İmalat Teknolojileri ve Uygulamaları
Cilt: 5, No: 3, 2024 (295-303)
Araştırma Makalesi
e-ISSN: 2717-7475

Manufacturing Technologies and Applications
Vol: 5, Issue: 3, 2024 (295-303)
Research Article
e-ISSN: 2717-7475

The Influence of Velocity and Pressure on Residual Stresses During The Backward and Forward Extrusion of AA6061 T6 Aluminium Alloy

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ARTICLE INFORMATION
Received: *18.11.2024*
Accepted: *20.12.2024*

Keywords:
Combined extrusion
Aluminum alloy
Residual stress
Wrench socket

ABSTRACT

The extrusion process is considered a cost-effective manufacturing method compared to alternative production techniques, offering excellent mechanical properties and high product quality. Combined extrusion further enhances efficiency by minimizing the need for additional processing steps, thereby saving time and reducing production costs. The die geometry and friction factors play a critical role in determining the success and quality of this process. In this study, AA 6061 T6 aluminium alloy was selected as the billet material to investigate a combined backward–forward extrusion process and to examine the influence of process parameters, such as velocity and pressure, on the residual stresses formed in the extruded products. Two punch types were utilized: a hexagonal punch for the backward extrusion direction and a square punch for the forward extrusion direction. For each punch type, three different cross-sectional areas (140, 130, 115 mm^2) and three different forming velocities (0.25, 0.5, 1 mm/s) were tested to assess the effect of forming pressure on residual stresses. The experiments were conducted using a heat-treated H13 steel die with a hydraulic press under lubricated conditions. The findings indicate that increasing the cross-sectional area of the punch, which corresponds to a reduction in pressing pressure, results in higher residual stresses at a constant velocity. The highest residual stresses were observed in the hexagonal region (1315 MPa), corresponding to the backward extrusion process. Intermediate stress levels (<990 MPa) were found in the middle regions between the backward and forward extrusion directions, while the lowest residual stresses (<588 MPa) were recorded in the forward extrusion region, associated with the square punch.

AA6061 T6 Alüminyum Alaşımının Geri ve İleri Ekstrüzyonu Sırasında Hız ve Basıncın Kalıntı Gerilmeler Üzerine Etkisi

MAKALE BİLGİSİ
Alınma: *18.12.2024*
Kabul: *. 20.12.2024*

Anahtar Kelimeler:
Birleşik ekstrüzyon
Alüminyum alaşımı
Kalıntı gerilim
Anahtar soketi

ÖZET

Ekstrüzyon işlemi, alternatif üretim tekniklerine kıyasla maliyet açısından etkili bir üretim yöntemi olarak kabul edilir ve mükemmel mekanik özellikler ve yüksek ürün kalitesi sunar. Kombine ekstrüzyon, ek işlem adımlarına olan ihtiyacı en aza indirerek verimliliği daha da artırır, böylece zamandan tasarruf sağlar ve üretim maliyetlerini azaltır. Kalıp geometrisi ve sürtünme faktörleri, bu işlemin başarısını ve kalitesini belirlemede kritik bir rol oynar. Bu çalışmada, birleşik geri-ileri ekstrüzyon işlemini araştırmak ve hız ve basınç gibi işlem parametrelerinin ekstrüde ürünlerde oluşan kalıntı gerilmeler üzerindeki etkisini incelemek için kütük malzemesi olarak alüminyum alaşımı AA 6061 T6 seçilmiştir. İki zımba tipi kullanılmıştır: geri ekstrüzyon yönü için altıgen zımba ve ileri ekstrüzyon yönü için kare zımba. Her zımba tipi için, presleme basıncının kalıntı gerilmeler üzerindeki etkisini değerlendirmek için üç farklı kesit alanı (140, 130, 115 mm^2) ve üç farklı şekillendirme hızı (0.25, 0.5, 1 mm/s)) test edilmiştir. Deneyler, yağlanmış koşullar altında hidrolik pres altında ısıl işlem görmüş bir H13 çelik kalıp kullanılarak gerçekleştirilmiştir. Bulgular, presleme basıncında bir azalmaya karşılık gelen zımbanın kesit alanının artırılmasının, sabit bir hızda daha yüksek kalıntı gerilimlerle sonuçlandığını göstermektedir. En yüksek kalıntı gerilimler (1315 MPa), geriye doğru ekstrüzyon işlemine karşılık gelen altıgen bölgede gözlemlenmiştir. Geri ve ileri ekstrüzyon yönleri arasındaki orta bölgelerde ara gerilim seviyeleri (<990 MPa) bulunurken, en düşük kalıntı gerilimler (<588 MPa), kare zımba ile ilişkili olan ileri ekstrüzyon bölgesinde kaydedilmiştir.

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To cite this article: B. Bakır, H. Aljawad, F. Mert, Ç. Karataş, The influence of Velocity and Pressure on Residual Stresses During The Backward and Forward Extrusion of AA6061 T6 Aluminium Alloy, Manufacturing Technologies and Applications,5(3),295-303, 2024.https://doi.org/10.52795/mateca.1576416

1. INTRODUCTION (GİRİŞ)

Metal-forming processes are among the most significant manufacturing methods for producing parts with diverse and complex geometries. These processes offer high productivity, efficient material usage, minimal waste, and superior mechanical properties. Extrusion, a key metal-forming process, is widely used in industrial applications due to its ability to produce intricate geometries. Extrusion processes are classified based on some factors such as material and punch movement direction, billet temperature, equipment orientation, and process type. The primary extrusion types include forward, backward, and radial extrusion. Combining these methods enables the production of more complex shapes, reduces costs and time, and enhances product quality.

For instance, radial extrusion combined with forward extrusion is used to produce seamless tubes with excellent mechanical properties from small cylindrical workpieces. This method generates high strains that improve material properties, as demonstrated in magnesium alloy processing under isothermal conditions. Microstructural analysis reveals a reduction in grain size due to dynamic recrystallization during severe plastic deformation, resulting in increased yield strength, ultimate strength, and doubled ductility [1].

Metal-forming processes are also critical for manufacturing micro-components, which are increasingly important in electronic and mechanical applications due to their high precision requirements. Brass microparts have been fabricated using a combined forward and backward extrusion process to study the influence of friction between the billet and die surface. Variations in grain size and lubrication effects were assessed using billets of constant diameter at different heat treatment temperatures. Results showed that dry conditions significantly impact grain size and friction more than lubricated conditions [2].

Another application of combined extrusion involves lateral and axial directions to produce bifurcated components for nuclear power plants. Numerical simulations are used to predict performance before experimental validation, focusing on critical areas such as corners and junctions. Increased strain and strain rates help reduce flaws, refine grain size, and enhance mechanical properties. Experimental findings align closely with finite element analysis results [3].

The forward-backward extrusion process has also been applied to aluminum alloy AA6013 using a revolving die to study the effects of die vibration frequency alteration. The KoBo technique, a modern method employing severe plastic deformation (SPD) at low temperatures with rotating deformation states, was utilized. Mechanical properties were evaluated after hot forming, T6 heat treatment, and KoBo processing. Tensile testing and transmission electron microscopy revealed that die vibration frequency significantly affects material flow and mechanical properties [4].

Lubrication plays a vital role in combined extrusion, reducing friction and required power while improving product quality. A novel lubrication system integrates servo press technology to ensure continuous lubrication during the process, particularly for hollow or deep parts. This system introduces lubrication during punch movement and withdrawal, which improves metal flow and reduces friction. Numerical simulations validated the effectiveness of this lubrication technique [5].

In some cases, combining backward, forward, and radial extrusion simplifies the manufacturing process and reduces production steps and costs. This approach has been used to deform aluminum alloys while analyzing the influence of die geometry. Experimental and numerical studies reveal potential defects and the impact of various parameters on part length and quality [6].

The demand for enhanced material properties, particularly in lightweight and hard metals, is growing across various applications. Severe plastic deformation processes, such as cyclic combined extrusion for aluminum alloys, address this need by improving mechanical properties through grain size reduction [7]. Complex geometries can be achieved using combined extrusion, accounting for friction and die geometry effects. Dead zones in the die, which cause defects, can be eliminated in steady-state combined extrusion processes [8].

An innovative method combining forward extrusion with equal channel angular pressing (ECAP) in a single die under hot working conditions has been employed to reinforce aluminum powders. This approach achieves superior mechanical properties and finer grain sizes compared to traditional extrusion methods [9].

The application of combined extrusion in ball and socket joints demonstrates the significance of compressive stresses and contact stress in the design and performance of these components [10]. In the case of hollow shapes, such as hexagonal components, combined forward-backward extrusion yields reliable results consistent with numerical analyses based on the upper-bound method. Finally, this method effectively evaluates stresses and pressures during the extrusion process [11].

E.H. Lee and R.L. Mallett [12] showed the residual stresses in parts produced by extrusion, which is one of the important problems that should receive great attention from researchers. The stresses inside the product lead to many defects, such as internal or external cracks while such parts are being used. R.M. Mc Meeking et al. [13] investigated the existence of residual stresses in parts after metal-forming processes had led to many problems. Such problems occurred because of non-uniform deformation and different distributions of strains in billets during pressing. X. Ma et al. [14] showed that for metal forming in general and aluminum extrusion in practice, the amount of friction between the billet and die wall has a great influence. N.S. Rossini, et al. [15] investigated how residual stresses always had an important effect on product quality and product properties, such as strength fatigue resistance. R.A. Hussien [16] showed that there was another effect of die geometry during combined backward-forward extrusion processes, especially an effect on stress and temperature during deformation. When the temperature distribution changed, the load and power also changed, so a numerical analysis was performed to determine the influence of flat and curved punch shapes on temperature rises and stress generation.

This study utilized the combined backward-forward extrusion process to examine the influence of velocity and pressure on the residual stresses of aluminum alloy AA 6061 T6.

2. MATERIAL AND METHOD (MATERYAL VE YÖNTEM)

A suitable die was designed and manufactured to achieve a combined backward–forward extrusion process for aluminium alloy AA 6061 T6. The die material was H13 and it was heat treated as HRC50. A hydraulic press machine was used with a maximum load capacity of 450 kN. The process was done using MOLYKOTE D321R lubrication. Two types of punches were used with the die with three cross-sectional areas using a reduction area 12%; (1) hexagonal punches (2) square punches. Three velocity values were used (Case 1=0.25, Case 2=0.5 and Case 3=1 mm/s). The workpiece, die , and room temperature are 25 C°. Cold extrusion is achieved using a stationary lower square punch and a moving hexagonal upper punch. The three pressures applied during the processes were applied to both square and hexagonal punches (Case 1=1.4, Case 2=1.6 and Case 3=1.8 kN/mm2).

The die, as shown Fig.1., consists of external parts for fixing the internal parts, which include hexagonal and square punches and three rings for keeping the punches and the axial movement during pressing. The lubricant is applied to billets and punches, and the velocity is constant during each pressing under three pressures.

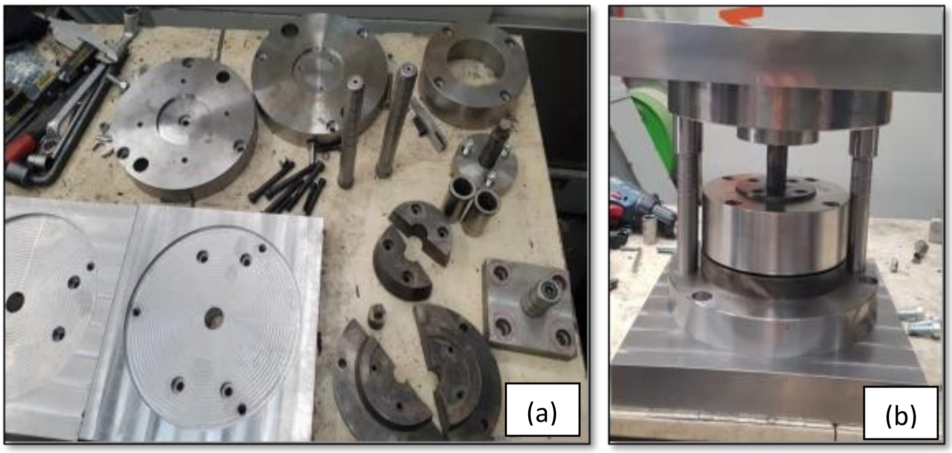


Figure 1. (a) Parts of the combined backward–forward extrusion process and (b) die assembly ((a) Birleşik geri-ileri ekstrüzyon işleminin parçaları ve (b) kalıp montajı)

The sets of punches are used in three conditions, and each set includes hexagonal and square punches with three types of billets that differ in their heights according to the punch cross-sectional areas. The punches are shown in Fig.2.

Figure 2. The types of three punch sets (Üçlü zımba setleri)

The workpiece material used in this study for the extrusion process was AA 6061 T6 aluminum alloy, selected due to its exceptional properties, which make it highly suitable for extrusion applications. Material properties used in this study was given in Table 1.

Table 1. Mechanical properties of AA6061 T6 aluminum alloy (AA6061 T6 alüminyum alaşımının mekanik özellikleri)

Density	2.70 g/cm³
Melting Point	650 °C
Thermal Expansion	23.4 x10^{-6} /K
Modulus of Elasticity	70 GPa
Tensile Strength	260 MPa
Hardness	95 HB

Three types of billet sets were prepared based on the specified process conditions and pressure requirements. These billets were designed for use with hexagonal and square punches and categorized according to three distinct heights, while maintaining a constant cross-sectional diameter across all samples. The wrench socket products has two sides one is hexagonal produce by backward extrusion and the other is square produced by forward extrusion process. The produced samples are shown in Fig. 3.

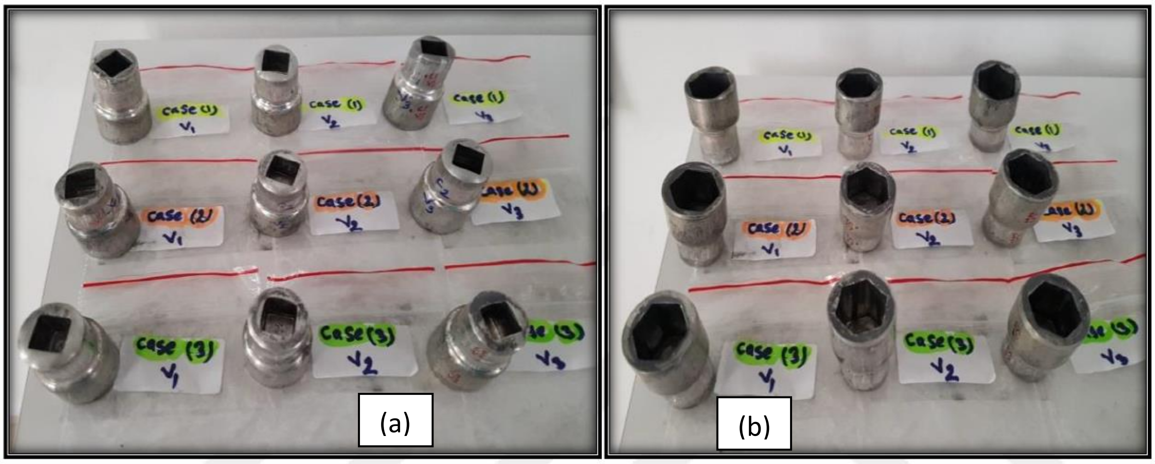


Figure 3. Samples for all cases: (a) Square side shape by forward extrusion; (b) Hexagonal side shape by backward extrusion (Tüm durumlar için örnekler: (a) İleri ekstrüzyonla kare kenar şekli; (b) Geri ekstrüzyonla altıgen kenar şekli)

The XRD 3003 TPS X-ray diffraction system was employed to measure residual stresses at various locations on the parts, as illustrated in Fig. 4. This method utilized a fixed penetration depth; however, potential errors may arise due to non-uniform penetration control. Accurate measurements rely on the samples being uniform, strain-free, and suitable for crystallographic texture analysis. The technique involves the dispersion of X-rays through a polycrystalline solid, producing diffracted beams that are analyzed by measuring angles in accordance with Bragg's Law.

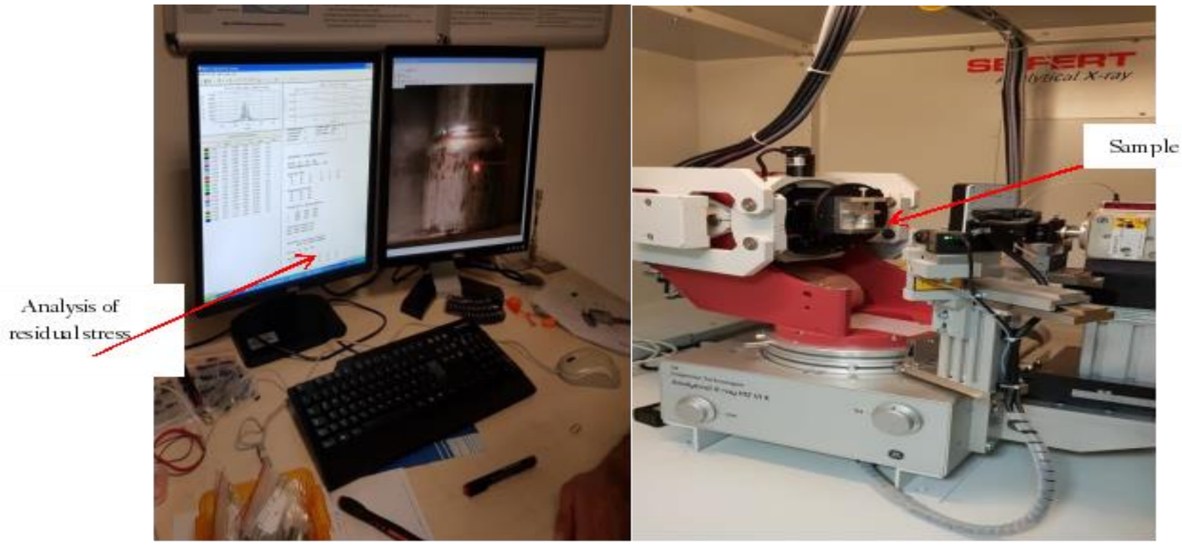
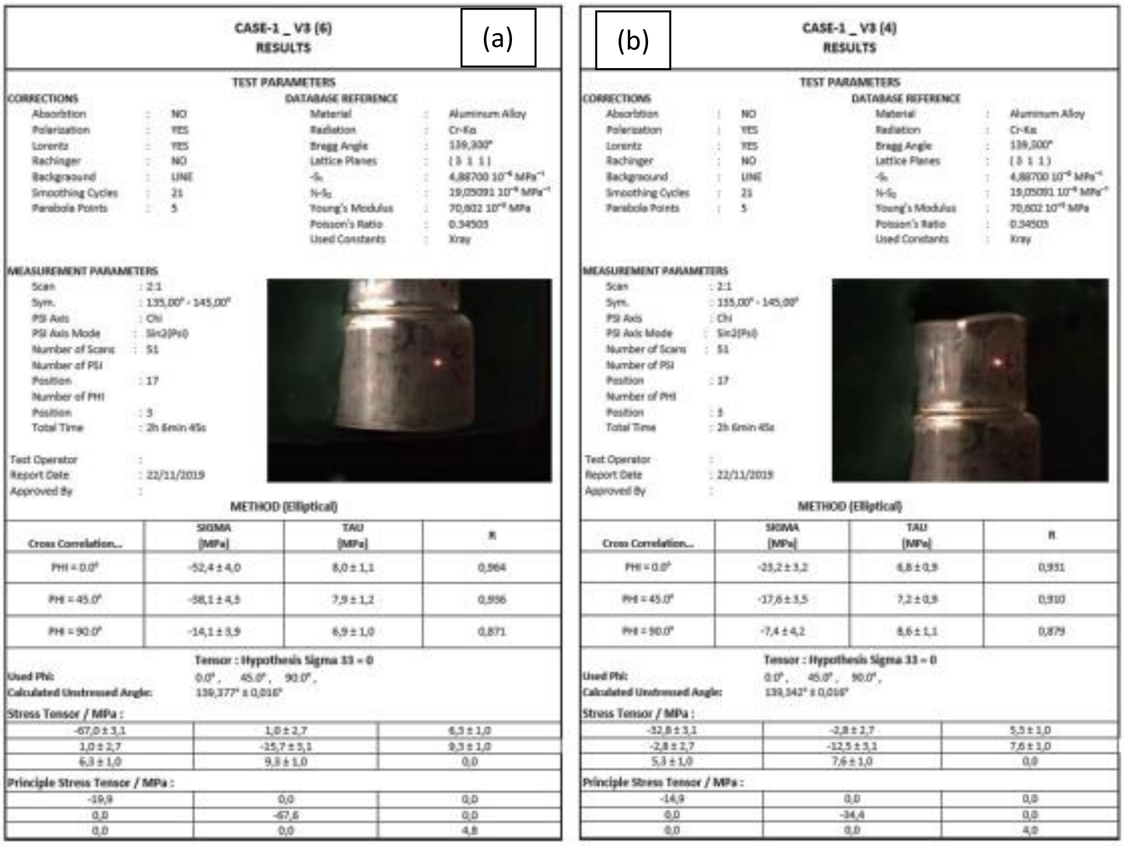


Figure 4. The XRD 3003 TPS X-ray diffraction system (XRD 3003 TPS X-ışını kırınımı sistemi)

3. RESULTS AND DISCUSSION (SONUÇLAR VE TARTIŞMA)

The residual stress test was performed using an X-ray machine for two points: (1) the backward region; and (2) the forward region and shown in Fig 5. This method is a non-destructive method and is a type of diffraction method that depends on calculating the residual stresses on the surfaces of the samples. It relies on the change in the strain calculated by elastic deformation and use Bragg`s law to convert the strain to the stress. The results of the stresses show that there is clear increase during the velocity duplicate in each case at constant pressure, and the highest value of stress =1315 MPa at the highest velocity v=1 mm/s in the backward region, and the minimum value of the stress was 470 MPa for the minimum velocity v1=0.25 mm/s in the forward region. These results indicate that during the combined forward backward extrusion process for wrench socket shape, the highest stresses occur in the backward region because of the opposite direction of metal flow relative to punch direction, which adds more strain and stress effects on the workpiece [16]. The middle region then recorded the second higher value and minimum values were shown in the forward region because of the direction of flow that is on the same direction of the pressing, which reduce, turbulent of flowing and the stress generated. This increase in stress has been observed in other studies and is attributed to the forced material flow caused by the interaction of two opposing movements [5,10,16]. For constant velocity , increasing the punch pressure led to a decrease in the residual stresses that lowest value of stress is 465 MPa in the forward region with the highest pressure p3=1.8 kN/mm^2.



(a)

CASE-1 _ V3 (6)
RESULTS

TEST PARAMETERS

CORRECTIONS		DATABASE REFERENCE	
Absorbtion	: NO	Material	: Aluminum Alloy
Polarization	: YES	Radiation	: Cr-Kα
Lorentz	: YES	Bragg Angle	: 139,300°
Rachinger	: NO	Lattice Planes	: { 3 1 1 }
Background	: LINE	-S₁	: 4,88700 10⁻⁶ MPa⁻¹
Smoothing Cycles	: 21	½·S₂	: 19,05091 10⁻⁶ MPa⁻¹
Parabola Points	: 5	Young's Modulus	: 70,602 10⁺³ MPa
		Poisson's Ratio	: 0.34503
		Used Constants	: Xray

MEASUREMENT PARAMETERS
Scan : 2:1
Sym. : 135,00° - 145,00°
PSI Axis : Chi
PSI Axis Mode : Sin2(Psi)
Number of Scans : 51
Number of PSI Position : 17
Number of PHI Position : 3
Total Time : 2h 6min 45s

Test Operator :
Report Date : 22/11/2019
Approved By :

METHOD (Elliptical)

Cross Correlation...	SIGMA [MPa]	TAU [MPa]	R
PHI = 0.0°	-52,4 ± 4,0	8,0 ± 1,1	0,964
PHI = 45.0°	-38,1 ± 4,5	7,9 ± 1,2	0,936
PHI = 90.0°	-14,1 ± 3,9	6,9 ± 1,0	0,871

Tensor : Hypothesis Sigma 33 = 0
Used Phi: 0.0°, 45.0°, 90.0°,
Calculated Unstressed Angle: 139,377° ± 0,016°

Stress Tensor / MPa :

-67,0 ± 3,1	1,0 ± 2,7	6,3 ± 1,0
1,0 ± 2,7	-15,7 ± 3,1	9,3 ± 1,0
6,3 ± 1,0	9,3 ± 1,0	0,0

Principle Stress Tensor / MPa :

-19,9	0,0	0,0
0,0	-67,6	0,0
0,0	0,0	4,8

(b)

CASE-1 _ V3 (4)
RESULTS

TEST PARAMETERS

CORRECTIONS		DATABASE REFERENCE	
Absorbtion	: NO	Material	: Aluminum Alloy
Polarization	: YES	Radiation	: Cr-Kα
Lorentz	: YES	Bragg Angle	: 139,300°
Rachinger	: NO	Lattice Planes	: { 3 1 1 }
Background	: LINE	-S₁	: 4,88700 10⁻⁶ MPa⁻¹
Smoothing Cycles	: 21	½·S₂	: 19,05091 10⁻⁶ MPa⁻¹
Parabola Points	: 5	Young's Modulus	: 70,602 10⁺³ MPa
		Poisson's Ratio	: 0.34503
		Used Constants	: Xray

MEASUREMENT PARAMETERS
Scan : 2:1
Sym. : 135,00° - 145,00°
PSI Axis : Chi
PSI Axis Mode : Sin2(Psi)
Number of Scans : 51
Number of PSI Position : 17
Number of PHI Position : 3
Total Time : 2h 6min 45s

Test Operator :
Report Date : 22/11/2019
Approved By :

METHOD (Elliptical)

Cross Correlation...	SIGMA [MPa]	TAU [MPa]	R
PHI = 0.0°	-23,2 ± 3,2	6,8 ± 0,9	0,931
PHI = 45.0°	-17,6 ± 3,5	7,2 ± 0,9	0,910
PHI = 90.0°	-7,4 ± 4,2	8,6 ± 1,1	0,879

Tensor : Hypothesis Sigma 33 = 0
Used Phi: 0.0°, 45.0°, 90.0°,
Calculated Unstressed Angle: 139,342° ± 0,016°

Stress Tensor / MPa :

-32,8 ± 3,1	-2,8 ± 2,7	5,5 ± 1,0
-2,8 ± 2,7	-12,5 ± 3,1	7,6 ± 1,0
5,3 ± 1,0	7,6 ± 1,0	0,0

Principle Stress Tensor / MPa :

-14,9	0,0	0,0
0,0	-34,4	0,0
0,0	0,0	4,0

Figure 5. The report of residual stresses given by the machine for (a) backward region (b) forward region ((a) Geri bölge (b) İleri bölge için makine tarafından verilen kalıntı gerilme raporu)

An X-ray diffraction (XRD) test was conducted to determine the residual stresses in the forward, backward and middle regions under three different velocity and pressure conditions. The analysis involved varying the product's angle and position relative to the X-ray beam, specifically adjusting the Bragg angle, to obtain optimal results. A similar procedure was applied in the forward region to evaluate residual stresses by altering the Bragg angles. The X-ray equipment was capable of calculating shear stresses, principal stresses, and residual stresses. Each point measurement required over two hours and involved multiple scans, with material properties such as Poisson's ratio and Young's modulus input into the system to ensure accurate calculations.

According to Fig 6., the stress analysis indicates elevated values, particularly in the central regions, due to the influence of opposing punch directions, which intensify frictional forces and promote turbulent metal flow. Conversely, the lowest stress values were observed in the forward region, where the metal flow aligns with the punch direction, resulting in reduced resistance. Compressive stresses are denoted by negative values in the results. Furthermore, at constant pressure, an increase in velocity corresponds to an increase in stress magnitude, highlighting the influence of processing parameters on stress distribution. The residual stresses were measured using an X-ray diffraction system across the forward (Figure 6 (b)), middle (Figure 6 (a)), and backward (Figure 6 (c)) regions of the material. The results indicate that, under constant pressure, an increase in velocity leads to a corresponding increase in residual stress in all regions. The data and accompanying graphs reveal that the middle region exhibited the highest residual stress values compared to the backward and forward regions, while the forward region consistently demonstrated the lowest stress values. This trend highlights the significant impact of material flow dynamics on the distribution of stress during the extrusion process [2-4, 17].

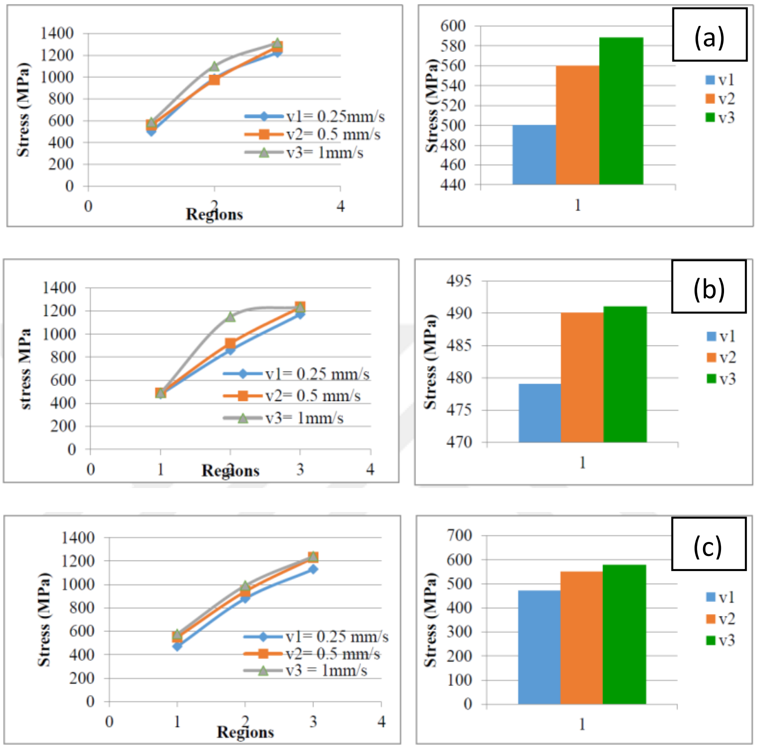


Figure 6. Stresses at different regions with constant pressure P3 = 1.8 kN/mm^2 and different velocities: (a) forward extrusion region, (b) backward extrusion region, (c) middle region

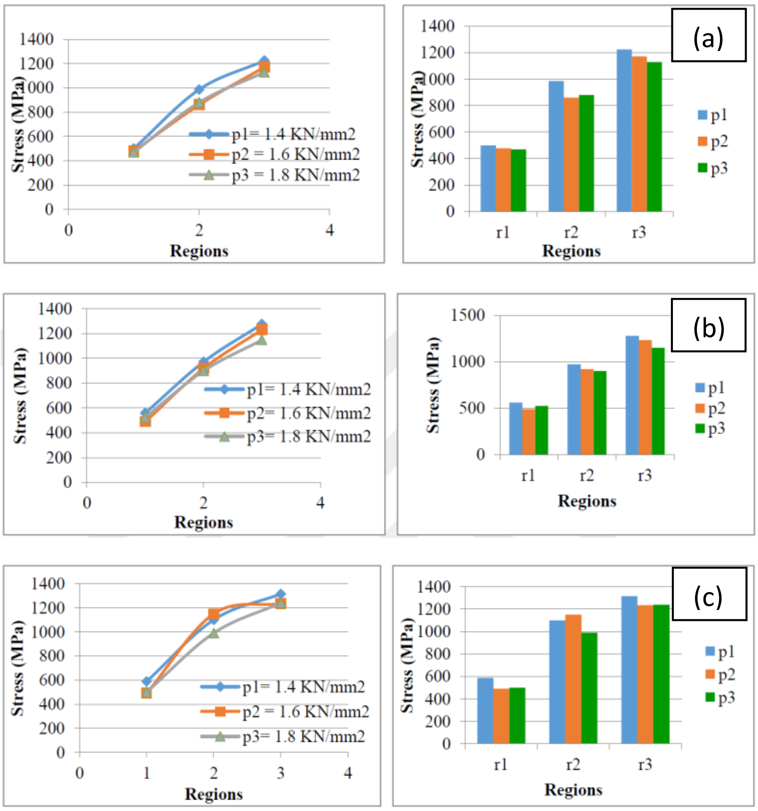


Figure 7. Stresses in different regions with constant velocity V3=1 mm/s and different pressures (a) forward extrusion region, (b) backward extrusion region, (c) middle region

At a constant velocity, an increase in pressure leads to a reduction in residual stresses, as shown in Fig. 7. This is attributed to the diminished effect of frictional forces and the heat generated under higher pressures, which consequently lowers the stress levels (Figure 7 (b)). The results show a decrease in stress values with increasing pressure at constant velocity, with the highest stresses observed in the middle region (Figure 7 (c)). In contrast, the forward region (Figure 7 (a)) exhibited the lowest stress values, likely due to the alignment of the metal flow with the direction of the applied pressure. The increased deformation speed during the extrusion process of aluminium alloys facilitates material heating and enhances formability; however, it also leads to elevated internal demands within the material [8, 18-20].

4. CONCLUSIONS (SONUÇLAR)

The combined backward-forward extrusion process demonstrated significant advantages over separate extrusion methods, including reduced production costs and time, improved final product quality, enhanced mechanical properties, more uniform residual stress distribution, and the ability to produce more complex shapes.

- Aluminium alloy AA 6061 T6 demonstrated excellent formability during the cold working of the combined extrusion process.
- Increasing the pressure to P_3 = 1.8 kN/mm² yielded optimal results, including improved product shape, uniform laminar flow and deformation, enhanced surface finish, reduced residual stresses, decreased deformation load requirements, and a slight increase in processing time.
- On the other hand, increasing the velocity to V_3=1 mm/s resulted in higher residual stresses and deformation loads. While this velocity improved laminar and homogeneous flow, surface finish, and dimensional accuracy, it also reduced processing time and increased the billet temperature.
- Based on these findings, the recommended velocity is V_2=0.5 mm/s, as it effectively reduces stress and load requirements while maintaining product quality, flow uniformity, and surface finish.

Thus, the optimal process parameters for the combined extrusion of aluminium AA 6061 T6 alloy are a pressure of P_3=1.8 kN/mm² and a velocity of V_2=0.5 mm/s, which balance stress reduction, load efficiency, and product quality.

ACKNOWLEDGMENTS (TEŞEKKÜR)

We would like to thank Magnum Engineering Industry and Trade Co. Ltd. for their technical and financial support.

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