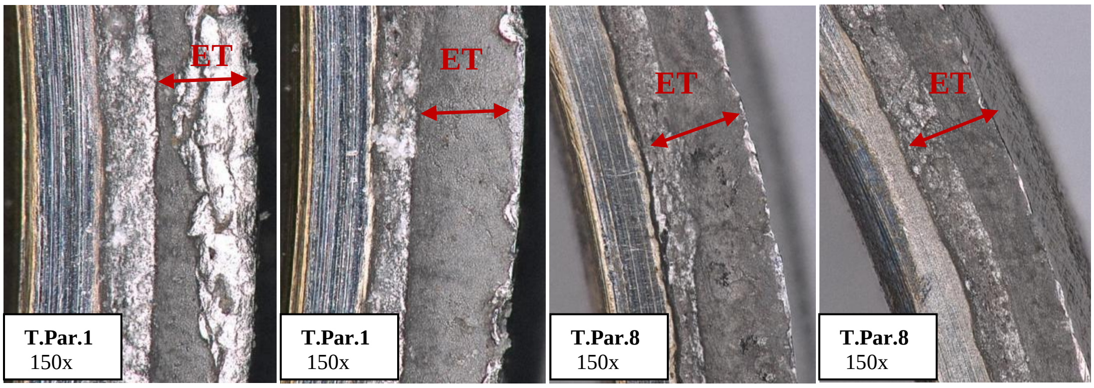


Figure 6.11 : Fracture surface of T.Par.1 and T.Par.8

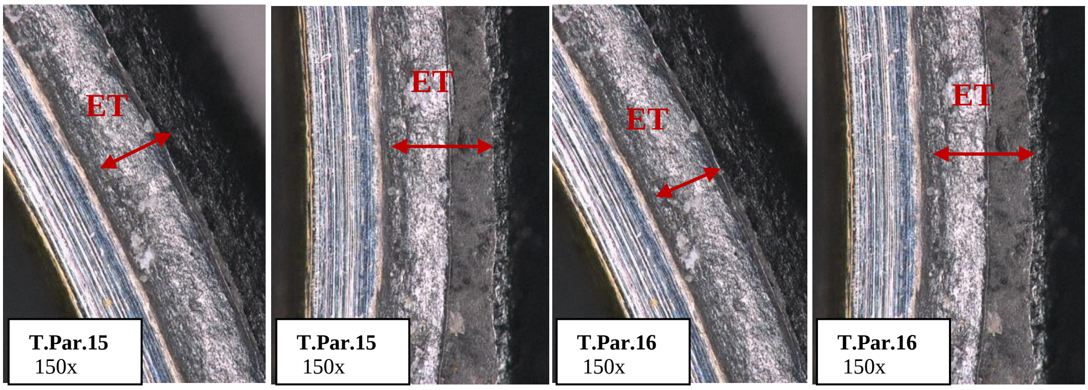


Figure 6.12 : Fracture surface of T.Par.15 and T.Par.16

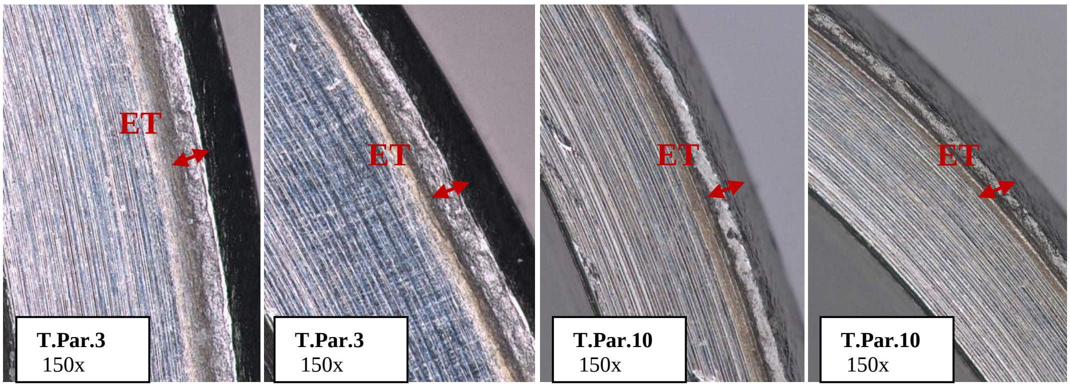


Figure 6.13 : Fracture surface of T.Par.3 and T.Par.10

'ET' differences were shown clearly at the images especially Figure6.12. The lowest 'ET' value can be seen hardly at T.Par.3 and 10. On the other hand, Figure 10 and Figure 11 images were similar each other due to different cleanliness situation because of different cleaning process. The main reason of differences between tensile strength levels were 'ET' value at trials.

6.2 Salt Spray Test and Analysis

Salt spray test occurred at Gasoline Factory of Robert Bosch Turkey- Bursa. Salt spray test provided to realize corrosion ability of parts. Salt spray test aim was created corrosive zone to parts.

Figure 6.14 : Salt spray test machine.

Aktorgehause made by 304 austenitic stainless steel and anschlussstuk made by 415 M martensitic stainless steel. In order to realize such an austenitic microstructure, steels are primarily alloyed with the element nickel. Besides the stabilization of the cubic-face-centered austenitic grain, structure nickel increases the corrosion resistance of a stainless steel in non-oxidizing acids. [27] Salt spray test process parameters were 2, 9 g/ l salt concentration and 35°C during 14 days. Tests applied 16 different condition welded parts.

Figure 6.15 : Parts image after salt spray test.

If shielding gas affected during laser welding process welded zone of the part surface would be shinny, metal color and unburned. T.Par.15 – T.Par.16 – T.Par.1 – T.Par.6 – T.Par.7 – T.Par.8 – T.Par.13 and T.Par.14 were not shown corrosive results after salt spray test on the welded zone. Although, T.Par.3 and T.Par.10 had shinny and unacceptable form surface at the welded zone, it was not shown corrosive effect.

Figure 6.3 shown T.Par.3 and T.Par.10 salt spray test result.

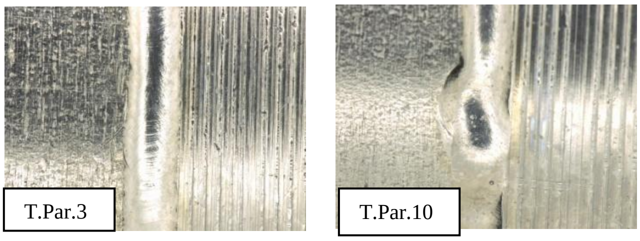


Figure 6.16 : Salt spray test result of T.Par.3 and T.Par.10

T.Par.2 – T.Par.4 – T.Par.5 – T.Par.9 – T.Par.11 – T.Par.12 were shown corrosive result because their welded zone surface had duty.

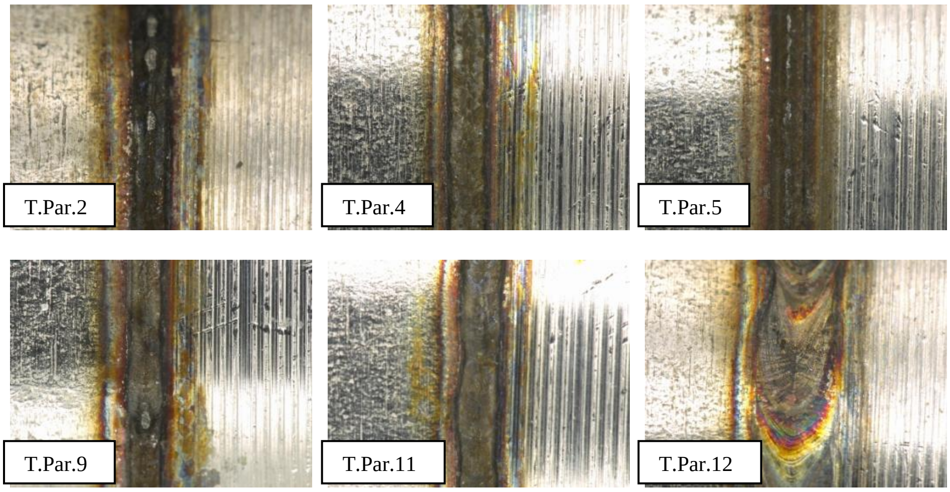


Figure 6.17 : Salt spray test results of T.Par.2 – T.Par.4 – T.Par.5 – T.Par.9 – T.Par.11 – T.Par.12

Experiments of at Figure 6.4 did not affect shielding gas during laser welding so their welded zones burned and dull. After salt spray test, their burned surface connected parts had duty.

Table 6.1 : Chemical composition of 304 stainless steel aktorgehause part [29].

C	S	P	Si	Mn	Cr	Ni	N	Cu
0.05	0.025	0.03	0.40	1.8	18.2	8.0	0.080	0.40

Table 6.2 : Chemical composition of 415 M stainless steel anschlussstuck part [28].

C	S	P	Si	Mn	Cr	Ni	N	Mo
0.04	0.003	0.025	0.40	0.80	15.0	4.60	0.050	0.80

Table 6.3 : Part of trials EDX results.

T.Par.Number	C	O	Si	Cl	V	Cr	Mn	Fe	Ni	Total
T.Par.4 – 1	3.20	9.62	2.43	0.33	0.43	33.51	7.23	40.52	3.06	100.00
T.Par.4 – 2	3.41	9.41	2.52	0.30	0.43	33.70	7.56	39.84	3.12	100.00

T.Par.5 – 1	4.21	7.47	2.43	0.34	0.45	35.50	9.24	37.28	3.29	100.00
T.Par.5 – 2	3.76	7.15	2.36	0.38	0.45	39.69	11.28	32.21	2.73	100.00
T.Par.11 – 1	3.37	11.40	2.19	0.32	0.36	31.20	8.28	40.45	2.44	100.00
T.Par.11 – 2	3.45	11.22	2.08	0.35	0.42	31.48	8.43	40.02	2.54	100.00
T.Par.12 – 1	1.63	3.65	0.92	-	-	17.62	1.89	67.80	6.49	100.00
T.Par.12 – 2	1.36	3.46	0.84	-	-	18.02	1.94	68.30	6.07	100.00

EDX analysis could be done by scanning electron microscopy and irregular point on the welding surface. T.Par.5 – T.Par.11 – T.Par.4 – T.Par.12 chose for the EDX analysis because of burned welding surface. Besides duty image on the burned welded surface, Cl element result from the EDX analysis proved the corrosion effect of the without shielding gas welding experiments. Result of this test could be said that, shielding gas prevented corrosion at laser welding assembly process.

6.3 Hardness Test and Analysis

Laser welding offers fast processing and low heat input, which allows joining thin walled steel parts at negligible thermal deformation. [26] Low heat input provides changing of microstructure at small area. That means, heat affected zone is small. To show heat affected zones and welding one's hardness difference hardness test applied. Figure 6.5 shows different welding zone structure measurement points. Standard was occurred to measurement for similar welding structure. Total 8 points measured at one microstructure. Left side mould of 16 parts measured.

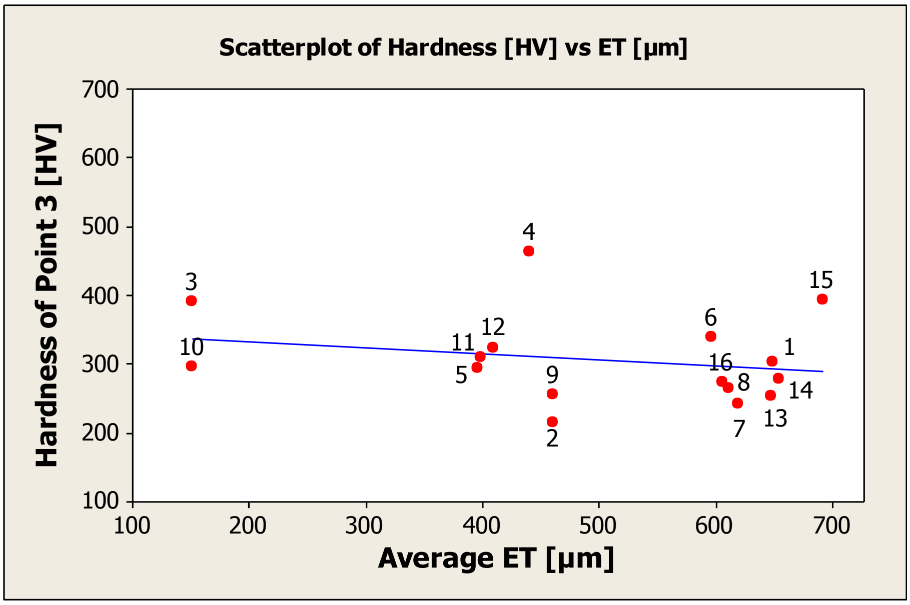


Figure 6.18 : Total hardness results of 3rd point.

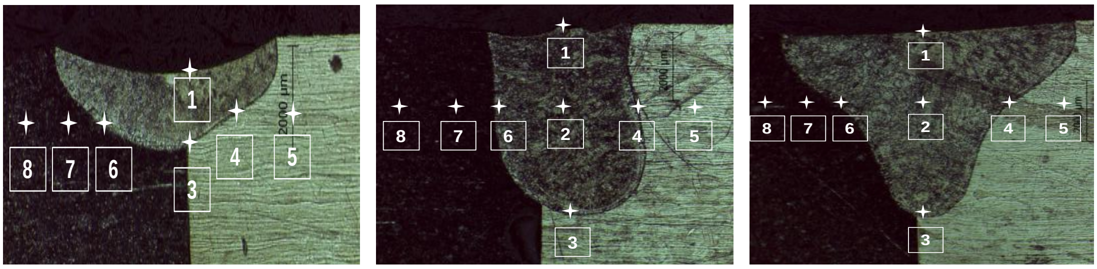


Figure 6.19 : Points of hardness measurement.

Hardness of all parts 3rd point which was tip of the laser-welded zone, selected to create ET and hardness graph. Since, top point could be interpreted ET's hardness changing behavior. Figure 6.12 shows, when ET increased hardness value decreased. This situation can be commented that ET increases, decreases hardness result generally due to high interaction between laser beam and microstructure of stainless steel during welding process. All 3-point comments are only assumption that attribute to general laser welding mode physics.

However, the hardness and laser welding 'ET' value have no relation between each other. The hardness values of laser-welded zone have no give reasonable result about process quality or effective.

Other individual points versus hardness values results were given at Appendix B.

7. CONCLUSION AND RECOMMENDATION

In the scope of this project the effect of cleaning process and welding parameters on the welding quality of injection parts were systematically examined.

The limits of validity of low temperature cleaning process have been investigated by counting amount of particle and analyzing the quality of laser welding. The amount of particle on cleaned part presented in this work indicates possibility of low temperature cleanin ıinstead of high temperature conventional cleaning process. The study has mainly focused on laser welding quality by changing cleaning condition and parameters of laser welding process. The results of laser welding process have demonstrated that vacuum condition and shielding gas rate are efficient to create keyhole mode at melt pool. Effective correlation of shielding gas rate and vacuum condition forms depth of melt pool (ET) whereas exclusively shielding gas rate increases bonding surface (NB) of welding. In addition, results of tensile test remark that fracture load of welded part frequently depend on ‘ET’ value. However, hardness of welded and its surrounding zone did not change in proportion to ‘ET’. Moreover, in salt spray test, the shiny surface of welded zone has not showed evidence corrosive attack which is formed by effective shielding gas rate condition.

Results of laser welding inspection after cleaning the samples at low temperature condition showed sufficient quality.

In conclusion, the parameters of laser welding process on quality of surface of parts are determining factor than the cleanliness.

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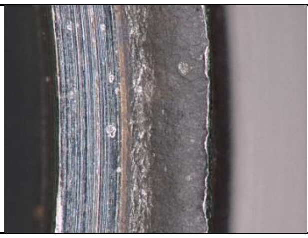
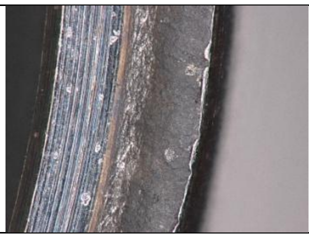
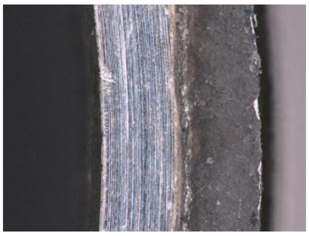
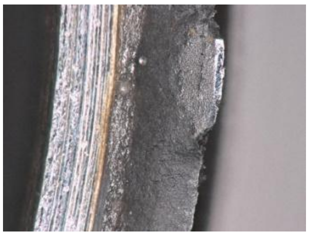
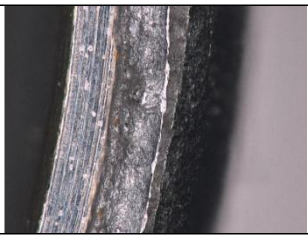
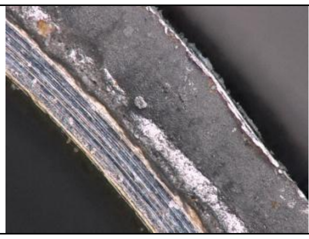
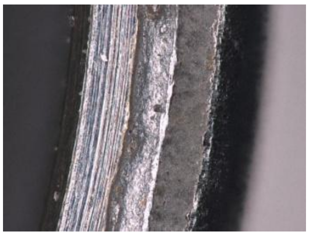
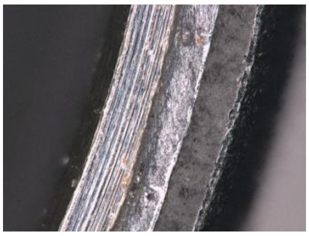
APPENDICES

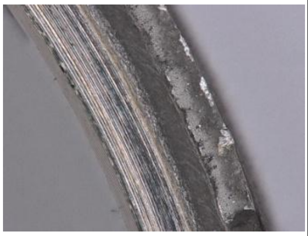
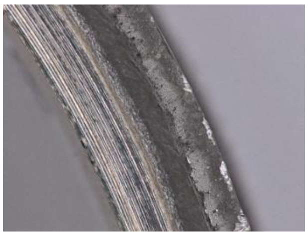
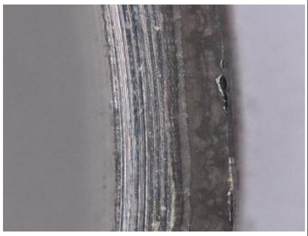
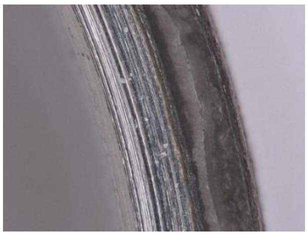
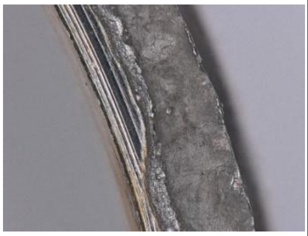
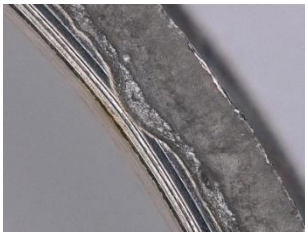
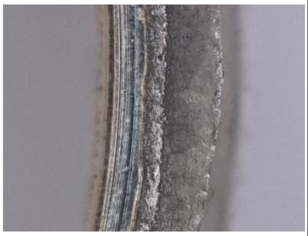
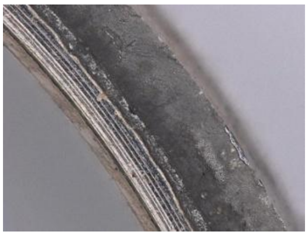
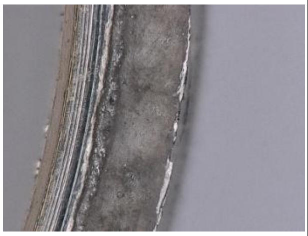
APPENDIX A: Welded parts fracture surface stereo images after tensile test.
APPENDIX B: Welded parts fracture surface SEM images after tensile test.
APPENDIX C: Hardness versus Average ET value graphs.
APPENDIX C: Tensile test graphs.

APPENDIX A

Appendix A.1 : Welded parts fracture surface stereo images after tensile test.(expansion 150x).

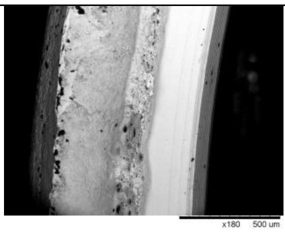
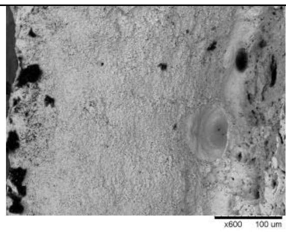
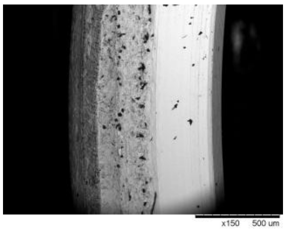
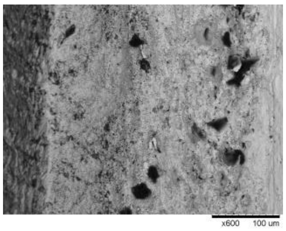
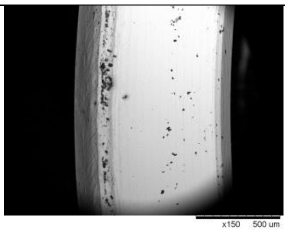
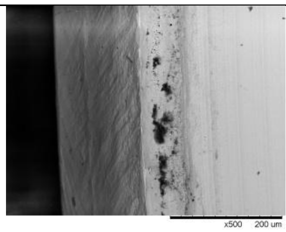
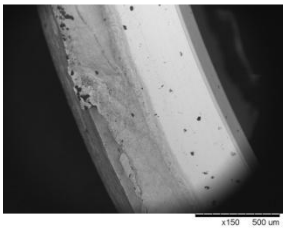
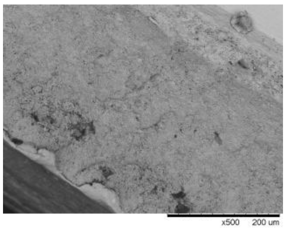
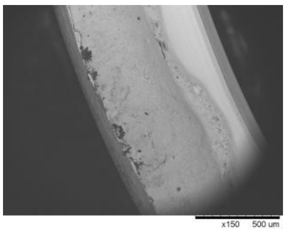
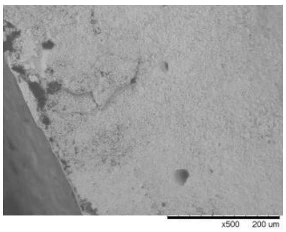
Cleaned Parts with 1.93% concentration		
T.Par.	Fracture Surface Image	
2		
4		
5		
6		
7		

Appendix A.1 (continued) : Welded parts fracture surface stereo images after tensile test.(expansion 150x).

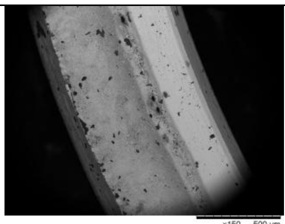
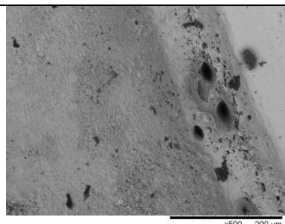
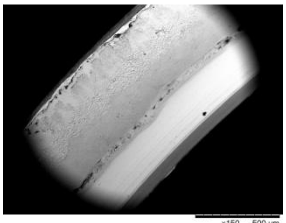
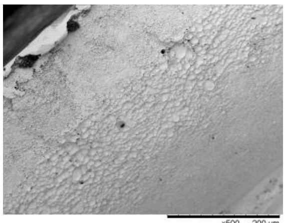
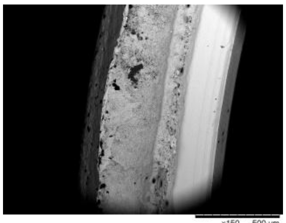
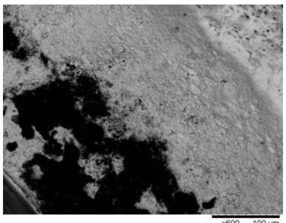
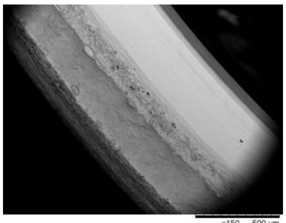
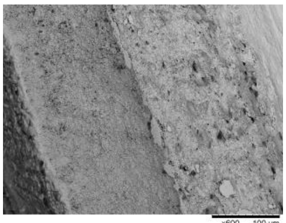
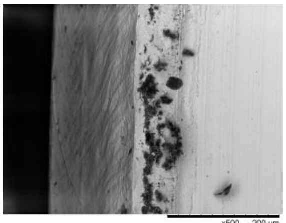
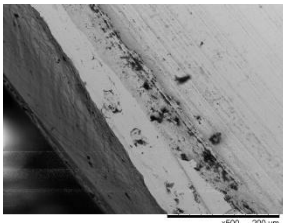
Cleaned Parts with 8% concentration		
T.Par.	Fracture Surface Image	
9		
11		
12		
13		
14		

APPENDIX B

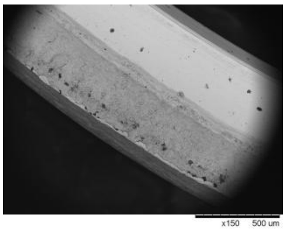
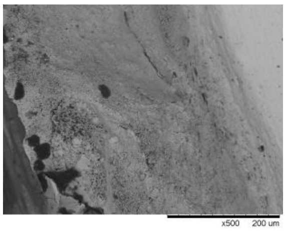
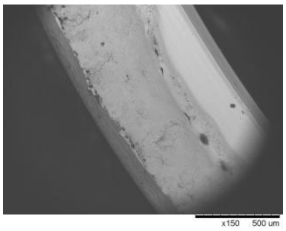
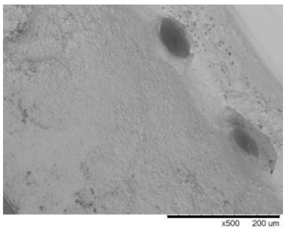
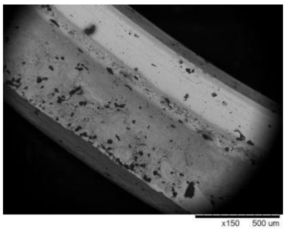
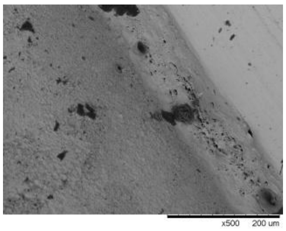
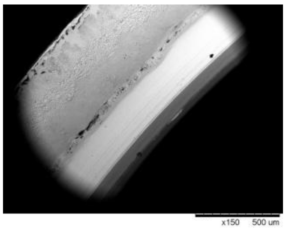
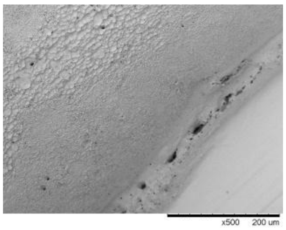
Appendix B.1 : Welded parts fracture surface SEM images after tensile test.

Cleaned Parts with 1.93% concentration				
T.Par.	Exp.	Fracture Surface Image	Exp.	Fracture Surface Image
1	150x		600x	
2	150x		600x	
3	150x		**600x**	
4	150x		500x	
5	150x		500x	

Appendix B.1 (continued) : Welded parts fracture surface SEM images after tensile test.

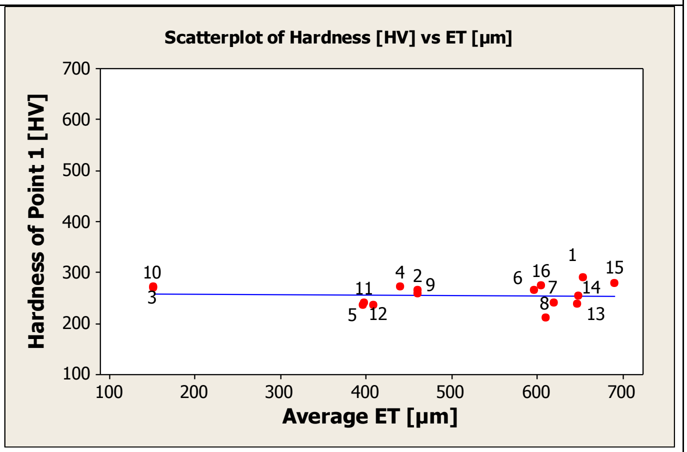
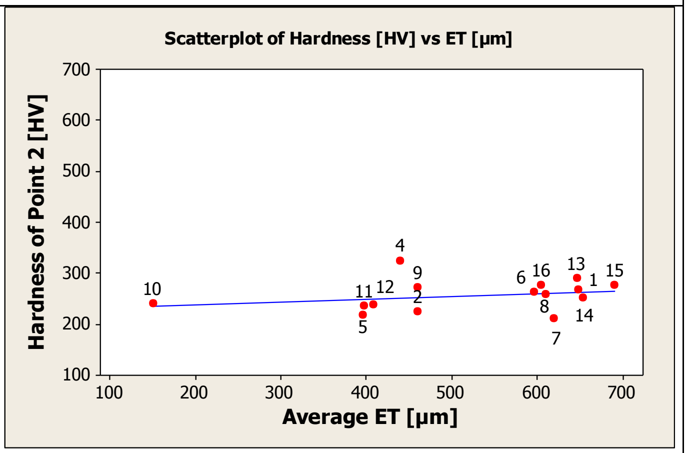
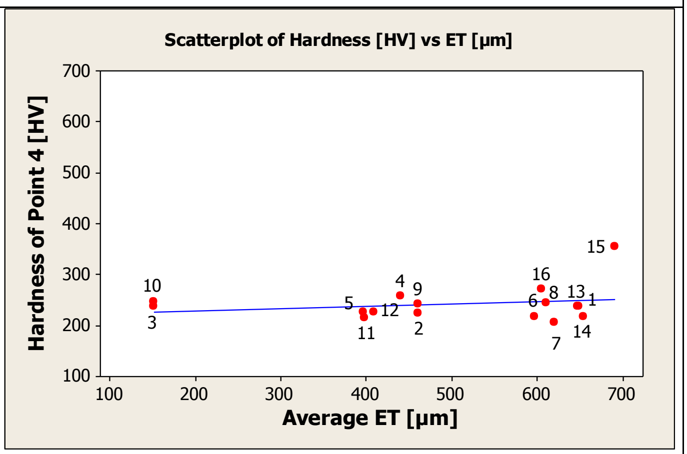
6	150x		500x	
T.Par.	Exp.	Fracture Surface Image	Exp.	Fracture Surface Image
7	150x		500x	
Cleaned Parts with 8% concentration				
T.Par.	Exp.	Fracture Surface Image	Exp.	Fracture Surface Image
8	150x		500x	
9	150x		500x	
10	150x		500x	

Appendix B.1 (continued) : Welded parts fracture surface SEM images after tensile test.

11	150x		500X	
2	150x		500x	
13	150x		500x	
14	150x		500x	

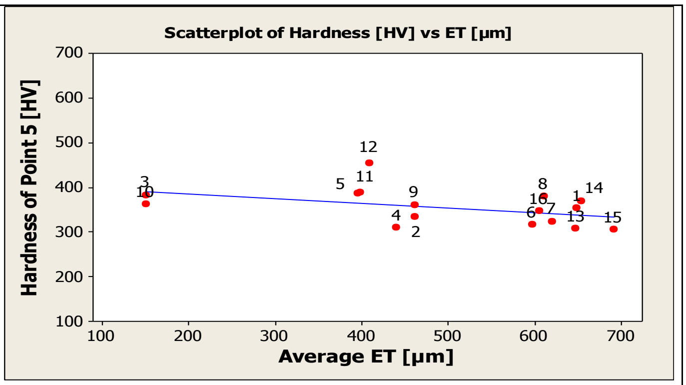
APPENDIX C

Appendix C.1 : Hardness versus Average ET value graphs.

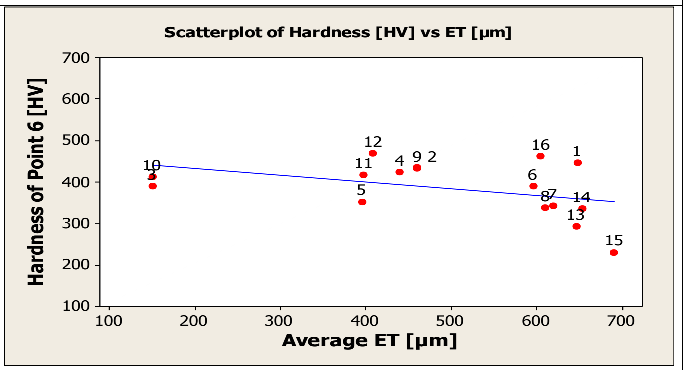
<table>
<tr><th>Hardness of Point.</th><th>Hardness versus Average ET value Graph</th></tr>
<tr><td>1</td><td>
</td></tr>
<tr><td>2</td><td>
</td></tr>
<tr><td>4</td><td>
</td></tr>
</table>

Appendix C.1 (continued) : Hardness versus Average ET value graphs.

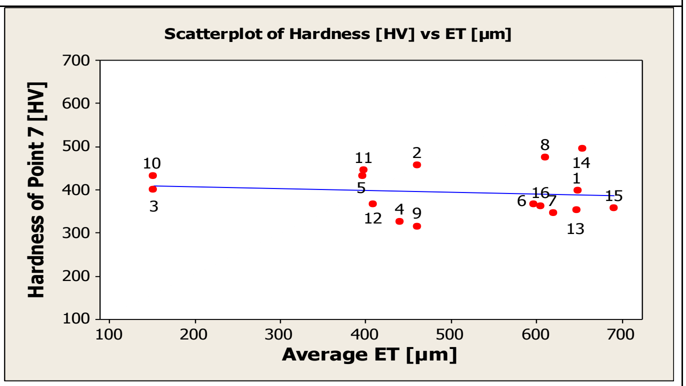
5



6



7



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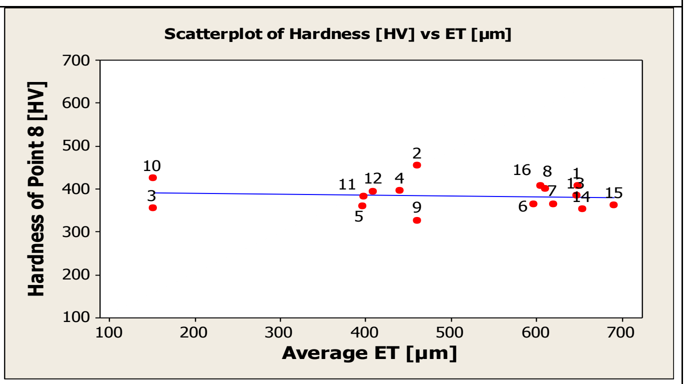
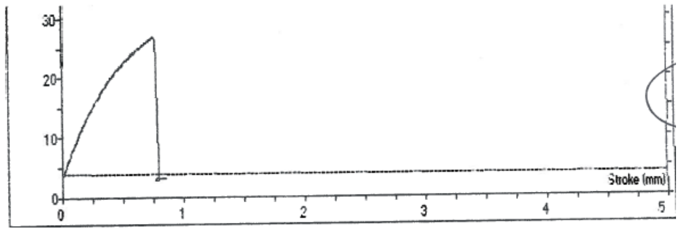
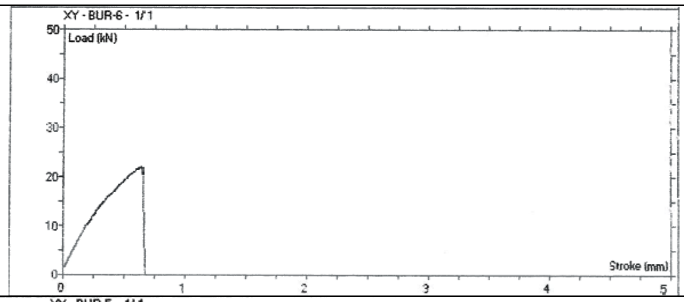
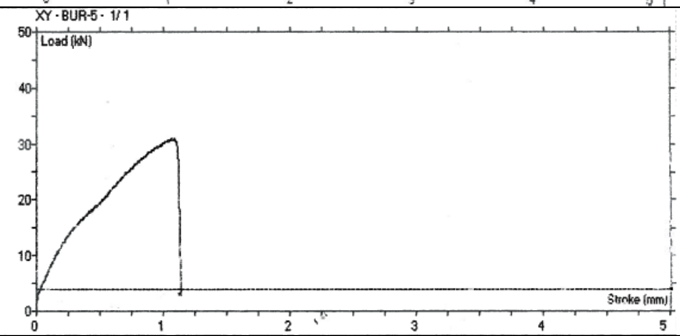
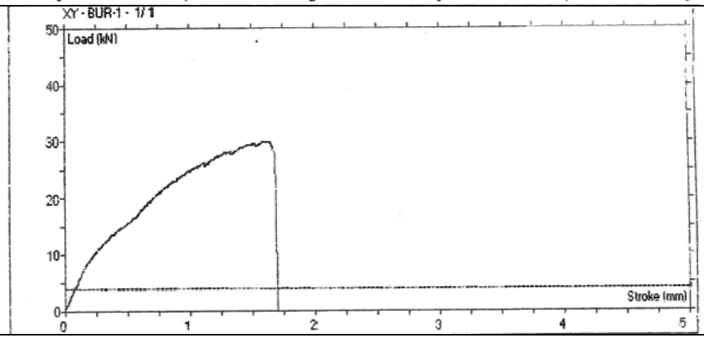
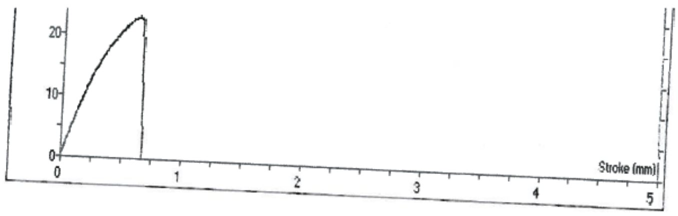
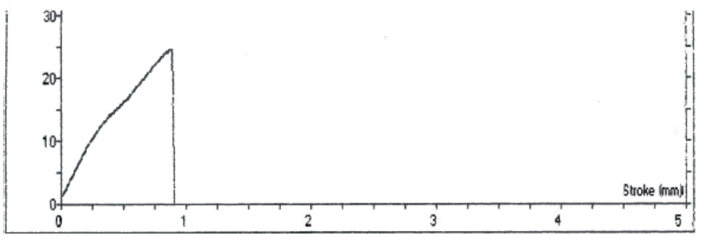
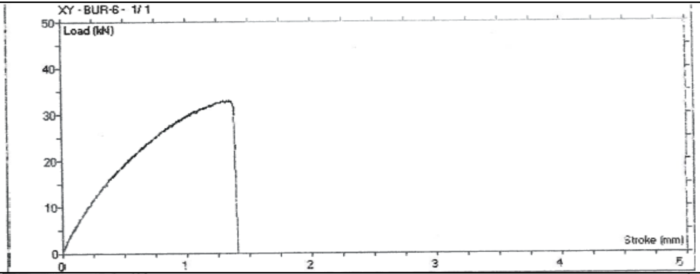
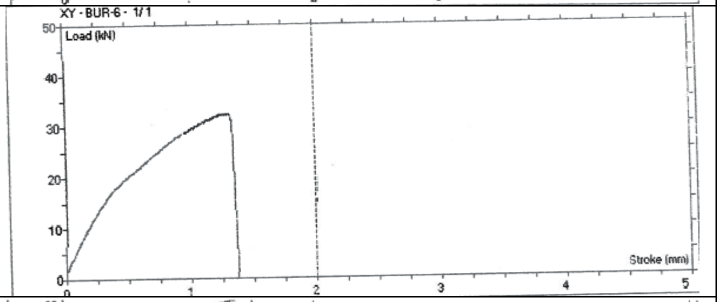
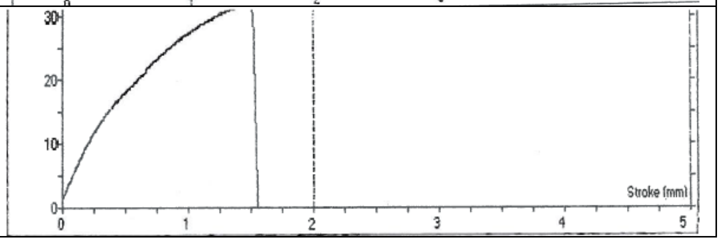


APPENDIX D

Appendix D.1 : Tensile test graphs.

T.Par.	Graph
2	
4	
5	
6	
9	

Appendix D.1 (continued) : Tensile test graphs.

11	
12	
13	
14	

CURRICULUM VITAE

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