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Investigating the Effects of Cold Bulge Forming Speed on Thickness Variation and Mechanical Properties of Aluminum Alloys: Experimental and Numerical

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ABSTRACT

In this work, cold bulge forming of an Aluminium-Magnesium (Al-Mg) sheet with a solid bulging medium is experimentally and numerically performed. Mechanical properties and thickness variations of Al-Mg sheet are evaluated before and after the forming process. The results indicated that the Al-Mg sheet has taken the desired shape without necking using the cold bulge forming process. Also, the experimental results showed significant improvements of 13 and 9.7% in yield and ultimate tensile strengths of Al-Mg sheet after bulge forming. It is proved that the maximum thickness reduction of Al-Mg blank is less than 6% after cold bulge forming. Numerical simulations of cold bulge forming of Al-Mg sheet are conducted using Abaqus finite element software. For this purpose, many numerical models were created and analyzed to investigate the effects of bulge forming speed on the blank thickness variation for different Aluminium alloys. In these simulations, four different speed of 1, 5, 15 and 25 mm/min are used as forming speeds. Numerical results of bulge forming of Al-Mg sheet were compared with experimental measurements and good correlation, less than 2.6% difference at critical zone, was observed between the results. Moreover, obtained results from numerical simulations for different Aluminium alloys showed that the thickness variations of formed Al-Mg sheet are more uniform by reducing the forming speed. Note also that, the less strength of material, the more uniform thickness variation is achievable along longitudinal direction of metal sheet.

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1. INTRODUCTION

Sheet metal forming as one of the most important key parameters in providing low cost manufacturing in the automotive industry has attracted a great deal of interest in recent years [1-3]. Incremental Sheet Forming (ISF) is an extremely flexible process using a single generic tool for an infinite variety of shapes with great advantages of lower cost, the use of a conventional CNC machine, reducing stress concentrations in material, the possibility of forming parts with any dimension, a good surface finish of the formed parts, and a high material formability [4]. Another innovative method which has been introduced in sheet metal forming industries is laser forming process. Laser forming is a non-contact method of 2D bending and 3D shaping of components using a moving heat source such as laser beam is one of the most economical methods of forming [5-7]. In contrast to these forming processes which need complex equipment, bulging is a novel forming technique for production of complex components from tubular blanks using internal pressure and axial loads [8]. In the bulge forming process, the tubular blank is held in a matrix with the desired shape and the hydrostatic internal pressure is applied using a liquid/gas pressure [9-11] or solid bulging medium [12-14]. When the axial load and internal pressure applied at the same time, the tube material flows into the die cavities and finally takes the shape of the die [12]. The use of a rubber rod as pressure carrying medium for metal forming has many advantages compared to conventional forming tools. For example, by using a rubber rod, the frictional forces between the tube blank and the rubber are developed; which produces lateral

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pressure to the tube in order to affect its expansion. Also, the insertion of the rubber rod is quick and convenient and cleaning or drying of the produced component after forming is not required. In recent years some of researches in the field of bulge forming have been performed.

McDonald and Hashmi [8] simulated solid bulge forming of cross-branch components with a three-dimensional model. Tabatabaei et al. [12] investigated the cold bulge forming of titanium alloy Ti55 in both experimental and numerical methods. Their results showed mechanical properties improvement of titanium alloy Ti55 after bulge forming. Girard et al. [13] used a nonlinear finite element analysis to investigate the deformation mechanisms during axisymmetric bulging of copper tubes using a urethane medium. Their results showed that, the friction between the tube and the urethane rod can be advantageous, if kept under control, as it can result in preventing excessive thinning of the tube. Ramezani et al. [14] after investigating static friction behaviour of polyurethane/metal contact in tube bulging process found the developed static friction model has better prediction of thickness distribution than Coulomb’s friction model.

As can be inferred from the presented literature review, many researchers have investigated the bulge forming process in recent years using different methods. Generally, these investigations have been limited to the bulge forming using viscous medium in comparison to solid medium. Also, numerical and experimental investigation of bulge forming process using polyurethane medium have been rarely investigated. Therefore, the main goal of this paper is to perform cold bulge forming process to shape Al-Mg alloy blank using experimental and numerical methods. Firstly, an experimental program was conducted to form Al-Mg tubes into the complex cylindrical die using polyurethane medium. For this purpose, a cylindrical Al-Mg tubes with constant thickness were prepared and were subjected under cold bulge forming. Mechanical properties of Al-Mg alloy were investigated before and after forming process. Also, thickness variation of sheet metal due to bulging were experimentally determined. Moreover, numerical simulation of this process for Al-Mg alloy blank was conducted in Abaqus software. Experimental and numerical results were compared and good agreement was observed between the results. In addition, numerical simulation of cold bulge forming for four different alloys was performed to obtain thickness variation of blank after bulging.

2. EXPERIMENTAL WORK

2. 1. Materials In this work, Aluminum-Magnesium alloy is used as a blank in bulge forming process. Chemical composition of used alloy are listed in Table 1. In order to prepare appropriate sheets for bulge forming process, preliminary blanks were trimmed based on desired pattern and then rolled. Finally, the specimens with a initial thickness of 2mm were prepared based on a hollow cylindrical shape. Note that, these specimens were prepared from annealed isotropic sheets.

Natural rubber, neoprene, polyurethane or other elastomers can be used as a flexible tool in the forming processes [12]. Due to their good chemical resistance, thermal stability and ability to withstand high forces, polyurethanes are used more in comparison to other elastomers. Although, polyurethane is deformable, it behaves like an incompressible fluid and when completely compressed, equal pressure is applied in all directions. After unloading, polyurethane returns to initial shape. Urethanes are produced in a wide range of hardness, which urethanes with Shore hardness in a range of 70 to 95 A^0 are typically used as metal forming tools [14]. In this paper, a polyurethane rod with shore hardness of 70 A^0 is used as a rubber medium.

2. 2. Bulge Test Bulge forming process of Al-Mg alloy was performed using a urethane rubber as a solid bulging medium. The setup of bulge forming process of the presented work is schematically shown in Figure 1. As can be seen in Figure 1, blank with hollow cylindrical shape was placed into the desired die. Moreover, a polyurethane rubber was inserted into the blank with minimum gaps between them. Finally, the hydraulic press with capacity of 325 kN compressed the rubber rod at a constant speed of 25mm/min. As a result of this compression, the blank was pushed completely into the desired die due to the internal pressure.

2. 3. Mechanical Property Characterization

2. 3. 1. Aluminium Alloys Uniaxial tensile test was used to evaluate the mechanical properties of Al-Mg bulge formed components. For this purpose, a total of 8 tensile test specimens were prepared according to D638-IV ASTM standard before and after bulge forming process [15]. In Figure 2, an Al-Mg standard specimen after uniaxial tensile test is shown.

TABLE 1. Chemical Composition of Al-Mg alloy sheet

Element	Al	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
Composition (%)	93.5-94.5	0.4	0.4	0.1	0.1-0.4	4.0-4.9	0.05-0.25	0.25	0.15

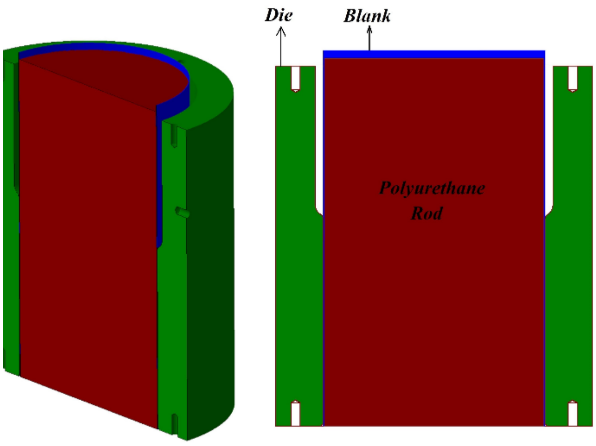

Figure 1. Three dimensional schematic model of bulge forming process using rubber medium

Also, to investigate the effect of bulging speed, mechanical properties of four different Aluminium alloys with various ductility were obtained using tensile test. Santam universal testing machine STM-20 with a 20kN load cell was used to perform uniaxial tensile tests. These tests were performed at four different speeds of 1, 5, 15 and 25mm/min.

2. 3. 2. Polyurethane Medium The compressive behaviour of polyurethane rod was obtained using simple compression test at four different speeds of 1, 5, 15 and 25mm/min. For this purpose, compressive specimens were prepared and tested according to D695 ASTM standard [16]. Four compressive cylindrical test specimens with height of 9 mm and diameter of 8.5 mm were prepared and tested at each test speed. Thus, a total of 16 tests were conducted.

3. NUMERICAL CHARACTERIZATION

In this paper, bulge forming process is also performed using Finite Element (FE) simulations. In the FE models, related components in cold bulge forming were modeled with the geometries as the same as experimental setup. The deformable cylindrical blank and urethane rod were embedded into the desired die with complex shape. In these simulations, the punch and the die were modelled as rigid components.

Figure 2. Al-Mg alloy standard tensile specimen after testing

Note that, nonlinear mechanical behaviour of polyurethane rod and Aluminium alloys were extracted from their stress-strain curves. The prepared model with its boundary conditions is shown in Figure 3. As can be seen in this figure, due to the symmetry, half of the model was conducted in Abaqus and symmetry boundary conditions were applied on the midline. For this purpose, the translational degree of freedom in X-direction (U1) and rotational degree of freedom about Y- and Z-axis are constrained on axisymmetric axis of polyurethane. Also, velocity along Y-direction and fully-constrained boundary conditions are applied to punch and die models, respectively. Moreover, some investigations were done to find the best element size for Al-Mg alloy sheet. It can be concluded from Table 2 that optimized number of elements for alloy sheets is 930. Also, 2520 elements were generated for polyurethane model. In addition, the type of used elements in these simulations is CAX4R. It should be noted that, the coulomb friction coefficient between all parts of the model is taken as 0.15.

4. RESULTS

4. 1. Experimental Bulge Forming In Figure 4, the bulge formed tube obtained from experimental work is shown. As it is seen in this figure, the bulge forming process of Al-Mg alloy using polyurethane medium was successfully performed and the tabular component was produced without any necking and wrinkling.

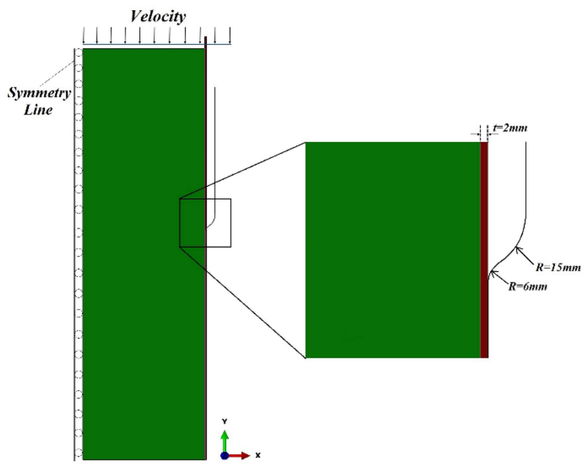

Figure 3. Applied boundary conditions in bulge forming model (the magnification shows the dimensions)

TABLE 2. Results of mesh convergence investigation for Al-Mg alloy sheet

Number of Elements	233	310	930	1860	3720
Stress (MPa)	317.6	320.3	321.2	321.5	321.6

Figure 4. Cold bulge formed Aluminium blank after bulge forming process using polyurethane medium

4. 2. Mechanical Characterization In Table 3, the results of uniaxial tensile test of a standard specimen of Al-Mg alloy before and after cold bulge forming are presented. As can be seen in Table 3, yield and ultimate tensile strength of Al-Mg alloy increase during the cold bulge forming due to strain hardening. Note also that, cold bulge forming process results in an increase of 13 and 9.7% in yield and ultimate tensile strengths of Al-Mg alloy, respectively. In addition, fracture strain of cold bulge formed samples is decreased by 22.7% due to strain hardening, meaning significant decrease in ductility of Al-Mg alloy sheet owing to effects of bulge forming process on alloy microstructures.

Also, in Figure 5 the stress-strain curves of four different Aluminium alloys such as: Al 7075-T6, Al 5083, Al 5052-H32 and Al 6061-T62 are presented. Note that, nonlinear tensile stress-strain data of these alloys were used as input material properties in finite element simulations. These four Aluminium alloys were collected in order to see the effects of different material strengths on formability of sheet metals after cold bulge forming process. As can be seen in this figure, Al-7075 T6 shows highest yield and ultimate strengths, approximately twice greater than Al-5052 H34, demonstrating the lowest value of 193 and 228 MPa for yield and ultimate tensile strengths, respectively. Moreover, the compressive behaviour of polyurethane rubber medium was investigated using simple compression test. Compressive stress-strain curve of polyurethane specimens at four different speed of 1, 5, 15 and 25mm/min are presented in Figure 6.

TABLE 3. Experimental tensile mechanical properties of Al-Mg alloy blank before and after process.

Test specimen	Yield Strength (MPa)	Ultimate Strength (MPa)	Fracture Strain
Before bulging	156.1	326.9	0.101
After bulging	179.7	362.2	0.078

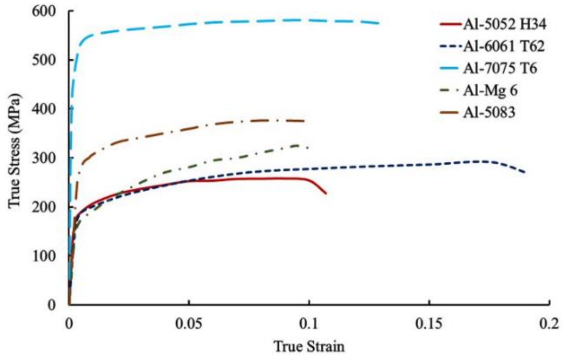

Figure 5. Tensile stress-strain curves of four different Aluminium alloys

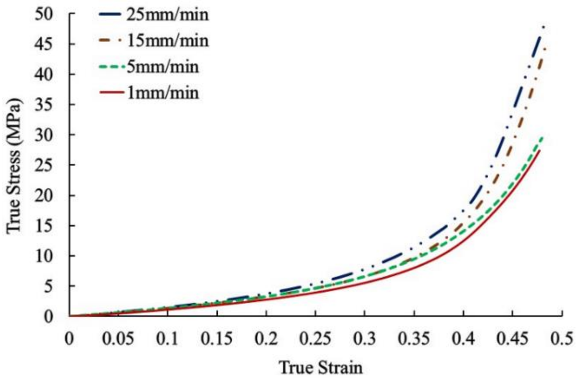

Figure 6. Compressive stress-strain curves of polyurethane specimens at four different speed

Note in this figure that, the strain hardening of test specimens increased dramatically at higher test speeds. It should be noted that, the nonlinear compressive behaviour of polyurethane rod at different test speed was used as input material properties for rubber medium in finite element simulations.

4. 3. Numerical Simulation Bulge forming process with a polyurethane medium for different Aluminium alloys has been performed numerically using Abaqus software. Numerical simulations were conducted in various bulging speeds for each Aluminium alloy. A bulge formed Al-Mg alloy with its stress contour is shown in Figure 7. As it is shown, two magnifications of bulge formed blank at critical and waste regions are shown. It can be seen in Figure 8, the thickness variation in critical zone are almost uniform. In addition, the maximum stress occurs at a region between critical and waste zones. It should be noted that the in the experimental works in order to obtain the final product, the waste region will be trimmed. In Figure 8, final product obtained by experimental and numerical works is shown.

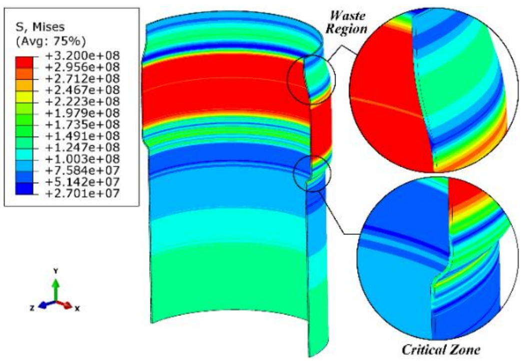

Figure 7. Stress contour plot in Al-Mg alloy blank after bulge forming process

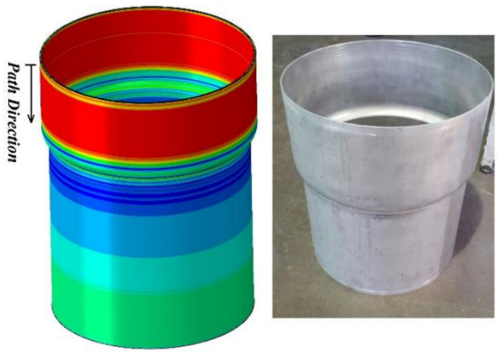

Figure 8. Comparison of final product obtained using numerical and experimental methods

Also, thickness variation in Al-Mg alloy blank obtained by numerical method is compared with experimental result. The result of this comparison is shown in Figure 9. As can be seen, the difference between experimental and numerical result at critical point is less than 2.6%. Thus, an excellent correlation is observed between numerical and experimental results.

Conducting an experimental program to investigate the effects of bulge forming speed on thickness variation of different alloys results in high cost of preparation and testing. For this reason, using numerical simulation is an efficient way to estimate mentioned parameters with good accuracy. In Figure 10, the effects of bulging speeds on the thickness variations of bulge formed parts are presented in the numerical work. As can be seen in Figure 10, thickness variations along the longitudinal direction in four different speeds of 1, 5, 15 and 25mm/min are shown. It should be noted that, by passing of critical zone, the blank thickness variation is negligible and is equal to initial blank thickness. Thus, this area is not presented in related diagrams. Note in Figures 10(a) through 10(d), thickness variation in Aluminum alloys are became more uniform as a result of speed reduction.

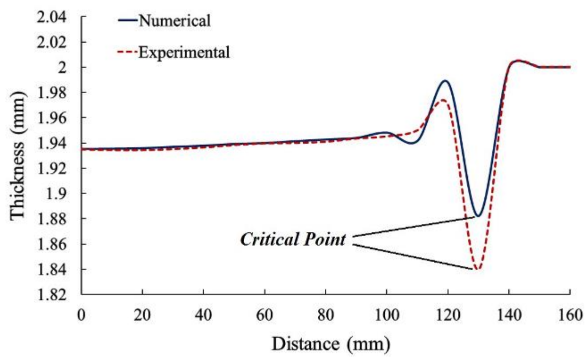

Figure 9. Comparison of thickness variation obtained using experimental and numerical methods

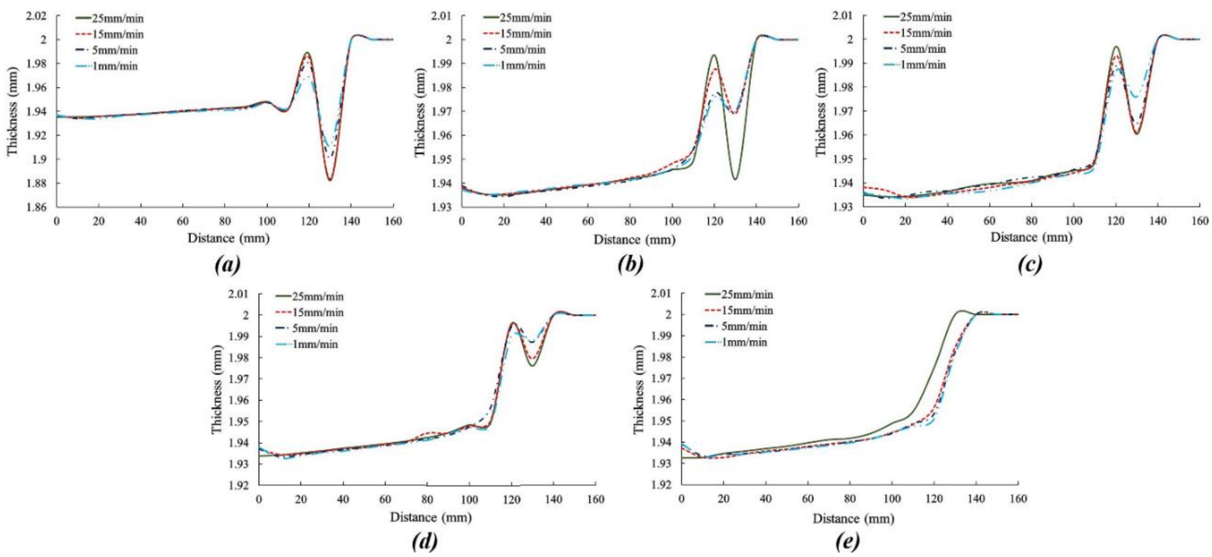

Figure 11. Thickness variation along with blank longitudinal direction at four different speed of 1, 5, 15 and 25mm/min, (a) Al-Mg, (b) Al 5083, (c) Al 7075-T6, (d) Al 6061-T62, and (e) Al 5052-H32

Also, initial stage of all bulged alloy sheets shows the same trend for thickness variation, approximately 1.94 mm. In Figures 10(a) through 10(d), some fluctuations can be seen due to reaching to critical zone of bulged sheets. Only in Figure 10(a), referred to Al-Mg alloy sheet, the thickness variation in critical zone (below 1.9 mm) is lower than the initial stage thickness, while in other Aluminum alloys, thickness in critical zone shows increasing trend compared to initial zone of bulged sheets. In Figure 10(e), different trend in thickness variation can be observed. In this figure, there is no fluctuation in thickness variation, followed by a continuous increasing to reach the end of longitudinal path. Also, it can be concluded from the results that the less strength of alloy materials, the more uniform thickness along longitudinal direction of sheet metal is achievable.

5. CONCLUSION

In this paper, experimental and numerical methods were used to shape Aluminium-Magnesium alloy sheets using cold bulge forming process. It was observed that, bulge forming of Al-Mg alloy blanks were successfully performed. Also, the investigation of Mechanical properties of Al-Mg alloy blanks before and after forming process shows drastic improvement in mechanical properties due to cold bulge forming. In addition, the thickness reduction in critical point of Al-Mg sheet is less than 6%. Numerical simulation of cold bulge forming was conducted in Abaqus finite element software. For this purpose, series of numerical models were used to investigate the effects of bulge forming speed on blank thickness variation for different Aluminium alloys. Firstly, numerical result of Al-Mg alloy bulging was compared with experimental measurements and good agreement was observed between the results. After validation of bulging numerical model, four different Aluminium alloy such as: Al-5083, Al 7075-T6, Al 6061-T62 and Al 5052-H34 are numerically shaped at four different speeds of 1, 5, 15 and 25mm/min. The results of these models suggest that with reducing the bulging speed, blank thickness variation became more uniform.

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چکیده

در این پژوهش، فرآیند بالج سرد ورق آلیاژی آلومینیوم- منیزیم با استفاده از واسط جامد به صورت تجربی و شبیه‌سازی انجام گردید. خواص مکانیکی و تغییرات ضخامت ورق آلومینیوم-منیزیم قبل و بعد از فرآیند شکل‌دهی محاسبه گردید. نتایج نشان داد که ورق آلومینیوم- منیزیم بدون گلویی شدن با استفاده از فرآیند شکل‌دهی بالج سرد به شکل دلخواه در آمده است. همچنین، نتایج آزمایشگاهی نشان‌دهنده‌ی بهبود قابل توجه ۱۳ و ۹/۷ درصدی در استحکام تسلیم و استحکام نهایی ورق آلومینیوم-منیزیم بعد از فرآیند بالج می‌باشد. این موضوع اثبات گردید که حداکثر کاهش ضخامت ورق آلومینیوم-منیزیم بعد از شکل‌دهی بالج سرد کمتر از ٦ درصد می‌باشد. شبیه‌سازی‌های عددی شکل‌دهی بالج سرد ورق آلومینیوم-منیزیم در نرم‌افزار اجزاء محدود آباکوس انجام گردید. به همین منظور، مدل‌های عددی بسیاری جهت بررسی اثرات سرعت شکل‌دهی بالج بر تغییرات ضخامت ورق برای آلیاژهای آلومینیوم متفاوت ساخته و تحلیل گردید. در این شبیه‌سازی‌ها، چهار سرعت متفاوت ۱، ۵، ۱۵ و ۲۵ متر بر ثانیه به عنوان سرعت شکل‌دهی استفاده گردید. نتایج شبیه‌سازی شکل‌دهی بالج ورق آلومینیوم-منیزیم با نتایج تست تجربی مقایسه گردید و همخوانی خوبی میان نتایج، تفاوتی کمتر از ۲/٦ درصد در ناحیه بحرانی، مشاهده شد. علاوه بر این، نتایج به دست آمده از شبیه‌سازی‌های عددی برای آلیاژهای آلومینیوم متفاوت نشان داد که تغییرات ضخامت ورق آلومینیوم-منیزیم شکل داده شده با کاهش سرعت شکل‌دهی یکنواخت‌تر گردیده است. شایان ذکر است، هرچه استحکام ماده کمتر، تغییرات ضخامت یکنواخت‌تر در راستای طولی ورق فلزی قابل دستیابی می‌باشد.

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