INVESTIGATION OF COLD WELDING AT STEEL-ALUMINUM COMBINATIONS VIA EXTRUSION PROCESS USING THERMO-MECHANICALLY COUPLED FINITE ELEMENT ANALYSIS

EKSTRÜZYON PROSESİ VASITASIYLA ÇELİK-ALÜMİNYUM KOMBİNASYONLARINDA SOĞUK KAYNAK OLUŞTURULMASININ TERMO-MEKANİK BAĞLI SONLU ELEMANLAR ANALİZLERİ İLE İNCELENMESİ

AKİF YALDIZ

Asst. Prof. MEHMET OKAN GÖRTAN

Supervisor

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ABSTRACT

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Akif YALDIZ

Master of Sciences, Department of Mechanical Engineering

Supervisor: Asst. Prof. Dr. Mehmet Okan GÖRTAN

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In this century, the importance of weight reduction studies has been increasing day by day, and the importance of hybrid structures have also increased. Especially, reducing the weight in aviation and automotive industries, emission rates can be reduced, costs can be reduced and also, more sustainable structure are created. Accordingly, cold welding method applied in extrusion process is an effective method to form hybrid structures. Although the cold welding process starts at room temperature, it reaches up to185 °C values formed between the parts. When the literature is examined we see that, the effect of treatment, surface enlargement and contact normal stresses between the materials were investigated by experimental and finite element method. However, these studies were done either mechanically or thermally. In this study, the contact normal stresses between the materials, surface enlargement values and temperature effect of material flow were examined by thermo-mechanical finite element analysis. Actually parameter effecting cold welding is investigated by thermo-mechanical finite element analysis. For this purpose, the properties of EN AW-6082 T6 and C10 (1.0301) plain carbon steel materials were tested by compression test and the parameters of Johnson-Cook material model were obtained and these parameters were implemented in a finite element model. The shape of the sample is cylindrical. The core of the cylindrical part is made of aluminum and the outer part is made of steel. The outer diameter of the used steel material is 15 mm. Diameters of aluminum materials are 6.5 mm, 7.5 mm and 8.5 mm. Cylinder materials were extruded to 11.1 mm and 9.6 mm, corresponding to 0.6 and 0.9 strain values, respectively. In addition, the materials were extruded at 30 °, 45 ° and 60 ° die angles. In this study, different plastic strain values, different die opening angle values, surface enlargement and contact normal stresses formed between the aluminum and steel parts were investigated thermo-mechanically by using finite element analysis. When the results are investigated, temperature of the materials are higher at high strain. In addition, maximum temperature is seen at exit of the deformation zone. When die angles are examined, on the aluminum part there is no significant effect but there is a significant effect on the steel part. Temperature of steel part increases by increasing die angle. Furthermore, there is any effect on material temperature when the heat treatment effect is investigated. Contact normal stress is an another factor effects of success of cold welding. It is generally expected that contact normal stress is 2 times yield of material. Contact normal stresses decrease by increasing die angle. Conversely, contact normal stresses is higher at high strain. Finally, when the surface enlargement is examined materials, diameters of materials does not affect surface enlargement and surface enlargement is higher on aluminum part than steel. Besides surface enlargement is higher at high strain value.

Keywords: cold welding, joining by plastic deformation, joining by forming, aluminum, steel, extrusion

ÖZET

EKSTRÜZYON PROSESİ VASITASIYLA ÇELİK-ALÜMİNYUM KOMBİNASYONLARINDA SOĞUK KAYNAK OLUŞTURULMASININ TERMO-MEKANİK BAĞLI SONLU ELEMANLAR ANALİZLERİ İLE İNCELENMESİ

Akif YALDIZ

Yüksek Lisans, Makina Mühendisliği Bölümü
Tez Danışmanı: Dr. Öğr. Üyesi Mehmet Okan GÖRTAN
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Bu yüzyılda özellikle ağırlık azaltma çalışmalarının önemi gün geçtikçe artmaktadır ve artan bu ihtiyaçla beraber hibrit yapılarının da önemi artmaktadır. Özellikle havacılık ve otomotiv sektöründe yapılan ağırlık azaltma çalışmalarıyla beraber emisyon oranları azaltılabilmekte, maliyetler düşürülebilmekte ve daha sürdürülebilir bir yapı oluşturulmaktadır. Bu doğrultuda ekstrüzyon işleminde uygulanan soğuk kaynak yöntemi hibrit yapıların oluşturulması için etkili bir yöntemdir. Soğuk kaynak yöntemi oda sıcaklığında başlamasına rağmen parçalar arasında oluşan sıcaklık 185 °C değerlerine kadar ulaşmaktadır. Yapılan araştırmalar incelendiğinde ısıl işlemlerin etkisi, yüzey büyümesi ve malzemeler arasında oluşan kontak normal gerilmeleri deneysel ve sonlu elemanlar yöntemiyle incelenmiştir. Fakat bu çalışmalar ya mekanik olarak yapılmış ya da termal olarak yapılmıştır. Bu çalışmada ise malzemeler arasında oluşan kontak normal gerilmeleri, yüzey büyüme değerleri ve malzemeler arasında oluşan sıcaklık değişimleri termo-mekanik olarak yapılan sonlu elemanlar analizleriyle incelenmiştir. Aslında soğuk kaynak yöntemini etkileyen faktörler termo mekanik analizlerle incelenmiştir. Bu doğrultuda EN AW-6082 T6 ve C10 (1.0301) yalın karbon çeliği malzemelerin özellikleri basma testi yapılarak Johnson-Cook malzeme modelinin parametreleri elde edilmiştir ve bu elde edilen parametreler sonlu elemanlar analizlerine aktarılmıştır. İncelenen parça silindirik bir şekle sahiptir. Silindirik parçanın çekirdeği alüminyum, dış tarafı ise çelikten oluşmaktadır. İncelenen çelik malzemenin dış çapı 15 mm'dir. Alüminyum malzemenin çapları da 6,5mm, 7,5mm ve 8,5mm olarak değişiklik göstermektedir. Silindir malzemeler sırasıyla 0,6 ve 0,9 gerinim değerlerine karşılık gelen 11,1 mm ve 9,6 mm'ye ekstrüze edildi. Ayrıca malzemeler 30°, 45° ve 60° kalıp açılarında ekstrüzyon işlemine tabi tutuldu. Bu çalışmada soğuk kaynak yöntemine etki eden farklı plastik gerinim değerleri, farklı kalıp açı değerleri, yüzey büyümesi ve alüminyum ve çelik parçaları arasında oluşan kontak normal gerilmeleri sonlu elemanlar analizleri ile termo-mekanik olarak incelenmiştir. Sonuçlar incelendiğinde yüksek gerinimlerde malzemelerin sıcaklıklarının daha fazla olduğu gözlemlenmiştir. Ayrıca maksimum sıcaklığın deformasyon bölgesinin son kısmında olduğu görülmüştür. Kalıp açısının malzemeler üzerindeki sıcaklık etkisi incelendiğinde aluminyum üzerinde bir etkisi yokken çelik malzeme üzerinde önemli bir etkisi vardır ve kalıp açısı arttıkça çelik malzemenin de sıcaklığının artmıştır. Yapılan incelemelerde ısıl işlemin malzemeler üzerinde sıcaklık bakımından bir fark oluşturmadığı görülmüştür. Kontak normal gerilmesi soğuk kaynak işlemini etkileyen parametrelerden bir tanesidir. Bu değerin soğuk kaynak işleminin başarılı olması için genellikle akma noktasının 2 katı olması gerekmektedir. Kontak normal gerilmesi kalıp açısı artıkça azalmaktadır. Buna ters olarak yüksek gerilim değerinde kontak normal gerilmeleri artmaktadır. Son olarak yüzey büyümesi incelendiğinde malzeme çaplarının yüzey büyümesinde bir etkisi olmadığı görülmüştür ve yüzey büyümesi aluminyum parça üzerinde çeliğe göre daha fazladır.Ayrıca yüksek gerinim değerlerinde yüksek yüzey büyümesi gerçekleşmişir.

Anahtar kelimeler: soğuk kaynak, şekillendirme ile birleştirme çelik, aluminyum, ekstrüzyon, plastik deformasyon ile şekillendirme

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SYMBOLS AND ABBREVIATIONS

FE	:	Finite Element
FEA	:	Finite Element Analysis
FEA	:	Finite Element Model
BC	:	Before Christ
°C	:	Centigrade Degree
°K	:	Kelvin Degree
MPa	:	Megapascal
kN	:	Kilonewton
HT	:	Heat Treated
AR	:	As Received
ASME	:	The American Society of Mechanical Engineers
API	:	American Petroleum Institute

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1. INTRODUCTION

In this century, the application of lightweight parts is more and more important, especially in the automotive and aerospace sectors. In addition, cost reduction, productivity and sustainability in production are becoming increasingly important. One of the most important ways of doing this is by joining the parts. There are many methods for joining the parts. When the joining methods from the past to the present are examined, it is seen that these are insufficient. For this purpose, new researches have been made on combining different or similar materials. These methods are generally divided into three groups. The first of these methods is mechanical joining process. The second type of chemical joining process. The last remaining method is the metallurgical joining process. In this thesis, metallurgical connection types will be emphasized. These connection groups as subheadings friction welding, electric arc welding, resistance upset butt welding, explosive welding, ultrasonic welding, friction stir welding, fusion welding and cold welding. One of the methods used to generate hybrid materials is cold welding [1-5].

There are lots of studies investigate effecting cold welding parameters. Heat treatment and surface preparation of materials are instigated. Heat treatment process is applied before cold welding. In this application C15, C45 and EN AW 6082 types of materials are used. More brittle materials which are artificially aged bonded better than materials which are naturally aged and soft annealed in the results. According to the results, surface preparation is a key parameter on cold welding. Brushing is a good effect on bonding of materials [6 ,7].

Punch velocity, punch stroke effect on bonding strength between pure aluminum A1070 and S10C steel parts is investigated on success of cold welding and results shows there is not any effect punch velocity on success of cold welding but increasing punch stroke is effect positively success of cold welding [8].

Temperature effect on bond strength of materials are investigated o the bond strength in joining by forging. Before the forging process the materials are heated 100 °C, 200 °C, 300 °C, 450 °C and 600 °C. As a result, bond strength is better room temperature and 600 °C [9].

Validation of numerical and empirical joining pipe processes of by cold welding. In this study friction effect is also investigated. FE model and experiment shows radial displacement, pipe deformation are correlated and there is negligible effect on pipe [10].

Validation of bond strength in cold welding is also investigated. In this study ABAQUS is used. With experiment and finite element analysis on ABAQUS. When the results are examined, there is a consistency between finite element analysis and experiments [11].

There is another investigation on cold welding. In this study numerical model on bonding mechanism is investigated and mathematical model is made [12].

When the investigated all of studies, there is not any investigation temperature effect on success of cold welding during process. Therefore, this study presents the cold-weld investigation in the steel-aluminum combination by extrusion using thermo-mechanically coupled finite element (FE) analysis.

2. STATE OF THE ART

Cold welding is (other name is cold pressure welding) made by plastic deformation executed at ambient temperature. The history of this method is thought to date back to 1000 BC. Many different materials such as Al-Cu, Al-Fe and Al-Ti can be combined with this method. Cold welding bonding mechanism is described by two methods [1, 4-5].

The first mechanism which is breaking cover layers when the pressure is reached threshold. Elastic and plastic deformation occurs due to normal and shear stresses at the contact surfaces of roughness structure. Consequently, cover layers starts to break and juvenile material is exposed. Thus, the bonding mechanism between two materials is achieved. This mechanism is related to contact normal stress and yield strength of the material [6].

The second mechanism is local thinning of the contaminant film. In this mechanism, contaminant film begins to crack after reaching a certain strain level and afterwards, joining between two materials is achieved. [6]

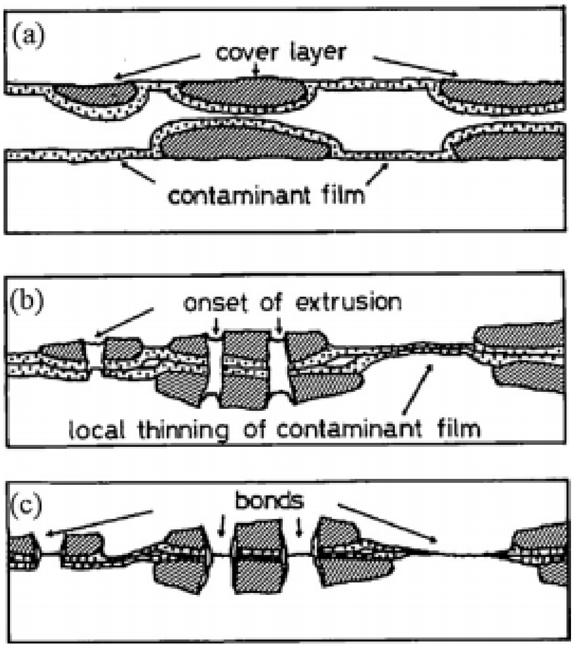

Figure 2-1: Model for bonding mechanism in cold welding. (a) Scratch brushed surface,(b) extrusion of virgin material and (c) bonding [7]

Advantages of solid state welding can be listed as follows [7];

- Strict and strong joining,

- Lightweight,
- Different materials can be used such as Al-Cu, Al-Fe, Al-Ti.

Disadvantages of solid state welding can be listed as follows [2]:

- Difficult to standardize,
- Hard to repair,
- Geometric inequality in combining.

Yoshida et al. [13] investigated on extrusion velocity, punch stroke effect on bonding strength between pure aluminum A1070 and S10C steel parts. In these investigation cylindrical billet material was used and different punch velocities are applied on samples. Aluminum and steel samples were polished before extrusion process. Samples were taken from the middle of the resulting material after extrusion to measure the strength of the bond formed between the materials. These specimens were then subjected to tensile testing. In addition, 2 dimensional simulations were performed by finite element analysis in order to investigate the bond strength of the surface expansion ratio between the materials. As a result of this study, it was found that the punch velocity had no effect on the bond strength between the materials. Furthermore, increasing the punch stroke has a more pronounced effect on bond strength of material. Moreover, FEA results showed that contact surface expansion ratio is influential in the high contact normal pressure condition.

Wohletz et al. [9] the investigated temperature effect on the bond strength of joining by forging. In this paper, Steel (C15) and aluminum (AW 6082-T6) are used. Steel samples are set to room temperature, 100 °C, 200 °C, 450 °C and 600 °C before forging process. Moreover, the aluminum samples are set to room temperature, 100 °C and 200 °C. As a result, it was shown that in all temperatures bonding between aluminum and steel can be achieved. In addition, the forging process carried out at different temperatures with bonding strength was investigated. It was found that the bonding strength of the material formed at room temperature and at elevated temperatures (600 °C for steel and 200 °C for aluminum) was better than the materials formed at intermediate temperatures.

Henriksen et al. [10] studied on the validation of numerical and empirical model of joining pipe to flange by cold forming. By experimental method, the pipe is placed in a flange surrounded by grooves. A divided enlargement tool is kept stationary in axial direction by using a retainer. An enlargement tool comprised of several sections that with shape a cylinder with an interior conical form. Hydraulic pressure moves piston into the sections while cold forming. By this way, sections are acted in tangential direction and they are opened in radial direction at the same time. Flange part and pipe are cold welded by radial forces. In this experiment setup, material of steel pipe is selected API standard 5L PSL 2, 10.2007, hot finished seamless line pipe and material of steel flange is selected ASME standard WN RTJ CL900 6" Schedule 80. The main purpose of this method is not to make the structure stronger or to reduce weight. The purpose of this method is to avoid arc welding method. In addition to this, studies on numerical modeling have been carried out by modeling of the pipe and flanged structure which is connected experimentally with finite element method in computer environment. For this purpose, an axisymmetric cylindrical model was built on FE model in ABAQUS.

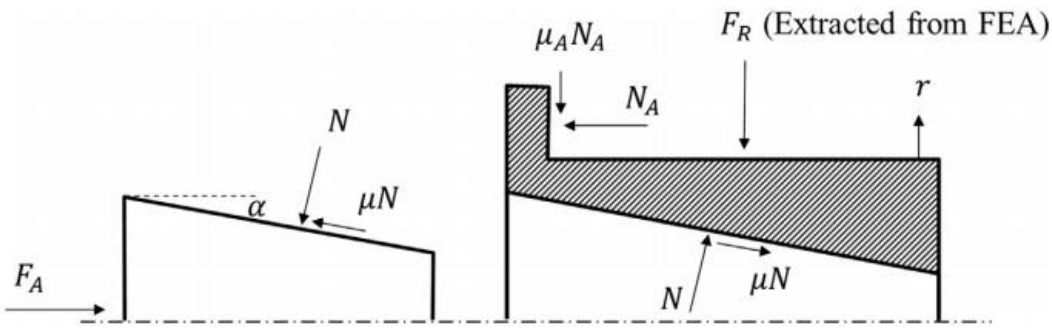

Figure 2-2 : Free body diagram of cone (left) and section (right) [10]

In this figure, FA is axial force; μ is the friction coefficient between cone and sections, FR is radial force and μ_A is the friction coefficient between sections and retainer. FA is calculated to equation 1.

$$F_A = \frac{F_R\,(\sin(\alpha) + \mu\cos(\alpha))}{\cos(\alpha) - \mu\sin\alpha - \mu_A\sin(\alpha) - \mu\mu_A\cos\alpha} \tag{1}$$

Yielding of pump pressure is the P and A is the piston area of hydraulic. P is calculated to equation 2.

$$P = \frac{F_A}{A} \quad (2)$$

The friction coefficient between the sections and the retainer was set 0.05 and the friction coefficient between cone and sections was set 0.3. In conclusion, FE model and experiment results showed radial displacement, pipe deformation are correlated and there is negligible the friction effect between pipe and sections.

Bambach et al. [11] investigated about finite element model of bond strength of joining by forming method with applying numerical simulations. In this investigation soft AA1050 and hard AA5754 samples are used. The samples are 250 mm in length, 20 mm in width and 2 mm in thickness. These samples were joined by cold welding at room temperature and rolling method was applied. Before cold welding process, the samples were heated to 400 °C and only the harder material was kept at 400 °C before the process was started. According to these properties, finite element model was built with ABAQUS. The important parameter is bond strength in normal and tangential directions. In this model Zhang and Bay's [12] model was implemented to the model. According to the results, loads can be used to determine whether a bond is formed between two different materials. Simplified models can also be used in this method.

Hayakawa et al. [8] studied on joining process of shaft and holed part by plastic deformation. In this study, both the experiment and the finite element method have been performed and a comparison has been made between the studies. The material of hole part was selected mild steel S45C and the material of the shaft part was selected pure aluminum A1200. Before the application of joining process samples are annealed. Effecting of joining process parameter which are bevel angle changing 0° to 8° of the inner surfaces of the holed part, surface roughness, different punch geometries and stroke length were investigated in this experiment and finite element method. Simufact Forming was used for FEA. Model was created axisymmetric and an isoperimetric quadrilateral element was selected for FEM. In the model elements can be re-constructed to avoid extreme deformation of elements. According to the results, joining process was accomplished successfully at each bevel angle. In addition, pulling out load of the parts were going up while bevel angle was increased. Furthermore, it was observed that the length of the punch had no effect on the joining process by experiment and FEM simulations. Also, increasing bevel angle help joining of two materials. Besides, it is seen that the effect on the roughness is important.

Akca et al. [3] examined joining by plastic deformation in aerospace applications. Advantages and disadvantages of solid state welding are compared to other joining process in this investigation. Solid state welding application was used in aerospace to join different materials aluminum and titanium. The purpose of using this method is to both reduce weight and is a cost effective method compared to other joining methods. In fact, the Airbus A310 / A320 wing panel was produced using this method.

Groche et al. [6] studied on effect of the heat treatment on the bond generation between steel and aluminum sample. In this investigation cold forging method was used for joining two materials to each other. Parameters which are the heat treatment of the samples before starting to process and aluminum and surface preparation of the samples are investigated effects on bond formation during cold forging. For this purpose, C15, C45 and EN AW 6082 types of material are used for FEM and experiment. According to results, heat treatment of steel and aluminum has a significant effect on bond formation. More brittle materials, artificially aged material can be bonded better than naturally aged and soft annealed. According to the experiment, surface preparation is crucial effect on bonding. Brushing has a key role to establish bond formation in cold forging. Because, the contact normal stress in brushing surfaces is higher than the clean surfaces.

Mori et al [7] examined overview of the joining by plastic deformation. In this study, metallurgical and mechanical joining types are overviewed. Parameters of cold welding parameter is investigated such as surface expansion and surface preparation method. Surface expansion X or degree of surface exposure Y is given in Equation 3, A_1 an A_0 represent final and initial interface area.

$$X = \frac{A_1 - A_0}{A_0}, \qquad Y = \frac{A_1 - A_0}{A_1} \tag{3}$$

Moreover, the critical value of the surface enlargement is investigated and surface preparation methods are investigating in this review.

Zhang et al [12] studied on numerical model for cold welding process. In this study, surface preparation type and bonding mechanism between metals in cold welding process are examined by experimentally and computer program to create numeric model of cold welding. Created numerical formulas are validated by experimentally in this study.

The extrusion process is one of the metal forming methods. In this method, the metal parts are passed through a certain opening by applying compression. In this process, the cross-sectional area is reduced and the elongated part is obtained. Finally, a part of the desired cross-sectional area and length is produced. There are many advantages in the extrusion process. The first of these can be obtained in various shapes, especially in combination with the hot extrusion process. The second advantage is that grain structure and strength properties can be improved. The third advantage is that the desired tolerance ranges are very close in cold extrusion. In addition, one of the other advantages is that no excess waste material is produced. There are many types of extrusion. These are called direct or indirect according to the extrusion direction or cold or hot extrusion according to the temperature [14].

Cold extrusion is often used to produce discrete parts and parts in a finished form. The advantages of this method improvement of strength of material via strain hardening, close tolerances, better surface finishing and high production quantity [14].

Hot extrusion process is include heating the workpiece over 0.5 times melting temperature. Thus, the strength of the workpiece is decreased and ductility of workpiece is increased. In this way, it is possible to produce in large quantities and in various forms [14].

Direct extrusion is shown Figure 2-3 also called forward extrusion. In this extrusion process the metal billet is placed into a container, and punch or ram compresses the metal billet and punch pushes the metal part towards the die with a certain speed or force. After the metal part passes through the die, material is obtained in the desired cross-sectional area and length. In this method friction between metal billet and container is higher and higher punch forces are needed [14].

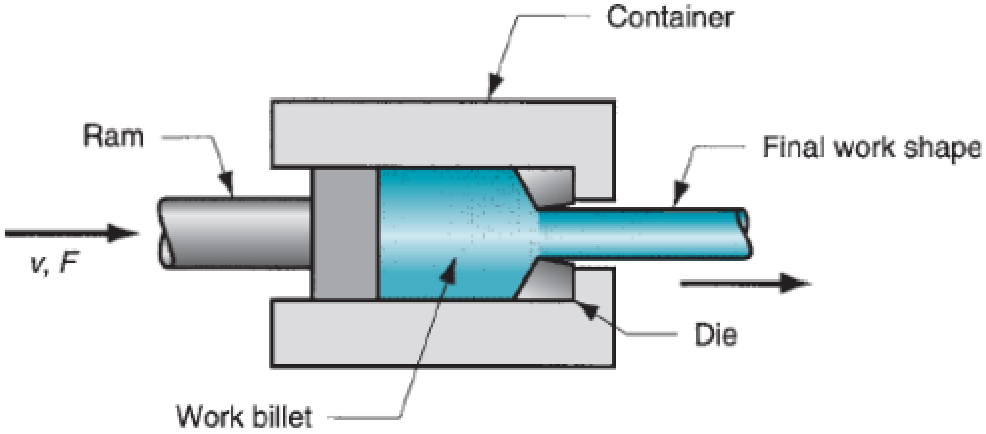

Figure 2-3: Direct Extrusion Process [14]

Indirect extrusion is also called backward extrusion and reverse extrusion and is shown Figure 2-4. The difference of this method from direct extrusion is that the metal part is fixed and the mold comes towards the metal part. In this way, with indirect extrusion in comparison with direct extrusion method less friction is occurred between metal billet and container [14].

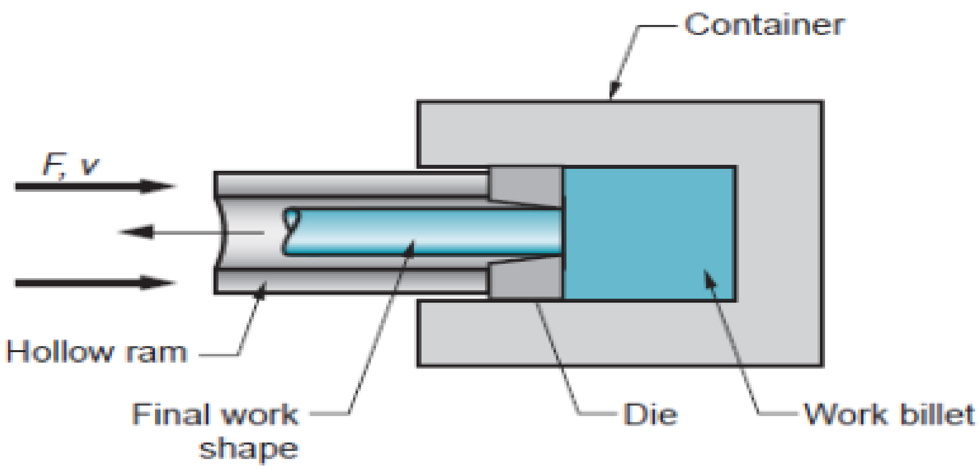

Figure 2-4: Indirect Extrusion Process [14]

3. MOTIVATION AND METHOD

When the previous studies are examined, it is seen that cold welding method is mostly examined by mechanical, numerical and experimental methods. In these investigations, the effects of heat treatments applied to materials on cold welding method, analytical examination of cold welding method, numerical methods with experiments and finite element analysis, as well as mechanical cold welding method studies are made. As a result of these investigations, it was seen that the effect of heat generated during cold welding process on cold welding process was not examined thermo-mechanically. For this purpose, in this thesis, the method of cold welding has been examined thermo-mechanically by finite element analysis. Firstly, material characterization was performed to extract the properties of the materials to be used in these analyzes. The data obtained were entered into the finite element analysis program using Johnson-Cook material model. Johnson-Cook material model is selected, because material properties can be implemented FE program by using this material model. Then, the surface enlargement data between the materials were calculated and the cold welding process was examined.

4. MATERIAL CHARACTERIZATION

First of all, material model of the aluminum and steel components are derived. For this purpose, tensile testing and upset tests are conducted on different conditions. In order to transfer the material properties of these tests to the finite element analysis, Johnson-Cook material model was chosen. This model uses the Equation 4 in the equation.

$$\sigma = (A + B\varepsilon^n) \cdot \left(1 + C \ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right) \cdot \left(1 - \left(\frac{T - T_0}{T_m - T_0}\right)^m\right) \qquad (4)$$

In this equation σ is equivalent yield stress, A is yield stress of material under reference conditions, B is the strain hardening constant, n is the strain hardening coefficient, ε is the equivalent plastic strain, C is the strengthening coefficient of strain rate, $\dot{\varepsilon}$ is the strain rate, $\dot{\varepsilon}_0$ is the reference strain rate, T is deformation temperature, T_0 is the room temperature and T_m is material melting temperature, m is the thermal softening coefficient represents.

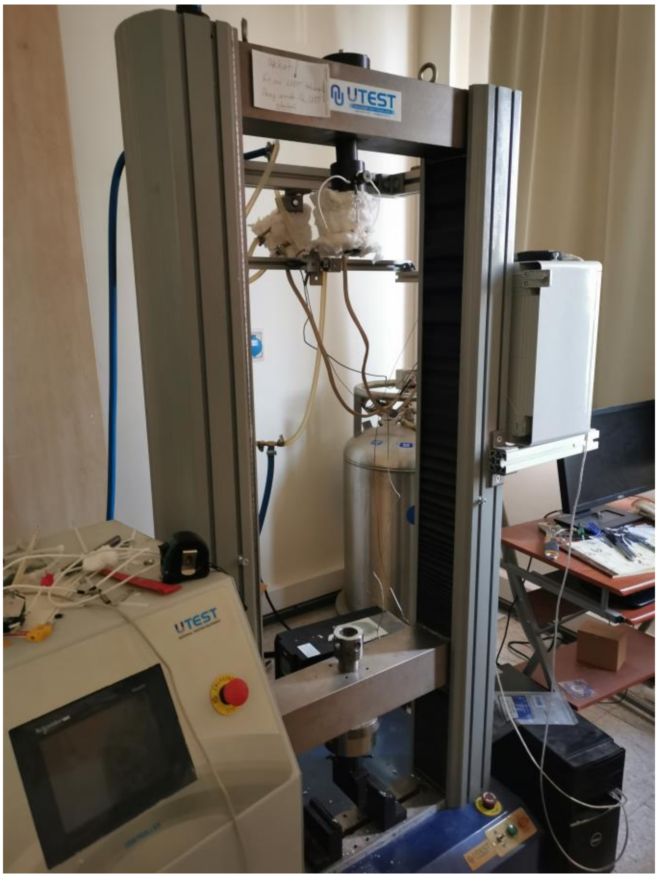

Figure 4-1 Tensile and Compression Test Device

It has been reported in previous studies that using the results of tensile and compression tests in modeling the mechanical properties of the material gives more accurate results in the finite analysis of metal forming processes such as extrusion [15]. Therefore, firstly tensile tests and yield and tensile strength of the material were determined and then these values were determined by compression tests and temperature and strain rate. All tensile and compression tests was made UTEST 50 kN servo mechanical tensile and compression test device which is shown Figure 4-1 and is in Hacettepe University Mechanical Engineering Department. For this reason, tensile test of material is made first. Then the yield and tensile strength of the material is determined by this test. According to these values, the temperature and strain rate of the material was determined by compression tests. MoS2 lubricant was used in compression tests to prevent barrel shape formation due to friction in the samples. This lubricant simplifies forming by greatly reducing the coefficient of friction for the contact normal stress and temperatures planned to be tested. Samples have an initial diameter of 6 mm and a height of 9 mm. During the tests, the specimens were pressed to a half height of 4.5 mm. The sample tested is shown in Figure 4-2.

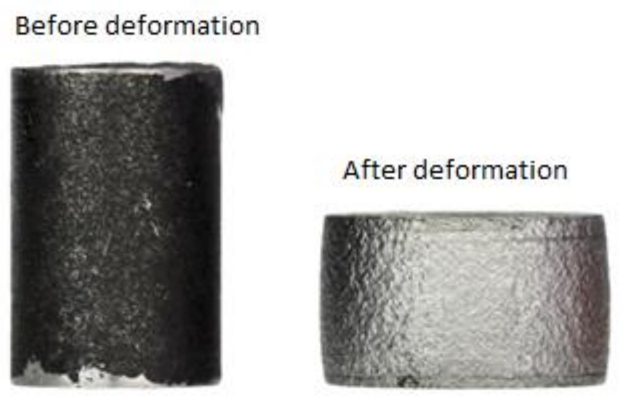

Figure 4-2: Compression test sample (left) and tested sample(right)

Compression tests were performed at 3 different temperatures (25 ° C, 100 ° C and 175 ° C) and 3 different strain rates (0.01 s^{-1}; 0.1 s^{-1} and 1 s^{-1}). Then the same compression tests are modeled in the finite element analysis. The pre-derived yield curve was used in the tests at room temperature and the material parameters were optimized to match the simulation results to the test results. The Johnson-Cook material parameters derived in this way are shown in Table 4-1.

Table 4-1: Derived Johnson-Cook material model parameters for (C10C)-Steel (AR)

Parameter	Value (C10C)-Steel
Mass Density[kg/m^3]	7,87
Young's Modulus[GPa]	210
Poisson's Ratio	0,3
A – Yield Stress [MPa]	653,4
B – Strain Hardening Constant [MPa]	76,2
n – Strain Hardening Coefficient	0,1
C – Strengthening Coefficient of Strain	0,01
$\dot{\boldsymbol{\varepsilon}}_{\mathbf{0}}$ – Reference Strain Rate [s^{-1}]	1
$\boldsymbol{T_0}$ – Room Temperature [°K]	298
$\boldsymbol{T_m}$ – Material Melting Temperature [°K]	1773
m – Thermal Softening Coefficient	3

Table 4-2: Derived Johnson-Cook material model parameters for (C10C)-Steel (HT)

Parameter	Value (C10C)-Steel
Mass Density[kg/m^3]	7,87
Young's Modulus[GPa]	210
Poisson's Ratio	0,3
A – Yield Stress [MPa]	225
B – Strain Hardening Constant [MPa]	500
n – Strain Hardening Coefficient	0,3
C – Strengthening Coefficient of Strain	0,01
$\dot{\boldsymbol{\varepsilon}}_{\mathbf{0}}$ – Reference Strain Rate [s^{-1}]	1
$\boldsymbol{T_0}$ – Room Temperature [°K]	298
$\boldsymbol{T_m}$ – Material Melting Temperature [°K]	1773
m – Thermal Softening Coefficient	3

Table 4-3: Derived Johnson-Cook material model parameters for EN AW-6082 T6 Aluminum

Parameter	EN AW-6082 T6
Mass Density[kg/m^3]	2,7
Young's Modulus[GPa]	70
Poisson's Ratio	0,33
A – Yield Stress [MPa]	297,8
B – Strain Hardening Constant [MPa]	111,1
n – Strain Hardening Coefficient	0,048
C – Strengthening Coefficient of Strain	0,0238
$\dot{\varepsilon}_0$ – Reference Strain Rate [s^{-1}]	1
T_0 – Room Temperature [°K]	298
T_m – Material Melting Temperature [°K]	828
m – Thermal Softening Coefficient	1,19

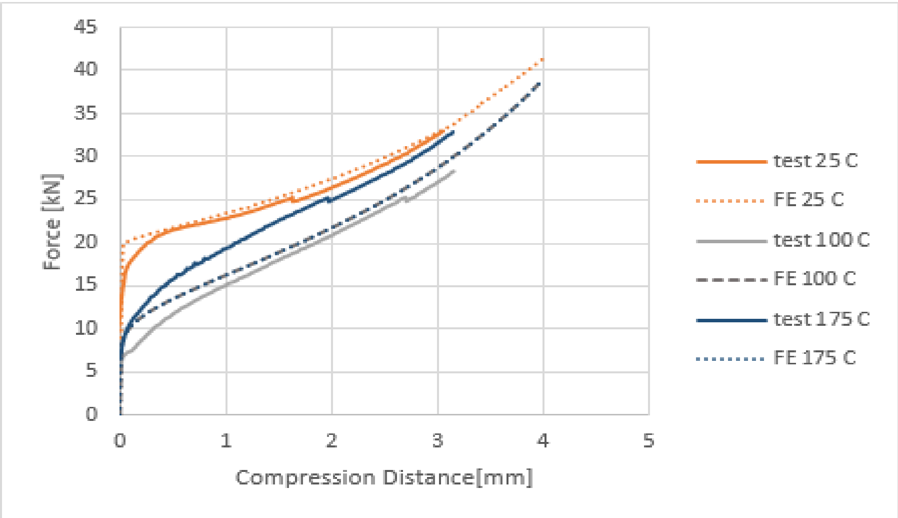

Figure 4-3: Comparison of force values obtained from upset tests using different strain and temperatures with finite element analysis results for heat treated

The results obtained with the material model parameters given in Table 4.1 and the experimental results are compared in Figure 4-3. In the Figure 4-3, it is seen that FE model at 100 °C and FE model at 175 °C is nearly same. Here, the results of the compression tests applied at different stretching speeds and temperatures are shown with continuous lines, and the results of repeated finite element analyzes with the Johnson-Cook material model parameters given in Figure 4-3 of the same experiment are shown with continuous lines. It was observed that the results of experiment and finite element analysis matched each other as a trend in the comparisons. There is a clear overlap between them when investigating the values. High differences were observed at 175°C in between experiment and finite element analysis.

5. FINITE ELEMENT SIMULATION MODEL

In this section finite element models of the cold extrusion processes via forward extrusion process were investigated with the software package MSC MARC/Mentat 2016. Axial symmetrical models were built because of cylindrical shape of the structure. The inner side of the investigated structure is aluminum and outside of the investigated structure is steel. The length of the workpieces were 25mm. The diameter of the outside of the steel is 15 mm. The diameter of the aluminum was changing 6.5 mm, 7.5 mm and 8.5 mm. The inner diameter of the steel is changing depending on the aluminum diameter. The workpieces are extruded to 11 and 9,8 mm diameters and these parameters are equal to respectively 0.6 and 0.9 plastic strain. There are three different die opening angle (2α) 30, 45 and 60, were used in the extrusion die design. Die geometry of extrusion process and FE model was shown in Figure 5-1 schematically.

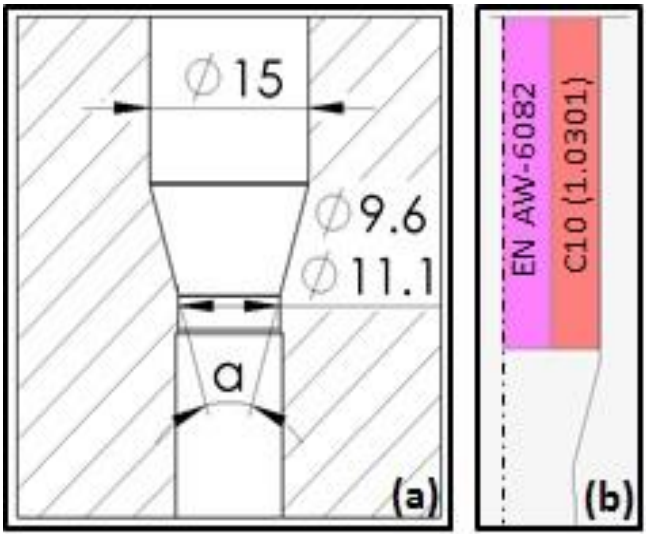

Figure 5-1: Schematically drawing of (a) extrusion die and (b) finite element model of the process

The wall of the die and punch were assumed to be rigid bodies. Heat transfer coefficient between extrusion part and punch is considered 20 W/m^2K and also heat transfer coefficient between steel part and the wall of the die is taken 20 W/m^2K. In addition to that, heat transfer coefficient between aluminum and steel is considered 5 W/m^2K. Before the process the length of the extrusion part is 25 mm and element number is 3000. Element type was chosen Full Hermann formulation, quadrilateral elements with an edge length of 0.25mm. The friction coefficient is considered to be constant 0.3 between aluminum and steel workpieces and the friction coefficient between the steel workpiece and die wall is assumed to be 0.05. Furthermore, glued contact was set between the punch and workpieces.

The boundary condition is shown Figure 5-2 and the velocity of the punch is assumed to be constant 10 $mm \cdot s^{-1}$ and the punch pushes 20 mm the extrusion part among the die. According to the velocity and distance, the extrusion process duration was taken 2 seconds to finish. The thermal properties of workpieces taken in the simulations from literature [5] and the mechanical properties workpieces was mentioned previous part.

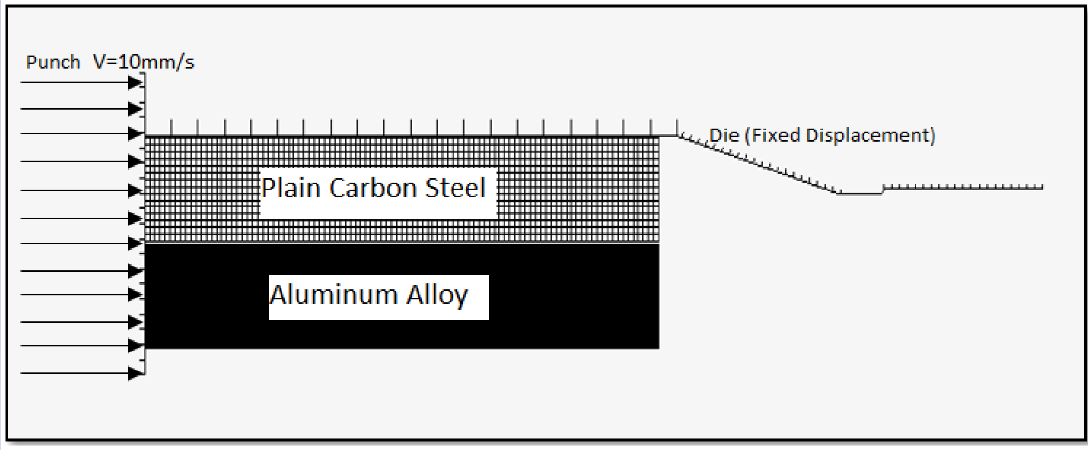

Figure 5-2: Boundary Conditions of Finite Element Model

6. FINITE ELEMENT ANALYSIS RESULTS

The surface enlargement calculation cannot be directly obtained by using the finite element analysis program. For this reason, surface enlargement calculation is made by using the Equation 3 which is given previous section and taking the data from the program. These data are displacement in the x direction, displacement in the y direction and strain values in the z direction. Initially, the length of each element is 0.25 mm and the element is square. These elements then become trapezoidal during extrusion. In order to find this field change, displacement values in x direction and displacement values in y direction are actually found in the new length value in x direction. Then the new z lengths are calculated with the strain value in the z direction. Thus, the last area and the first areas are calculated and the surface expansions can be calculated with the change between them. This calculation algorithm is given in the Figure 6-3.

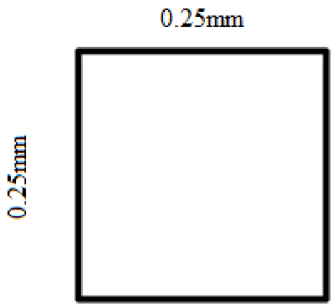

Figure 6-1: Initial dimension of element size

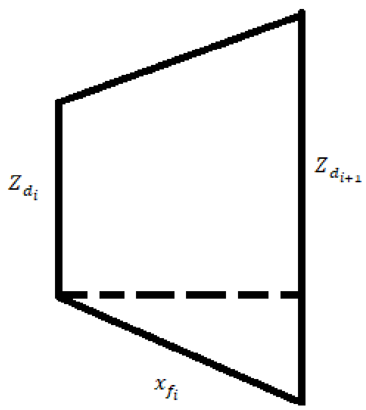

Figure 6-2 : Final dimension of element size

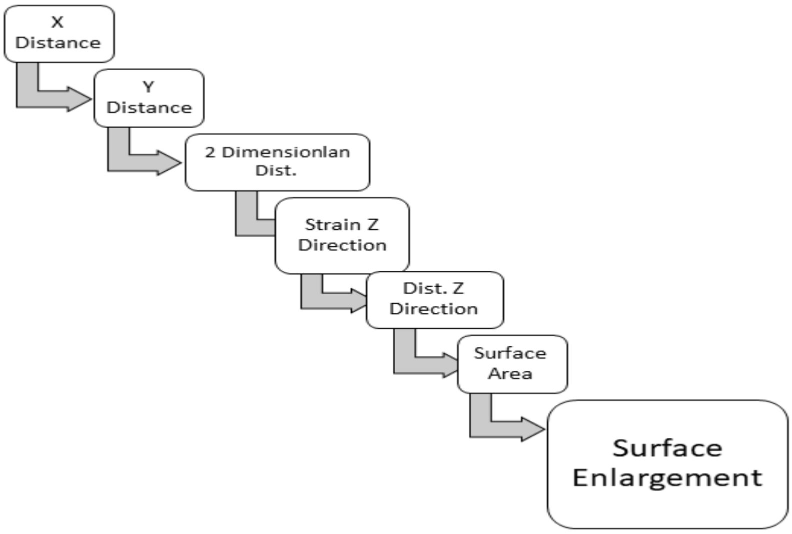

Figure 6-3: Flow chart of the Surface Enlargement Calculation

In the flow chart, firstly x distance and y distance of element is calculated. The distance x and y calculation is shown in Equation 5, Equation 6 and Equation 7. Then, the distance z direction is calculated by using the strain in z directions. Also, the distance z calculation is shown Equation 9. Thereby, area is calculated by distance of element and it is shown in Equation 10. Consequently, surface enlargement is calculated.

$$\Delta x_i = DispX_{i+1} - DispX_i \tag{5}$$

$$x_{f_i} = x_i - \Delta x_i \tag{6}$$

$$\Delta y_i = DispY_{i+1} - DispY_i \tag{7}$$

$$X_{d_i} = \sqrt[2]{{x_{f_i}}^2 + {\Delta y_i}^2} \tag{8}$$

Strain z

$$Z_{d_i} = 0.25 \times e^{\varepsilon_{z_i}} \tag{9}$$

$$A_i = \frac{Z_{d_{i+1}} + Z_{d_i}}{2} \times X_{d_i} \tag{10}$$

Surface enlargement is derived by (11)

$$X = \frac{A_{i+1} - A_i}{A_i}$$

Several factors which are temperature, contact normal stress, strain, geometry of extrusion part, die opening angle and heat treatment, effect cold welding process. In order to investigate these parameters FE-simulations data are used to compare with each other.

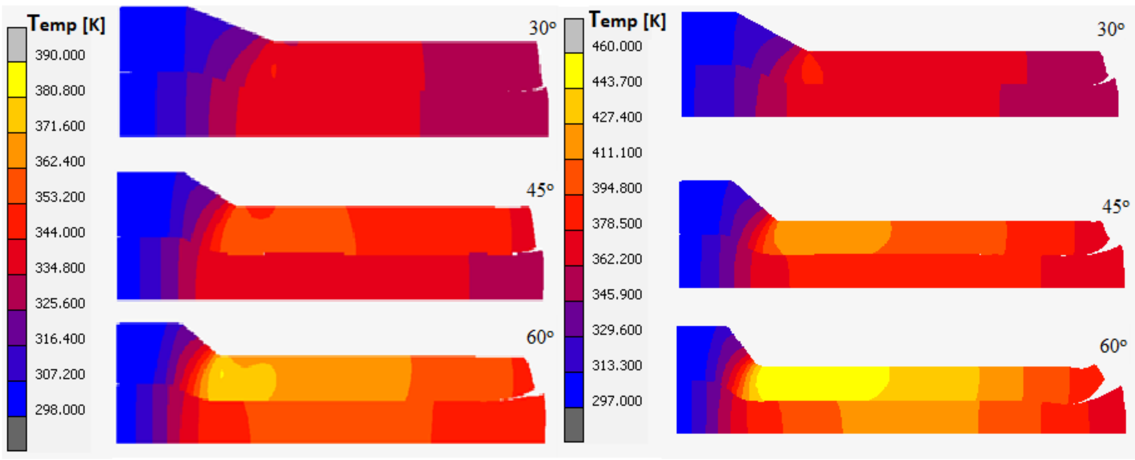

Figure 6-4: Predicted temperature distribution at (a) 0.6 strain heat treated and (b) 0.9 strain heat treated

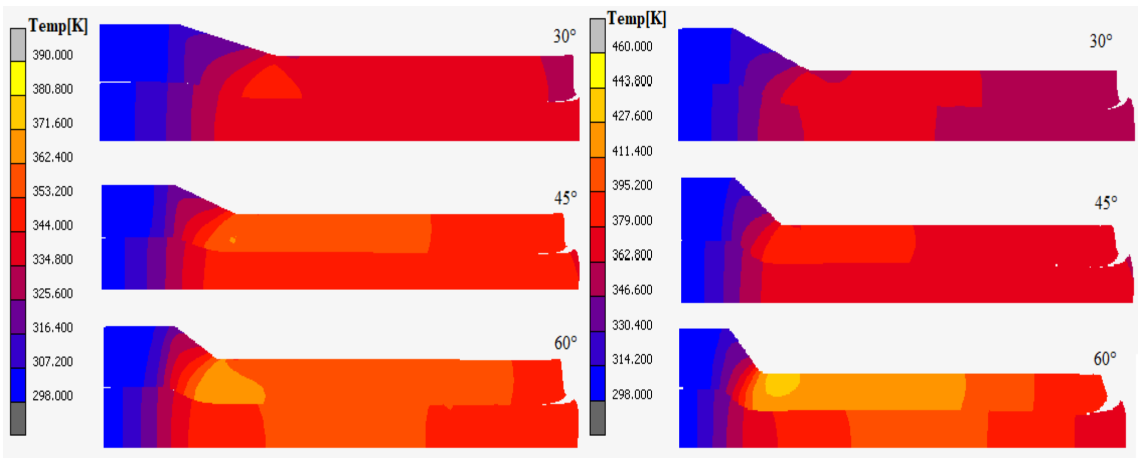

Figure 6-5 Predicted temperature distribution at (a) 0.6 strain heat treated and (b) 0.9 strain as-received

Figure 6-4 and Figure 6-5 show temperature distributions on the extrusion part geometry via different strains and channel angles. As the channel angle increases, the clearance between aluminum and steel materials becomes more apparent at the end of the extrusion. In addition, when the plastic strain is 0.9, it appears that the opening becomes more pronounced. Even in the pair of materials, the aluminum is more deformed in the direction of extrusion than steel. In addition, 2 different types of material is examined in terms of temperature. When the results are investigated, there is no temperature effect on as-received and heat treatment material.

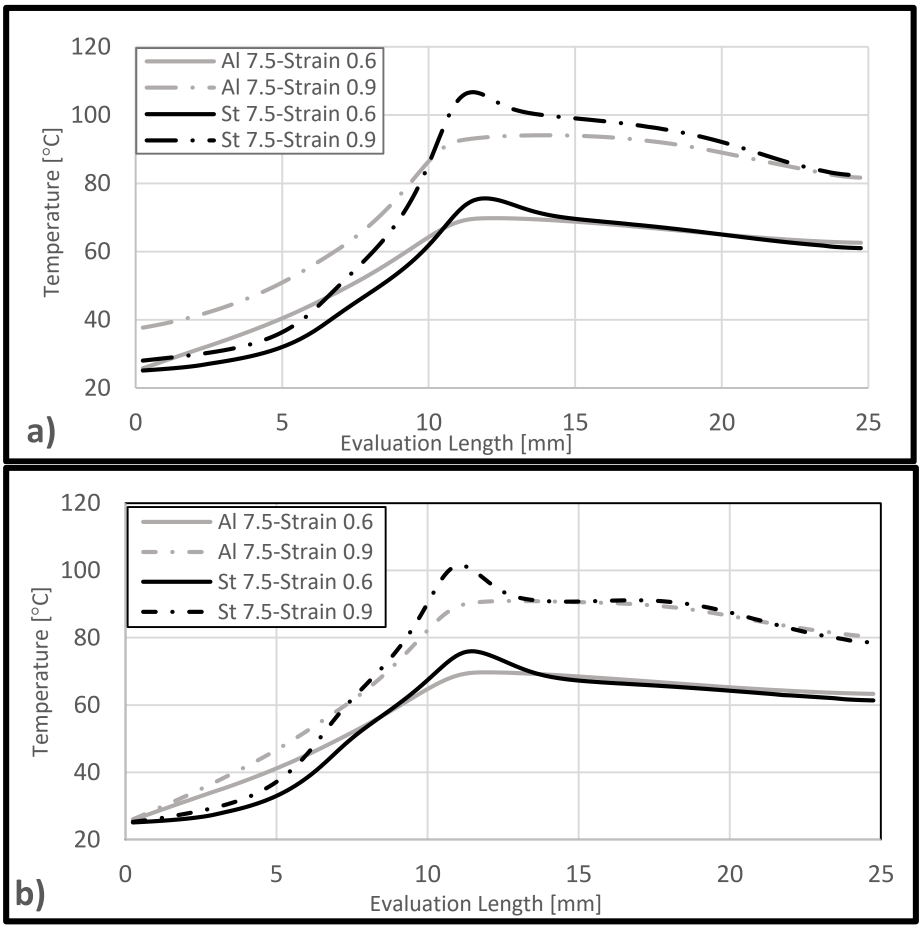

Figure 6-6: Temperature distribution along the aluminum-steel contact line (Channel angle 30°) (a) heat treated b) as-received

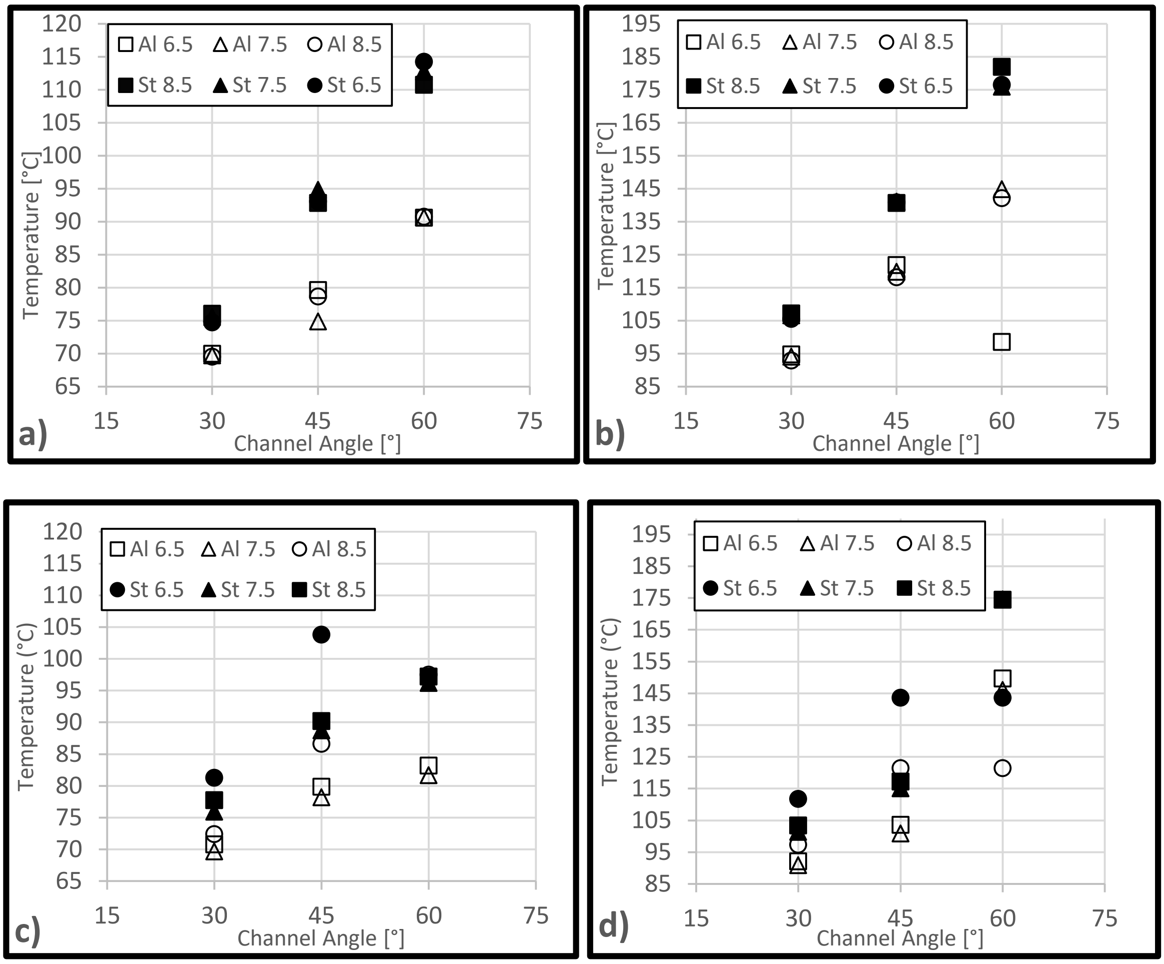

Figure 6-7: Maximum temperatures at varying channel angles and workpiece diameters at (a) 0.6 strain heat treated (b) 0.9 strain heat treated (c) 0.6 strain as-received and (d) 0.9 strain as-received

The temperature parameter on the contacting surfaces is an important factor for the cold welding process. High temperature increases the diffusion rate in the joining of materials. In addition, with increasing temperature, the yield strength of the material decreases and the surface deformation becomes easier under contact normal stresses. Therefore, the temperature distributions on the steel and aluminum samples were examined primarily. It was observed that the temperature was higher at 0.9 strain values due to the increase of plastic deformation. In addition, it has been observed that as the channel angle increases, the temperatures increase. This is because the reduced contact area between the workpiece and the tool. Consequently, the less contact space between the workpiece and the tool, the less heat transfers between the workpiece and the tool.

In addition, when the Figure 6-4 and Figure 6-5 are examined, it is observed that the maximum temperature between steel and aluminum occurs at the exit of the deformation section. The temperature drops after reaching the maximum temperature is not significant. The maximum temperature values of the aluminum and steel parts according to the channel angles and material thickness are given in Figure 6-6. It is clear that channel angle has an insignificant effect on the maximum temperatures on the surface of aluminum material. For both investigated strains, differences are very limited. On the other hand, channel angle has a more definite effect on the maximum temperatures on the surface of steel material. Nevertheless, the sample geometry has an insignificant effect on the maximum temperatures of both materials on their contacting surfaces.

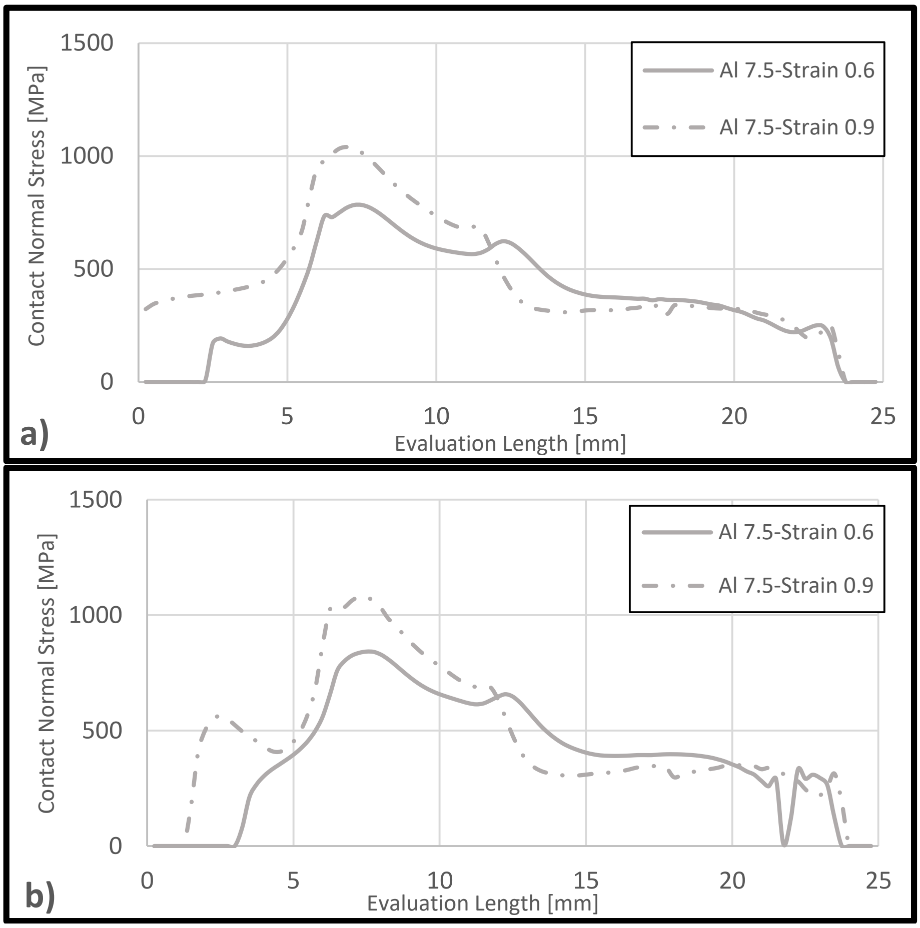

Figure 6-8 Contact normal stress distribution along the aluminum-steel contact line (Channel angle 30°) (a) heat treated (b) as-received

The contact normal stress parameter is quite important in cold extrusion process in order to achieve bonding between used materials. It is recommended that the contact normal forces in cold welding process be more than twice the yield strength of the material. Therefore, contact normal stresses along the contact surfaces between the materials are shown in Figure 6-8. It was observed that the materials entered the deformation zone at the first peak and also, they went out deformation zone at the second peak. Thus, it is understood that the cold welding process occurs between two peaks.

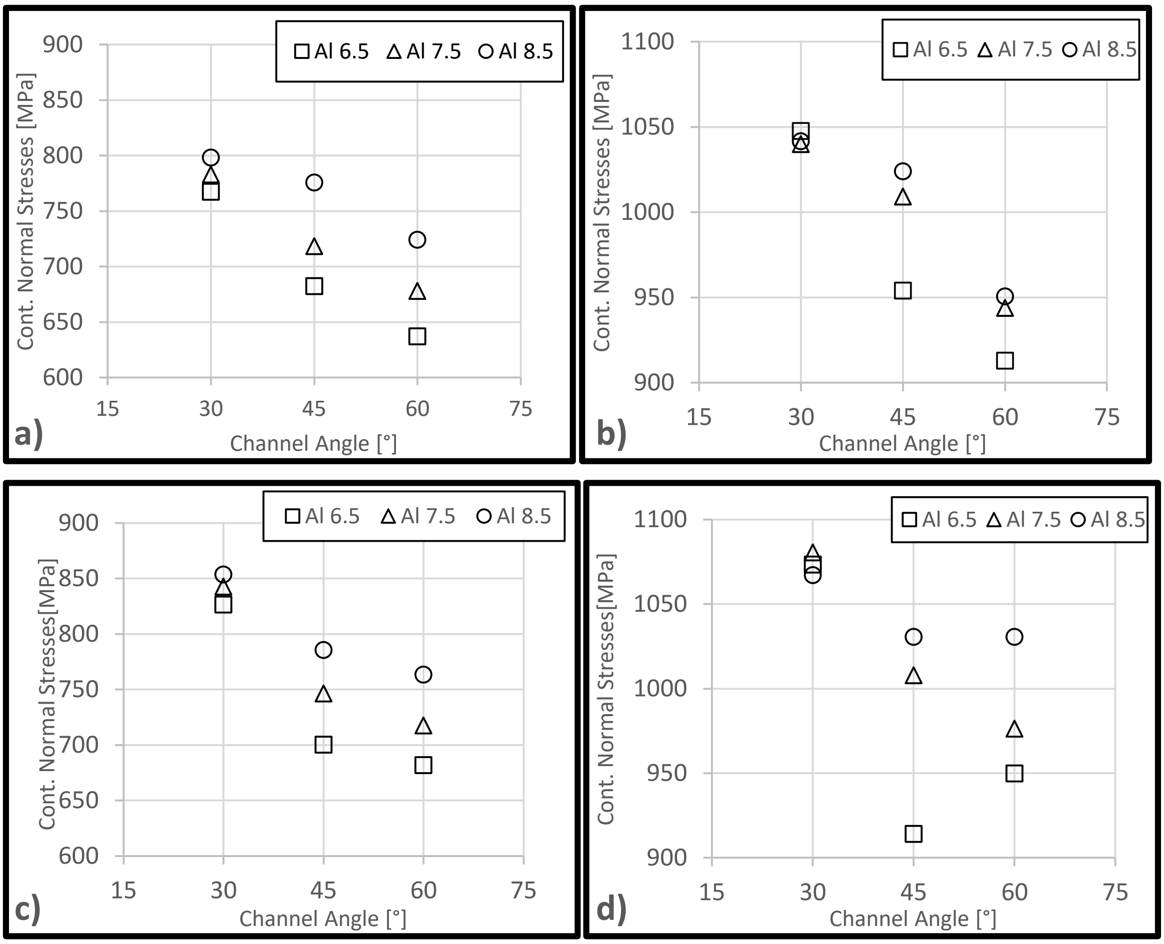

Figure 6-9: Maximum contact normal stresses at varying channel angles and workpiece diameters at (a) 0.6 strain heat treated (b) 0.9 strain heat treated (c) 0.6 strain as-received (d) 0.9 strain as-received

Contact normal stresses are shown Figure 6-9 according to die angle changes and different radius value of materials. Die angle and radius of materials effect contact normal stresses. Contact normal stress is one of the parameter effect of success cold welding. Considering the figures, it is observed that contact normal stresses decrease when die angles increase. Also, the contact normal stresses are raised significantly by the increment strain values. At low strain values, contact normal stress values between heat treated materials are higher than as-received treated materials. In addition, at low strain values, contact normal stress values between as-received materials are higher than heat treated materials. However, the contact normal stress values are very close at high strain values. This is because strength of as-received materials increases by rising of strain. Therefore, differences between contact normal stresses for both material type reduce.

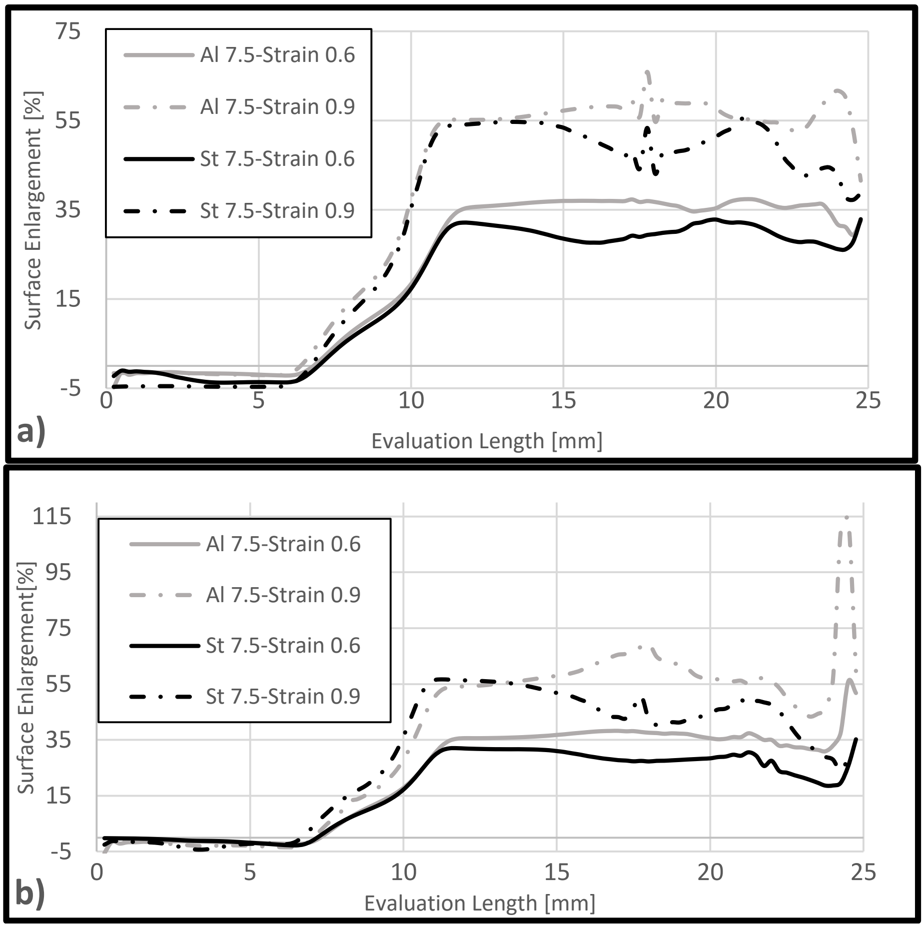

Figure 6-10 Surface enlargement distribution along the aluminum-steel contact line (Channel angle 30°) (a) heat treated (b) as-received

Surface enlargement is one of the parameters that show that cold welding process has been performed successfully. The minimum surface enlargement value, which indicates that bonding between material pair has been formed successfully, is 30%. For this purpose, the surface enlargement values in the material pair were examined in Figure 6-10 and Figure 6-11. **Error! Reference source not found.**First, it is observed that the surfaces of both materials grow to the end of the deformation zone. After that, it was found that the surface enlargement values remained constant.

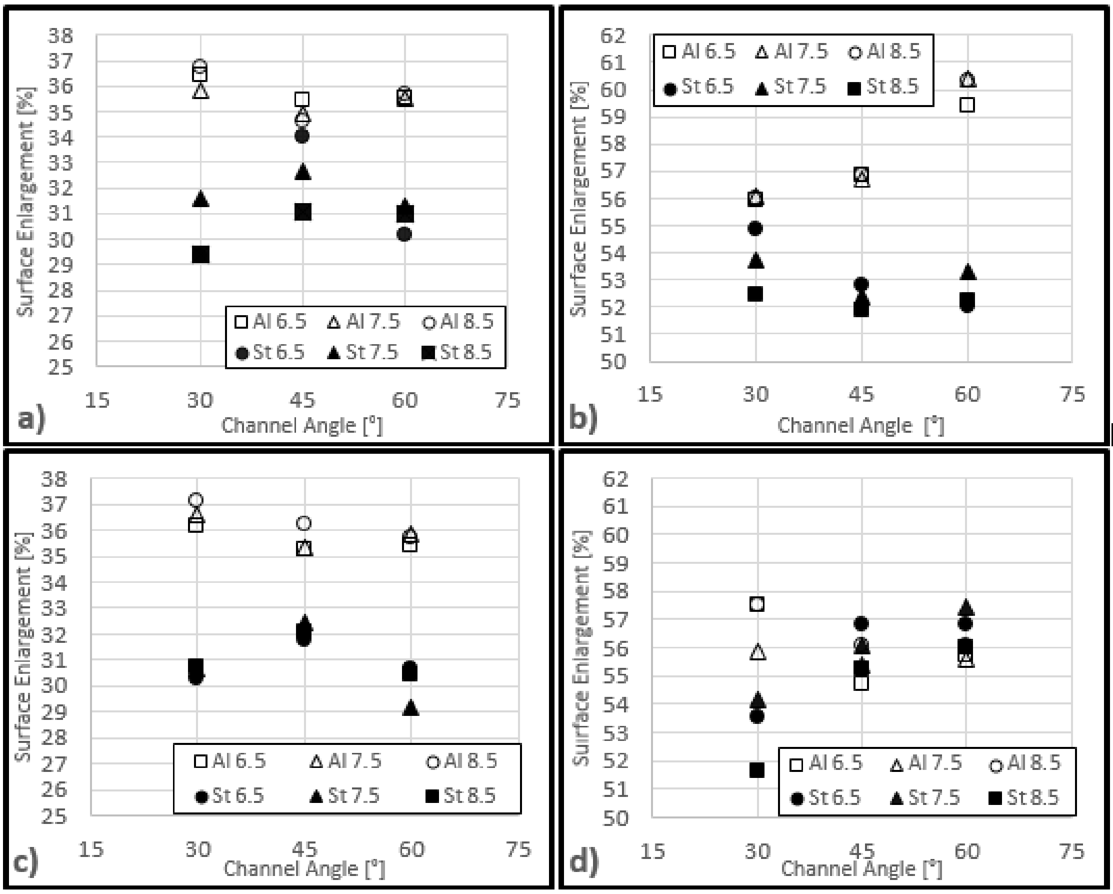

Figure 6-11: Average surface enlargements at varying channel angles and workpiece diameters at (a) 0.6 strain heat treated (b) 0.9 strain heat treated (c) 0.6 strain as-received (d) 0.9 strain as-received

In Figure 6-11, investigation of the surface enlargement changing, which is related to part and die geometry, is taken to account the average value of 5 mm after reaching maximum surface enlargement. It is understood that the part geometry has an unimportant effect on the surface enlargement. Furthermore, surface enlargement value of aluminum part higher than of steel part. Similar results are obtained at high plastic strain. In addition, die geometry and heat treatment process has not important effect on the surface enlargement. It is also understood that the plastic strain is an important factor on surface enlargement. Considering all values, surface enlargement values are higher than 29% and it is very close the critical values for successful cold welding process.

7. DISCUSSION

When the effect of temperature on cold welding were examined Figure 6-4, Figure 6-5, Figure 6-6 and Figure 6-7, it was expected that the temperature between the materials would be higher in AR-steel and aluminum compared to HT-steel and aluminum. This is because the yield strength of AR material is higher than HT material. However, the maximum temperatures between AR-steel and aluminum and the maximum temperatures between HT and aluminum are similar. This shows that the yield strength of the material in cold welding method has no effect on the temperature formed between the materials. In addition to them, temperature is effected the area of the deformation zone. Therefore, increasing channel angle decreases effective area and increase temperature.

When the maximum contact stresses between the materials were examined, it was observed that the yield strength of the AR-steel material was 3 times higher than that of HT-steel, but the difference in maximum contact stresses between the materials was found to be higher at low strain values. However, it was observed that the contact normal stresses are very close to each other at high strain values. This can be understand when the Table 4-1and Table 4-2, strain hardening coefficient is effect contact normal stresses at high strain values.

When surface enlargement values were examined, it was observed that maximum surface enlargement could be achieved high strain values. Therefore, when the surface expansions obtained at high tension values are examined, it is understood that it provides sufficient values in the operations with both HT-steel and aluminum and AR-steel and aluminum materials.

8. SUMMARY AND OUTLOOK

The main purpose of this study is to investigate the effect of the temperature differences between the materials during cold welding process on cold welding formation. In addition, whether the parameters geometry of parts, channel angle and different strain values had an effect on the cold welding process were investigated. For this purpose, the properties of EN AW-6082 T6 and C10 (1.0301) plain carbon steel materials were tested by compression test and the parameters of Johnson-Cook material model were obtained and these parameters were implemented in a finite element model.

Channel angle has a significant effect on the maximum temperatures on the surface of steel material. Otherwise, channel angle has an insignificant effect on the surface of the aluminum material. In addition, there was no difference in temperature in cold welding application between AR-steel and aluminum and HT-steel and aluminum. The contact normal stress has fallen in correlation to increasing strain.

The effect of sample and die geometry on the contact normal stress is significant and contact normal stress effect success of cold welding. But, that decreasing in contact normal stress is certainly when the aluminum diameter is small. On the contrary, contact normal stress is similar in 8.5 mm aluminum core diameter. As a result, when the diameter of the aluminum sample is larger, aluminum core is compressed by steel part. When material type effect is compared on contact normal stress, AR-steel material has more effect than HT-steel. Because, yield strength of the AR-steel is more than HT-steel.

The effect of sample and die geometry on the surface enlargement is insignificant. Surface enlargement is critical for success of cold welding and it has to be higher than %30. The strain values have a significant effect on the surface enlargement. In addition to, material type has an insignificant effect on surface enlargement.

In the future works, FE simulation results should be validated with experiments. For this purpose, experiment setup is currently being building. However, the results cannot be included in this study since it is not finished yet.

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