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ORIGINAL ARTICLE

Hot forming process with synchronous cooling for AA2024 aluminum alloy and its application

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Abstract Hot forming process with synchronous cooling (HFSC) for heat-treatable, high-strength aluminum alloys is a novel technique to solid dissolve and then form and quench blanks at the same time. After the HFSC procedure, microstructures of final products can directly determine their mechanical properties. To investigate the technological processes of HFSC and the effects of this novel technique on the microstructure and mechanical properties of the final products, experiments were launched on AA2024 aluminum alloys in H18 and O tempers processed by hot bending process with synchronous cooling and two traditional cold forming methods. Then, springback and microstructure of the final products were analyzed and mechanical properties of material were measured by tensile tests. The results show that HFSC can improve the formability of AA2024 aluminum alloy, simplify the production process of parts, and improve the dimensional accuracy of the final products with reduced springback and no warp distortion. After natural aging for 96 h at room temperature, the products subjected to the hot bending process with synchronous cooling exhibited a significant increase in strength. Additionally, material hardening was observed in the formed regions of the products that were formed by hot bending with synchronous cooling, where the alloy's yield strength was higher than that in other regions.

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Keywords Hot forming process with synchronous cooling · AA2024 aluminum alloy · Mechanical properties · Metallographic structure

1 Introduction

Since significant weight loss in final products without affecting structural performance has been an ever-increasing demand in aerospace and auto industries, lightweight materials become a reasonable choice [1, 2]. Thanks to their light quality, high strength, and stiffness, heat-treatable, high-strength aluminum alloys showed great potential in aerospace [3, 4] and auto [5] industries and become the first lightweight material used for the production of lightweight cars, planes, and spacecraft. Heat-treatable, high-strength aluminum alloys include 2XXX, 6XXX, and 7XXX series. The 6XXX series is mainly used in auto industry, while 2XXX and 7XXX are used in aerospace industry. However, sheets of these alloys are difficult to be formed into complex contoured parts by traditional cold stamping processes because of their narrow plastic deformation range, low cracking resistance, and Young's modulus. An elevated forming temperature in warm [6] or hot [7] can improve their formability, but other problems, like grain growth, high energy consumption, and low productivity, also emerge. Moreover, after a forming process, the formed parts also need solution and aging treatments to achieve the performance requirements, so the possibility of warp distortion during solution treatment exists. Therefore, a low-cost technique, improving the formability while maintaining the strength, is crucial for the widespread use of heat-treatable, high-strength aluminum alloys.

Since the formability of aluminum alloys can be improved by either cryogenic [8] or elevated [9] forming temperatures, the hot forming process with synchronous cooling (HFSC) is a novel technique to form sheets of heat-treatable, high-strength aluminum alloys into complex contoured parts. In HFSC, blanks are solid dissolved and subsequently formed and quenched at the same time [10]. This procedure evolved from hot stamping process of high-strength steels [11–14]. The basic procedure of HFSC is shown in Fig. 1. First, the blank is heated to the solution treatment temperature and held for a period of time so that the strengthening phase is dissolved into the α(Al) matrix. Second, the blank is transferred to the press and then formed and quenched in water cooling dies. In this step, a semi product with a microstructure of supersaturated solid solution (SSSS) and a precise shape is formed. Finally, the semi product is trimmed to the final shape and aged to obtain full strength. Compared with traditional forming methods, this technique shortens processing time and produces parts with high formability, negligible springback, and effective mechanical properties [15].

Not so many researchers have studied HFSC. Garret et al. investigated the feasibility of this novel technique for AA6082 alloy [16]. Researchers from Imperial College London reported formability and failure features of AA2024 [15] and AA6082 [17] processed by HFSC. Chen et al. launched a pilot study to simulate HFSC operations for AA6016 aluminum alloy using a thermoforming simulator and verified that the strength of AA6016 was improved after HFSC [10]. Jeon et al. conducted a feasibility study on die quenching of AA2024 aluminum alloy billet using servo press [18] and then investigated the die-quenching limit of this material [19]. Wang et al. obtained the power law constitutive model of AA6016-H18 under hot forming process with synchronous cooling operations [20].

HFSC is different from traditional forming processes. The temperature of the blank drops rapidly during HFSC due to the heat transfer between sheet metal and water cooling dies. In addition, the heat transfer mechanism and the cooling rate of the blank are different from those when the blank is quenched in water or other media. These differences may lead to the changes in the microstructures and mechanical properties of heat-treatable, high-strength aluminum alloys.

The main objectives of the present research are to investigate the technological processes of HFSC and its effects on microstructures and mechanical properties of final products. A sheet of AA2024 aluminum alloy was chosen as the object, and the alloy processed by HFSC was compared with that by traditional cold forming technique in terms of springback, geometry, dimension accuracy, mechanical properties, and microstructures.

Table 1 Chemical compositions of 2024 (mass fraction, %)

Si	0.4
Fe	0.3
Cu	4.1
Mn	0.67
Mg	1.52
Cr	0.03
Zn	0.18
Ti	0.06
Al	The rest

2 Experimental procedures

2.1 Materials and tools

A commercial AA2024-H18 aluminum alloy sheet with a thickness of 0.8 mm was selected. Its compositions are listed in Table 1. The sheet was cut into blanks with a size of 190×80×0.8 mm, and the blanks' length direction was along the rolling direction. The initial blanks were in an H18 temper, and some of them were annealed into an O temper for the experiment through the following procedure: blanks were held at 400 °C for 2.5 h and then cooled down to room temperature with a cooling rate of 20 °C/h. Special dies, installed on a modified high-speed hydraulic press, were employed to conduct hot bending process with synchronous cooling, as shown in Fig. 2. A water cooling system was designed within the dies to transfer heat out.

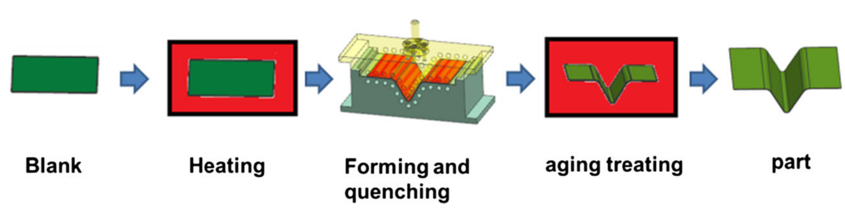


Fig. 1 Basic chain of HFSC

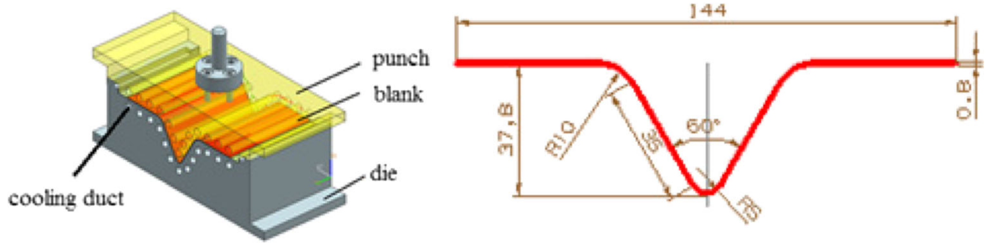


Fig. 2 Dies for hot bending process with synchronous cooling

2.2 Forming method and process

An outline of the experiment is shown in Fig. 3. The forming methods were classified into six categories: hot bending process with synchronous cooling of AA2024 in H18 temper (HHFSC) and O temper (OHFSC), solution treatment subsequent to forming process of AA2024 in H18 temper (HFS) and O temper (OFS), and forming process subsequent to solution treatment of AA2024 in H18 temper (HSF) and O temper (OSF).

In the hot bending with synchronous cooling experiments (HHFSC and OHFSC), the blanks were rapidly heated to the solution treatment temperature of 495 °C and held for 5 min. Then, they were directly transferred to the press and subsequently formed and held for 1 min in the dies. The formed parts were quenched by the water cooling dies during the forming and holding processes. For HFS and OFS, the blanks were formed at room temperature and then heated to 495 °C and held for 5 min in a furnace. Finally, they were quenched in water at room temperature. In the experiments using HSB and OSB, the blanks were first heated to 495 °C and held for 5 min in a furnace and then quenched in water at room temperature. After that, the quenched blanks were formed in dies at room temperature. The interval between quenching and forming was within 10 min. All the samples underwent 96 h of natural aging for further experiments.

2.3 Tensile test

A uniaxial tensile test was conducted with a constant strain rate of 0.00025 s^{-1} to evaluate mechanical properties of the AA2024 samples formed using different methods. Each of the samples to be tested was cut into a certain shape by WEDM, as shown in Fig. 4.

2.4 Metallographic test

The grain size and general microstructural texture of the cold-mounted AA2024 specimens, which were cut from the samples formed using different methods, were observed through optical microscopy. The specimens were etched in Keller's etchant for 15–20 s, wiped with a cotton ball and nitric acid, and then thoroughly washed by water and dried. Digital micrographs of the specimens were then captured using a PME Olympus Tokyo metallographic microscope.

3 Results and analysis

3.1 Forming accuracy

The samples formed using different methods are shown in Fig. 5. The R5 fillet of the AA2024-H18 sample cracked during HFS process, because AA2024-H18 al-

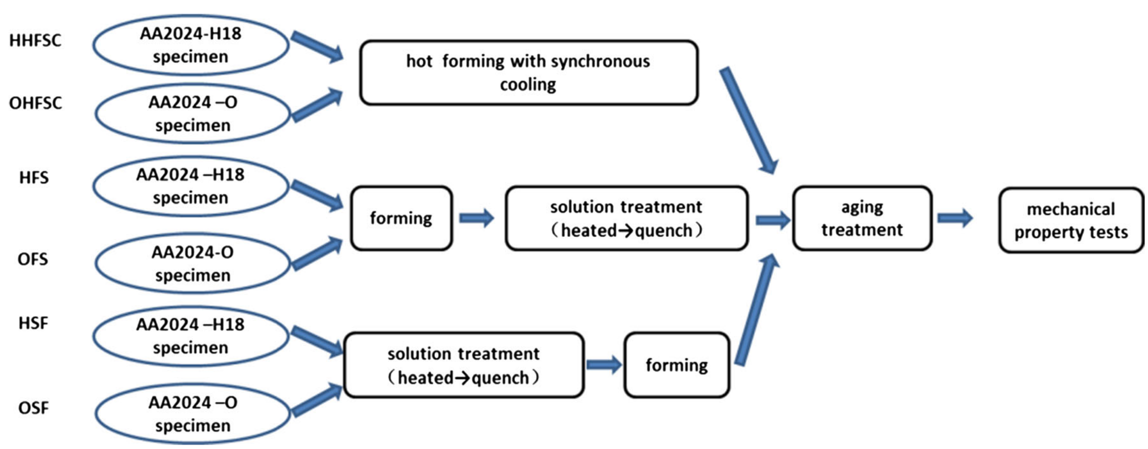


Fig. 3 Experiment outline

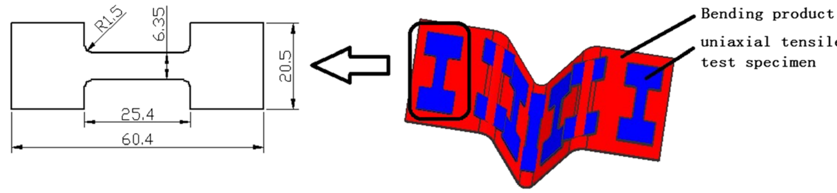


Fig. 4 Specimen for uniaxial tensile test

loys hold narrow plastic deformation range and low cracking resistance. However, as the alloys' ductility was improved by annealing treatment [21] and solution treatment [22], the R5 fillet of OFS, HSF, and OSF samples was successfully formed and there was no crack in the R5 fillet of HHFSC sample either. This means that the HFSC technique, as an annealing treatment and solution treatment, can improve the formability of AA2024-H18 alloys. However, the improvement is mainly attributed to the elevated temperature, not the microstructure evolution. In general, the heat-treatable, high-strength aluminum alloys are cold formed in O temper, which means that pre-annealing is a prerequisite to high ductility before cold forming process the alloys in other tempers (such as T and H tempers). However, as blanks are solid dissolved at solution treatment temperature and then formed at elevated temperature during HFSC, the initial temper has no influence on the forming process. Therefore, HFSC can reduce the production cost by skipping a pre-annealing process.

The volume change of the aluminum alloys during the quenching process of solution treatment caused internal stress and led to apparent warp distortion in the flange region of HFS and OFS samples, as shown in Fig. 5 (highlighted by the red arrow). In the forming process subsequent to solution treatment process, even though warp distortion caused by solution treatment decreased, it still remained in the flange regions of HSF and OSF samples. However, during the hot bending process with synchronous cooling, warp distortion was completely eliminated by securing the specimens in the closed dies during quenching.

The springback values of AA2024 aluminum alloy samples formed using different methods are compared in Fig. 6, where the OFS samples were measured before solution treatment. The bending angle was designed as 60°. The HHFSC and OHFSC samples had springback angles as small as 0.42° and 0.62°, respectively, thanks to the significantly reduced yield strength at elevated temperatures. In the forming process subsequent to solution treatment process, as the blanks were solution treated before forming, the alloying elements were distributed in the α(Al) matrix and resulted in a supersaturated solid solution. There was lattice distortion in the supersaturated solid solution, which contributed to the increase of yield strength. Thus, the springback angles of the HSF and OSF samples were larger, up to 3.79° and 4.43°, respectively. In the solution treatment subsequent to forming process, since the fillet of the AA2024-H18 specimens cracked, only the springback angle of the OFS samples was measured and presented as 1.24°. The relatively small angle was caused by softening during annealing treatment.

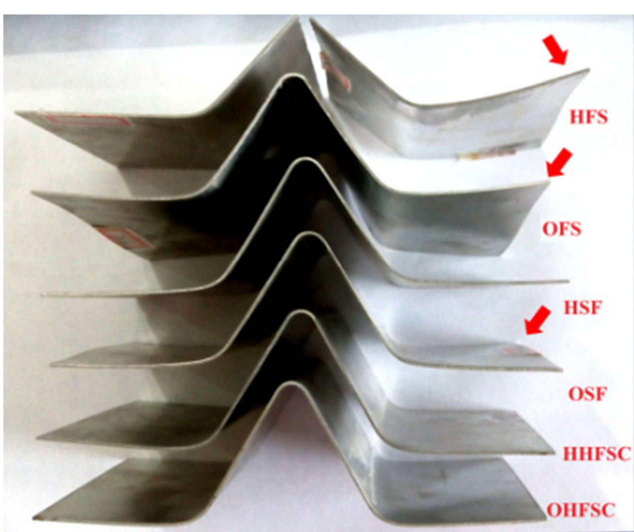


Fig. 5 AA2024 aluminum alloy samples formed using different methods

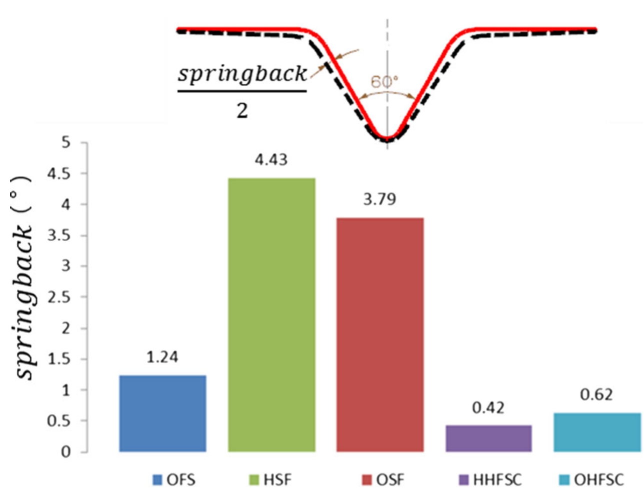


Fig. 6 Springback of samples

Table 2 Average mechanical properties of AA2024 aluminum alloy samples

	Hot bending with synchronous cooling		Solution treatment subsequent to forming		Forming subsequent to solution treatment		Requirement in the ASTM standard for AA2024-T4 aluminum alloy
	Sample						
	HHFSC	OHFSC	HFS	OFS	HSF	OSF	
Elongation (%)	19.1	19.5	–	21.3	19.2	19.3	15
Yield strength (MPa)	317.5	311.7	–	283.2	291.5	290.2	275
Ultimate tensile strength (MPa)	476.1	468.0	–	456.2	447.4	444.6	425

3.2 Mechanical properties

The mechanical properties of AA2024 aluminum alloy samples are presented in Table 2. The samples were formed using different methods and then subsequently went through 96 h of natural aging. Because of the identical solution treatment and aging treatment, the original tempers of the samples had little influence on mechanical properties. As shown in Table 2, the average mechanical properties of HHFSC and OHFSC samples met the requirements of the ASTM standard for AA2024-

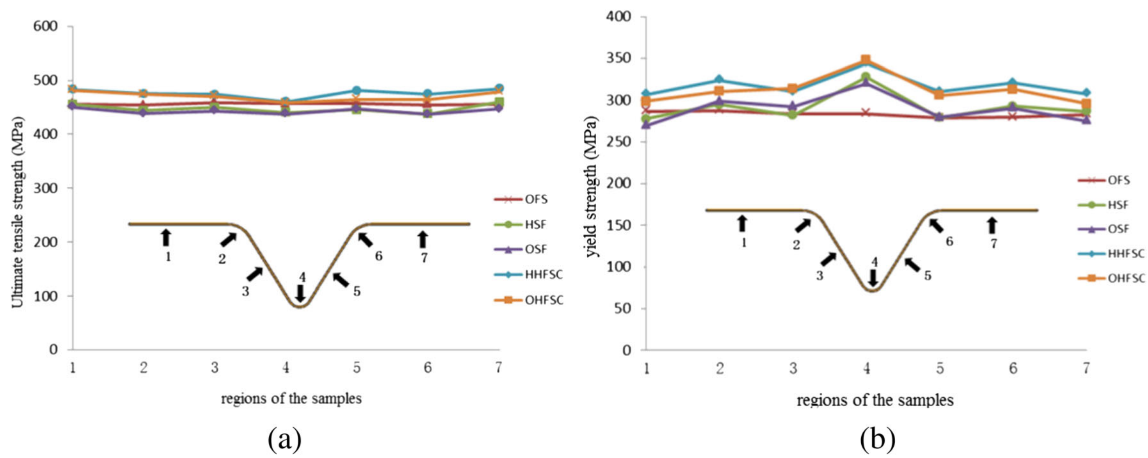
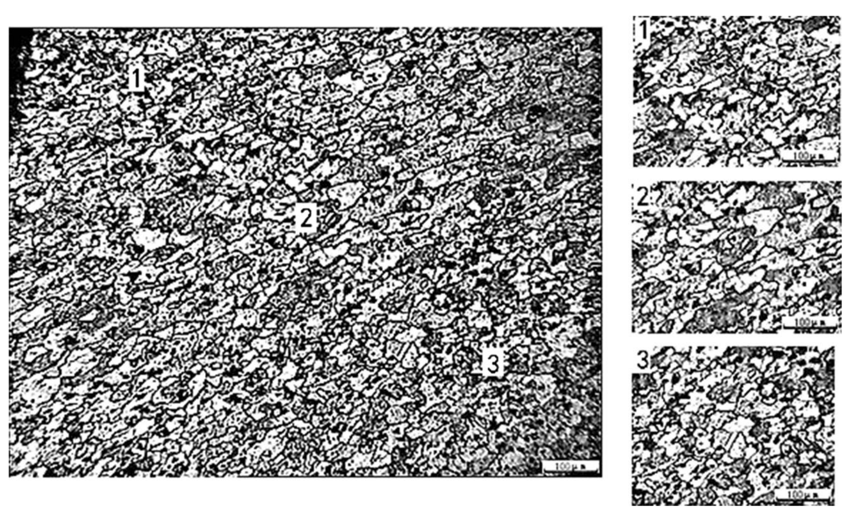


Fig. 7 Final strength of AA2024 aluminum alloy samples. **a** Ultimate tensile strength. **b** Yield strength

Fig. 8 Microstructure of the formed region of the HHFSC sample



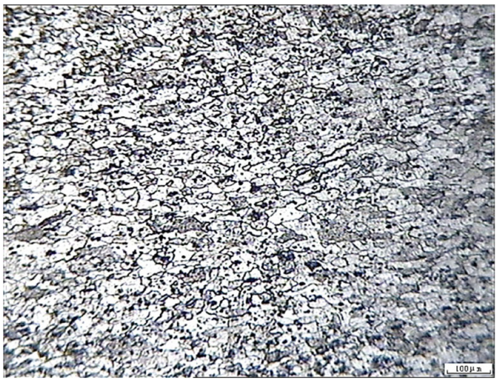


Fig. 9 Microstructure of the unformed region of the HHFSC sample

T4 aluminum alloy [21]. The yield strength and the ultimate tensile strength of the samples formed by the hot bending process with synchronous cooling are the highest, which demonstrates that the new technique can improve the strength of AA2024 aluminum alloy. The elongation of the samples formed by the hot bending process with synchronous cooling is lower than that of the OFS samples while roughly equal to those of HSF and OSF samples.

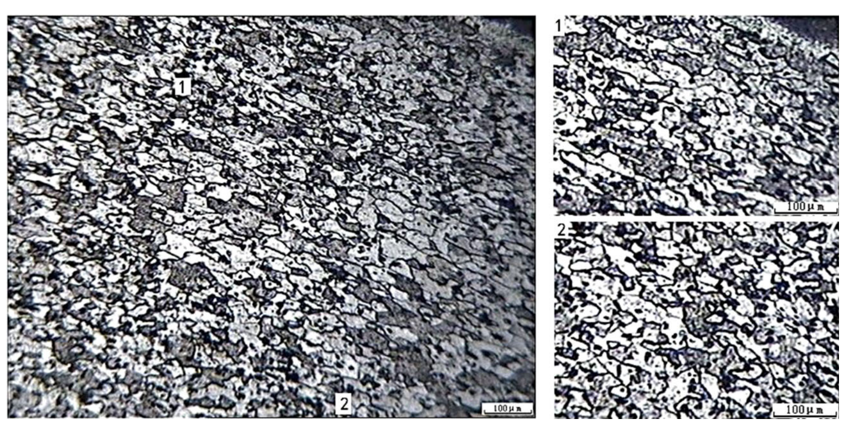
The final strengths of AA2024 aluminum alloy samples formed using different methods and then subsequently went through 96 h of natural aging are presented in Fig. 7. Although the ultimate tensile strength at different locations of the samples was consistent (Fig. 7a), the yield strengths of the bended fillets of HHFSC, OHFSC, HSF, and OSF samples were a little higher (Fig. 7b). Because of the static recovery and static recrystallization during solution treatment, the yield tensile strengths of OFS samples were equal. For HSF and OSF, since forming process was undergone after solution treatment, the work hardening was retained in final products. HHFSC, OHFSC, HSF, and OSF samples exhibited the same yield tensile strength distributions. All these can help to conclude that the hot bending process with synchronous cooling can improve the yield strength of AA2024 aluminum alloy in the formed regions.

Fig. 11 Microstructure of the formed region of the OFS sample

3.3 Microstructures

The bending section of the HHFSC specimen can be divided into three different areas according to deformation modes, as shown in Fig. 8. The grain of area 1 is obviously elongated at a certain direction, which indicates the elongation deformation occurred in this area. The grain of area 3 is relatively small since it was the compression deformation that occurred during the forming process. Area 2 is in the middle of the bending cross section where the grain size is between 1 and 3, the same as that in the unformed regions of the HHFSC specimen, as shown in Fig. 9. In the isothermal hot forming process, the grains' sizes were supposed to be equal in all regions of the product. However, due to the dynamic recovery and recrystallization in the bending section, microstructures at different regions of the HHFSC specimens varied with the deformation, which indicates that part of the effect of working-hardening had retained, so the yield strength of the deformed regions was higher than that of the non-deformed regions. The microstructure in the deformed region of the HSF specimen is similar to that of the HHFSC specimen, as shown in Fig. 10, but holds a

Fig. 10 Microstructure of the formed region of the HSF sample



larger grain size. The difference in grain sizes may be attributed to dynamic recrystallization during the hot bending process with synchronous cooling, and compared with HHFSC specimen, HFS specimen possessed a lower strength, because of its larger grain size. OFS specimen housed consistent grain shape and size in different regions due to the solid solution treatment after forming, as shown in Fig. 11, and the grain size of OFS specimen is significantly larger than that of other specimens, leading to the minimal strength of the forming region.

4 Conclusions

In this paper, experiments were conducted on a sheet of AA2024 aluminum alloy processed by hot bending with a synchronous cooling method and other traditional forming technologies and the methods were compared by investigating the samples in terms of springback, geometry and dimension accuracy, mechanical properties, and microstructures. Finally, some conclusions were drawn as follows:

1. HFSC can significantly reduce springback and eliminate warp distortion, which improves the dimension accuracy of the final products, and it can also improve the formability of AA2024 aluminum alloy due to the elevated forming temperature.
2. After natural aging treatment, the strength of AA2024 aluminum alloy products that underwent HFSC was higher than that of products formed by the traditional cold forming. The yield and tensile strengths of AA2024 aluminum alloy products after HFSC processing reached 476.1 and 317.5 MPa, respectively.
3. HFSC-processed products retained material hardening in the formed regions which can improve the yield strength of the formed regions.

HFSC can simplify forming processes and reduce costs for AA2024 products. This technique has great potential in aviation, aerospace, transportation, and other fields.

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