The optimized tensile and fatigue properties of electromagnetically stirred and thermally transformed semi-solid 357 and modified 319 aluminum alloys

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Abstract

The mechanical properties of 357 and modified 319 semi-solid formed (SSM) aluminum alloys are reported. Some alloys were electromagnetically stirred (EM) while other alloys were formed from ingot which was not stirred during solidification but had undergone a semi-solid thermal transformation (SSTT) during heating to produce a spherical microstructure suitable for semi-solid forming. The T4, T5 and T6 tensile properties were also optimized for both SSTT alloys using various aging studies of formed parts. The T6 fatigue properties of both SSTT alloys were also investigated. The SSM tensile and fatigue properties were superior to conventionally cast alloys and the properties of SSTT appear at least comparable to SSM prepared by EM.

Keywords

Semi-solid aluminum, mechanical behavior, fatigue.

Riassunto

Vengono descritte le proprietà meccaniche delle leghe di alluminio 357 e 319 modificata formate nello stato semisolido (SSM). Alcune leghe sono state agitate elettromagneticamente (EM), altre formate da lingotti che non sono stati agitati durante la solidificazione, ma erano stati sottoposti ad una trasformazione termica nello stato semisolido (SSTT) durante il riscaldamento, con lo scopo di produrre una microstruttura sferica idonea alla formatura semisolida. Le proprietà tensili T4, T5 e T6 sono state ottimizzate per ambedue le leghe SSTT impiegando vari studi dell'invecchiamento di parti formate. Le proprietà a fatica T6 delle due leghe sono state ugualmente analizzate. Le proprietà tensile e di fatica SSM si sono rivelate superiori a quelle delle leghe colate in modo tradizionale. Le proprietà delle SSTT appaiono almeno paragonabili a quelle delle SSM preparate per EM.

Parole chiave

Alluminio semisolido, comportamento meccanico, fatica.

INTRODUCTION

This investigation studied semi-solid (SSM) aluminum-silicon alloys produced by electromagnetic stirring (EM) and also semi-solid thermal transformation (SSTT). It was demonstrated that Air-SlipTM direct chill (ASDC) casting with high solidification rates produces a fine-grain as-cast ingot that may simply form a fine spheroidized semi-solid structure upon reheating [1]. [Conventional semi-solid ingot preparation involves the use of mechanical or electromagnetic stirring (EM) during solidification to obtain a spheroidal structure leading to favorable rheological properties [2].] Thus, semi-solid material can be produced without the typical semi-solid processing. This new process has been termed Semi-Solid Thermal Transformation (SSTT). The SSTT using ASDC ingot also allows, with reheating, sufficient spheroidicity of small particles in reasonable time (e.g., 2 min) without excessive grain refining additions. The favorable formability and tensile properties of semi-solid 356/357 type alloys following SSTT and high pressure commercial forming were reported by the authors in [1]. The purpose of this research is to optimize the tensile properties of T5 and T6 of SSTT 357, EM 319, and a modified SSTT 319 (DF53) principally by determining the effects of aging treatments on formed parts. The SSTT 357-T6 and SSTT DF53-T6 fatigue properties were also examined. All of these properties are compared with conventionally cast 356, 357 and 319 properties.

EXPERIMENTAL PROCEDURES

The SSTT 357 and modified SSTT 319 (DF53) aluminum alloys used in this study were provided in the form of Air-SlipTM direct chill cast ingots, typically about 81.3 mm in diameter, from Northwest Aluminum Company (NWA), The Dalles, Oregon. The Air-SlipTM direct chill cast ingots were heated to SSTT temperature and formed into various configuration parts including DF53 seatbelt recliner housings, DF53 solid cylinders with 12.7 mm diameter and 76.2 mm length and 357 shift actuators, all at HMM in Arkadelphia, Arkansas. HMM induction heated the ingots to about 588(C for about 2 min. at temperature, followed by pressing into parts. Some of the semi-solid thermal transformations of DF53 were also performed at NWA. The NWA DF53 samples were heated to 584(C under a pressure of about 0.01 MPa and then water quenched. The total time above 566(C, temperature at which softening of the sample occurred, was 3 min. These NWA pressed parts were utilized for the T6 optimization study. The EM 319 was provided by Pecheney as pressed tapered solid cylinders with diameters of 25 and 30 mm at each end. The compositions of all ingots are listed in Table 1. The SSTT modified 319 (DF53) and EM 319 have very similar compositions.

The EM tests were performed at the Univ. Ancona, while SSTT tests were performed at Oregon State Univ. The OSU tensile tests and constant stress-amplitude fatigue tests were performed on a servohydraulic Instron 8521 machine using a collet-type gripping system. The typical gage dimensions of the microtensile specimens extracted from formed parts were 2.03 mm diameter and 8.13 mm gage length. The tensile specimen dimensions from DF53 solid cylinders were 2.03 mm diameter and 8.13 mm gage length. The microtensile specimen dimensions for SSTT DF53 pressed at 0.01MPa samples for T6 optimization studies were 2.03 mm diameter and 8.13 mm gage length. The EM specimens had a square gage of 6 (6 mm and a length of 25 mm. The testing strain rates were between 0.67 (10-3 and 10-3 s-1 for all tests.

RESULTS AND DISCUSSION

Tensile Properties of SSTT 357, Modified 319 (DF53), and EM 319

The T5 and T6 tensile properties of semi-solid thermally transformed (SSTT) 357 and DF53 and EM 319 aluminum alloys, as well as typical as-cast A356 aluminum alloy, are listed in Table 2. T5 values are, naturally, somewhat lower than T6 values. The SSTT 357 and modified 319 (DF53) parts formed at HMM were T5 optimized and the data are illustrated in Figs. 1 and 2. It appears that optimum T5 occurs for 6-12 hrs aging at 171-182°C for 357 and 8-12 hrs aging at 171-193°C for SSTT DF53.

The transformation temperature to liquid of DF53 was determined before T6 properties were optimized. The solution temperature for T6 was selected as 518°C based on DSC results.

TABLE 1 - Composition Ranges of Aluminum Alloys Used in This Study (wt %)

	Si	Fe	Cu	Mn	Mg	Ni	Zn	Ti	Ga	Sr
DF53 (Modified 319) (SSTT)	5.61 to 6.32	0.12 to 0.15	2.62 to 3.13	---	0.30 to 0.38	0.004 0.012	---	0.09 to 0.127	0.01 to 0.03	0.009 to 0.029
319 (EM)	5.76	0.13	2.9	0.02	0.33	---	0.02	0.02	---	---
319 [3] (cast)	5.50 to 6.50	1.00	3.00 to 4.00	0.50	0.10	0.35	1.00	0.25	---	---
357	6.55 to 6.73	0.11 t 0.13	0.00 to 0.02	---	0.50 to 0.56	---	---	0.11 to 0.12	0.01 to 0.03	0.022 to 0.028
A356 [4]	7.0	0.11	0.04	0.01	0.36	---	0.01	0.15	---	---

Table 2 - The As Quenched, T4, T5 and T6 Tensile Properties of Formed SSTT 357, Modified 319 (DF53), EM 319 and Conventionally Cast Aluminum Alloys (2-6 tests are associated with each value of this study).

Alloy	Yield Stress (MPa)	UTS (MPa)	Elongation (%)
SSTT 357-T5[1]	219	289	5.5
Conventionally (Sand) Cast 357-T5	117	179	3.0
SSTT 357-T6[2]	288	339	6.3
EM 357-T6 (semi-solid) [1]	300	341	10.8
Conventionally (Sand) Cast 357-T6 [6]	296	345	2.0
SSTT DF53-T5[3]	224	327	5.2
EM 319-T5[4]	237	292	2.8
Conventionally (Sand) Cast 319-T5 [6]	179	207	1.5
SSTT DF53-T6[5]	316	387	4.8
SSTT DF53-T6[6]	351	409	5.9
SSTT DF53-T6[7]	299	398	10.2
EM 319-T6[8]	334	379	1.6
EM 319-T6[9] [7]	320	405	5.0
Conventionally (Sand) Cast 319-T6 [6]	164	250	2.0
SSTT DF53-T4[10]	234	370	13.4
SSTT DF53[11]	128	307	18.6
Conventionally (Sand) Cast A356-T6 [6]	207	278	6.0

[1] 8 hrs at 182°C (from shift actuator) from optimization study Fig. 1
[2] 7 hrs at 177°C with solutioning at 538°C for 3 hrs from formed parts (parts are illustrated in [8])
[3] 8 hrs at 193°C (Fig. 1) from optimization study Fig. 2
[4] Electromagnetically stirred semi-solid, solid cone, aged at 170°C for 4 hrs
[5] 6 hrs at 171°C with solutioning at 500°C for 5 hrs from formed parts (parts are illustrated in [8])
[6] 6 hrs at 171°C (from solid cylinder) with solutioning at 518°C for 10 hrs
[7] 12 hrs at 154°C (from solid cylinder) with solutioning at 518°C for 10 hrs
[8] Electromagnetically stirred semi-solid, solid cone, solutionizing at 500°C for 4 hrs., aged at 170° for 16 hrs
[9] Electromagnetically stirred semi-solid bars, solutionizing at 505°C for 6 hrs, aged at 170°C for 10 hrs
[10] 4 days at 18°C (from solid cylinder) with solutioning at 518°C for 10 hrs
[11] Less than 0 hrs. at 0°C after water quenched (from solid cylinder) with solutioning at 518°C for 10 hrs before test

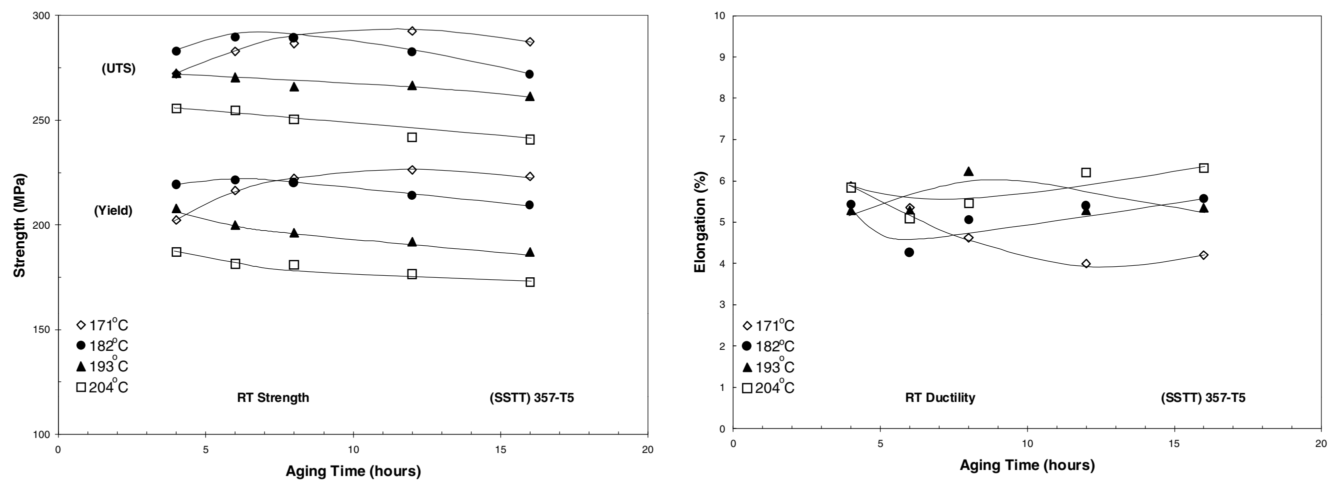

Fig. 1: The T5 (a) UTS, (b) yield strength, and (c) elongation of various aging times and temperatures for SSTT 357 formed parts.

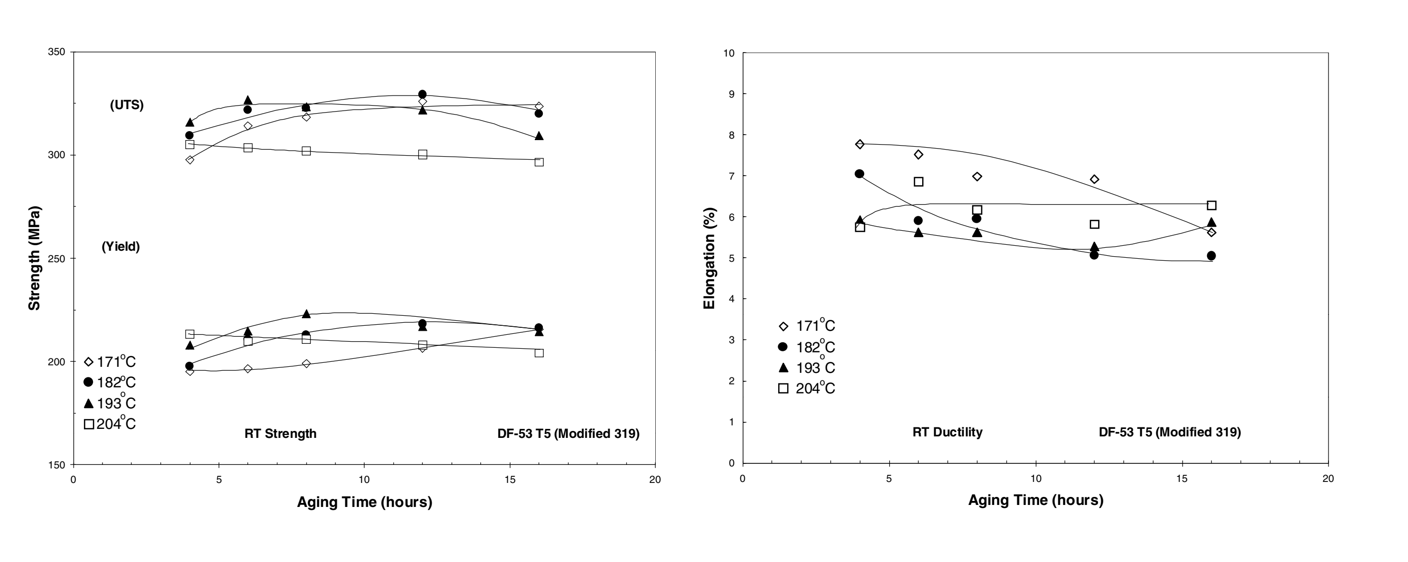

Fig. 2: The T5 (a) UTS, (b) yield strength, and (c) elongation of various aging times and temperatures for SSTT DF53 formed parts. (Each point is an average of two tests.)

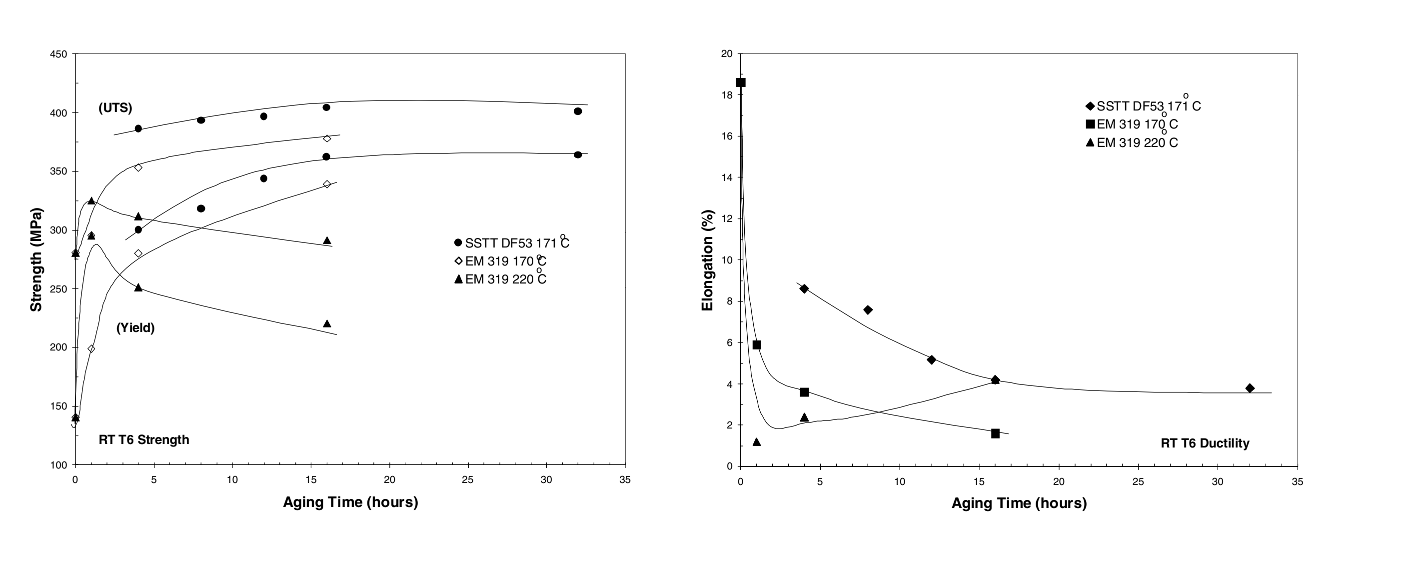

Fig. 3: The T6 UTS, yield strength, and elongation of various aging times at temperature of 171°C for SSTT modified 319 (DF53) and EM 319. SSTT specimens were extracted from pressed ingot at 0.01 MPa.

The relationship between solution time and T6 properties of SSTT DF53 was determined. It appears that best solution time is 10-16 hrs at 518°C for a 6 hr, 193°C age (a higher age temperature was selected to expedite this part of the study). The T6 properties of SSTT DF53 were optimized for a 171°C age (171°C based on an HMM study [5]) and are illustrated in Fig. 3 along with EM 319 T6 data. It appears that the optimum T6 occurs for 12-16 hrs for this aging temperature, somewhat longer than determined by HMM. It also appears that the EM and SSTT aging trends are comparable.

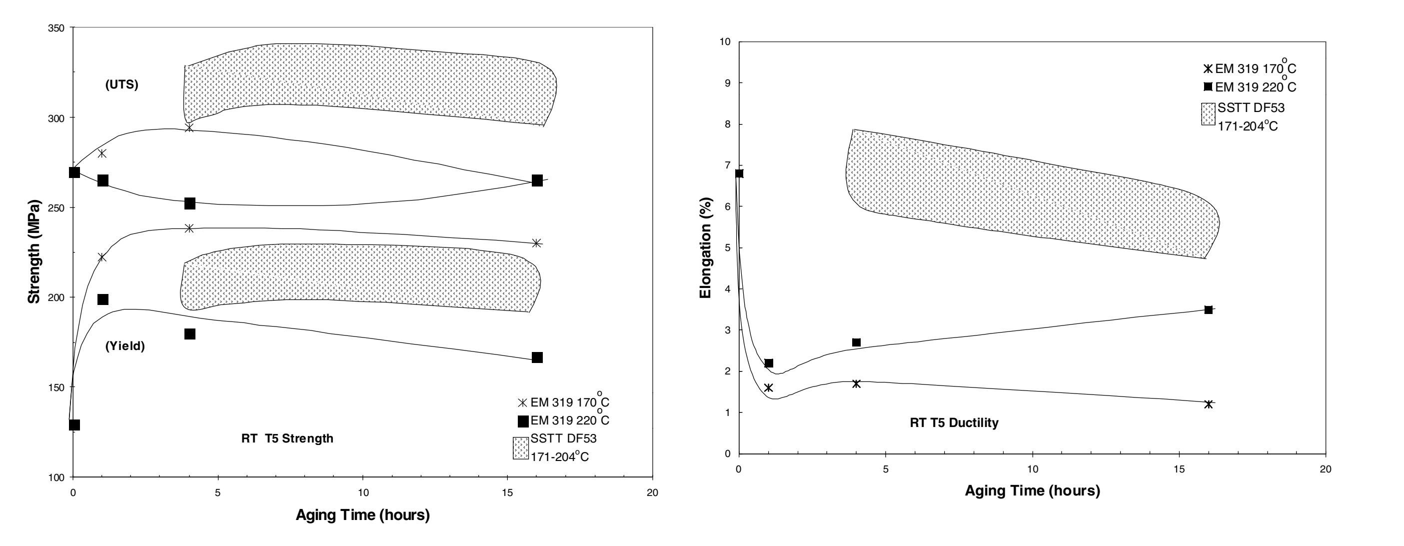

Fig. 4: The EM 319-T5 data are illustrated along with SSTT DF53 ranges

The T5 data of EM 319 of a similar composition to SSTT DF53 is plotted in Fig. 4. The trends and strength appear comparable. One difference is that peak properties for EM occurred at about 4 hrs at 170°C rather than 12, or so, for SSTT. Also, the strength of EM was somewhat lower (10%) than SSTT. The ductilities of the EM semi-solid appear lower as well. Of course, this EM semi-solid work only represents a single EM study. Some EM data suggest somewhat higher ductilities [7]. It is found that the ductility of SSTT DF53 may increase (from 5.9 to 10.2%) with some decrease in strengths (yield strength from 350 to 300 MPa and UTS from 409 to about 400 MPa) depending on the aging temperatures. Table 2 also lists the T4 properties of SSTT DF53. It is observed that even T4 yield and ultimate properties of SSTT DF53 (370 MPa UTS, 234 MPa yield strength and 13.4% elongation) are much better than T6 properties of conventionally cast 319 [4] (250 MPa UTS, 164 MPa yield strength and 2.0% elongation). The SSTT DF53 has good ductility of 18.6% before any aging treatment which is also illustrated in Table 2. It should also be noted from Table 2 that SSTT DF53 T6 (with similar T6 practice) has similar tensile properties for the complex configuration parts and the simpler configuration solid cylinders (with only slightly better properties for cylinders). (Two-step aging studies were also performed to assess the effects of an initial temperature from 110 to 154°C followed by a second age at 193°C; however, an appreciable improvement in properties was not observed [8]). Figure 5 is a micrograph of SSTT 319.

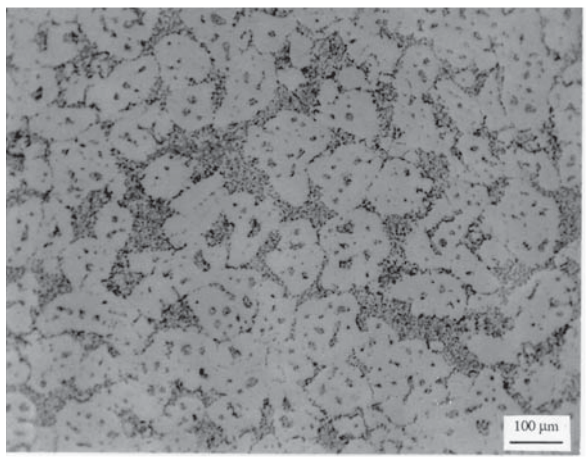

Fig. 5: An optical micrograph of semi-solid SSTT modified 319. Specimen is "as-received"

Fatigue Properties of SSTT 357-T6 and a Modified 319 (DF53)-T6

An important aspect of this research is a study for the constant stress-amplitude fatigue behavior of semi-solid SSTT formed parts of 357-T6 and DF53-T6. The fatigue results are illustrated in Fig. 6. Figure 6 also shows the constant stress-amplitude fatigue data of conventional cast A356-T6 alloy [6] as compared to SSTT data. It is observed that for the same stress amplitude, the numbers of cycles to failure for semi-solid 357-T6 (solution annealed at 538°C for 3 hrs and aged at 177°C for 7 hrs) alloy is larger than those of conventionally cast A356-T6 alloy. It is also illustrated that the cycles to failure of SSTT DF53 T6 (solution annealed at 500°C for 5 hrs and aged at 171°C for 6 hrs) are longer than that of conventionally cast 319 [9,10] although the heat treatments were not specified in the literature and are assumed to be in the as-cast condition (F). As mentioned earlier, SSTT 357 and DF53 have higher T6 tensile properties compared to conventionally cast and this is consistent with the superior fatigue properties.

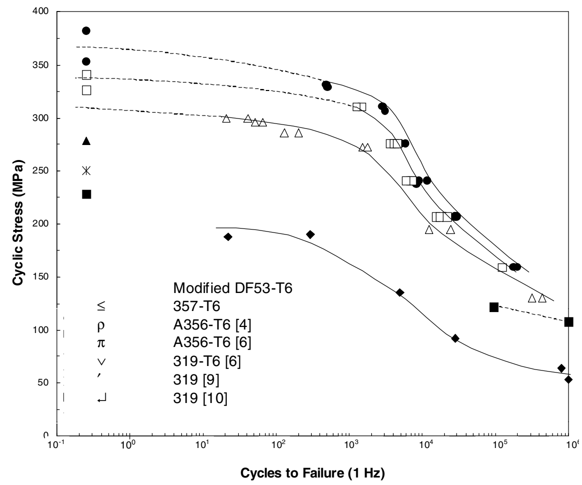

Fig. 6: The fatigue behavior of formed (SSTT) semi-solid 357-T6 (annealed at 538°C for 3 hrs and aged at 177°C for 7 hrs) and (modified 319) DF53-T6 (annealed at 500(C for 5 hrs and aged at 171°C for 6 hrs), compared with conventional cast A356-T6 [4,6] and 319 (F) [9,10].

CONCLUSION

Producing formed parts from semi-solid 357 and modified 319, in these cases, by thermal transformations, or SSTT, without any mechanical or electromagnetic (EM) stirring steps, and also by electromagnetic stirring, results in improved tensile and fatigue properties over cast aluminum automotive parts. The SSTT and EM alloys appear to have comparable mechanical properties.

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