Thermo-mechanical Treatment of Austempered Ductile Iron

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Introduction

- Hot and warm working of cast materials refine the as-cast structures, close up the internal shrinkage cavities and gas porosity, and reduce the segregations of alloying elements.

- Additionally, they provide deformed and/or recrystallized austenite and thus result in an increased number of sites for the subsequent transformation processes.

- This method has recently attracted research and industrial interest as a technique for the strength improvement in ductile irons (DI). Forged ductile iron products have been promoted as replacements of some types of steel forgings.

- Ausforming of DI is a subdivision of the above-mentioned processing method. The deformation in the ausforming process is introduced into the austempering schedule just after quenching but before any substantial transformation of austenite.
- Ausforming provides mechanical driving force in the form of strain defects in addition to the chemical thermodynamic driving force. This can be used to accelerate the rate of stage I of austempering.
- The enhanced nucleation rate of ausferrite and C-enriched austenite leads to finer and more homogeneous ausferrite, which in turn, results in a dramatic increase in strength, hardness and wear resistance.

- In the newly developed DI with dual matrix (DM). The matrix structure consists of a soft phase — ferrite and a hard phase — either martensite or ausferrite (acicular ferrite and high carbon austenite).
- Special interest for such material is due to the improved combination between its strength and ductility and its enhanced machinability compared to the single hard phase matrix.
- In the framework of the current study, hot deformation in the austenitic region after austenitization is combined with introducing of pro-eutectoid ferrite to the matrix to produce thermo-mechanically processed ductile iron.
- Additionally, the effect of ausforming process and the effect of processing parameters on the transformation kinetics, microstructure evolution and mechanical behavior are studied.

Experimental Procedure

Studied Material

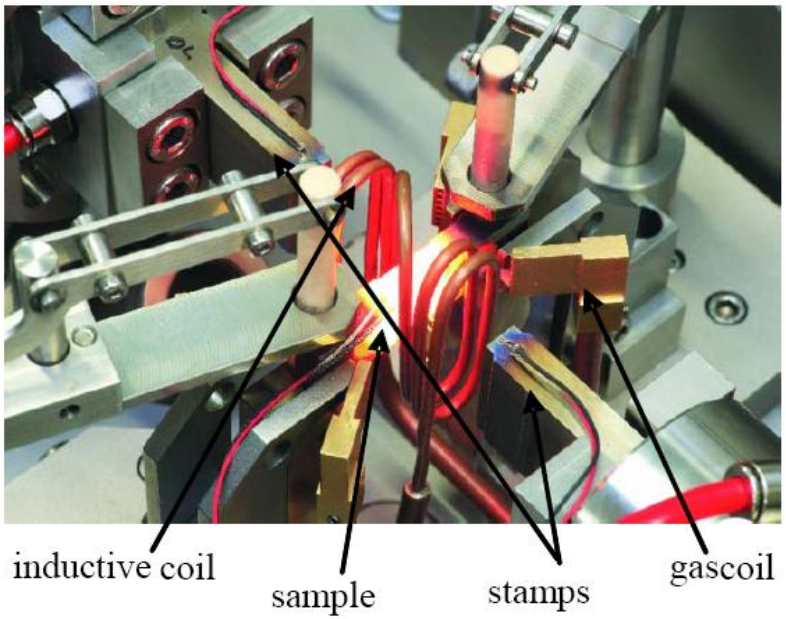
C	Si	Mn	Al	Mg	S	P
3.68	2.48	0.29	0.31	0.035	0.011	0.029

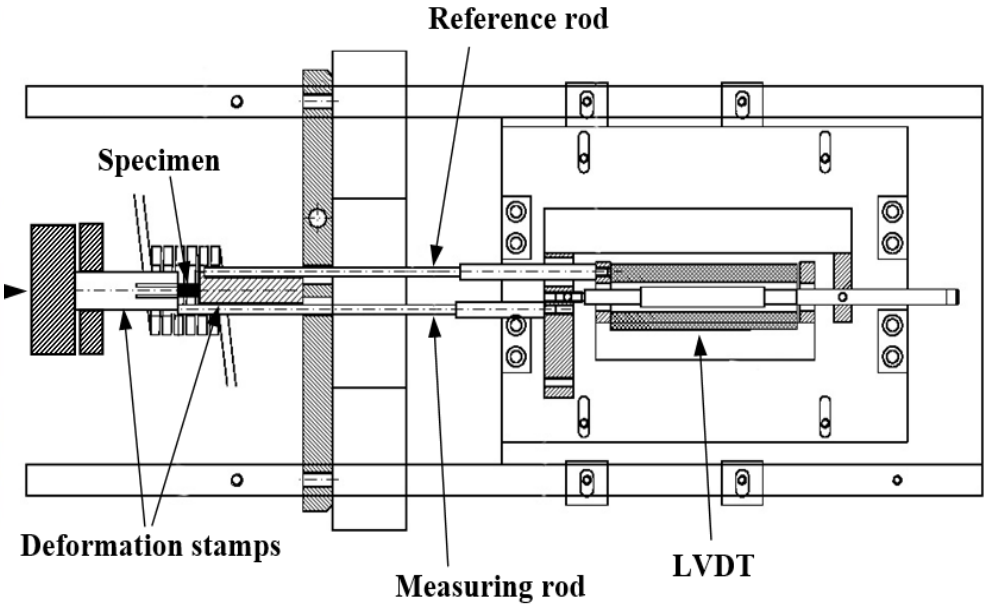
- Melting was performed in a 100Kg induction furnace.
- The base irons were treated with a 9.5 wt% Mg, FesiMg alloy for spheroidisation followed by post-inoculation with 75 wt% FeSi using the vortex method.



VORTREX UNIT

Thermo-mechanical processing and dilatometry





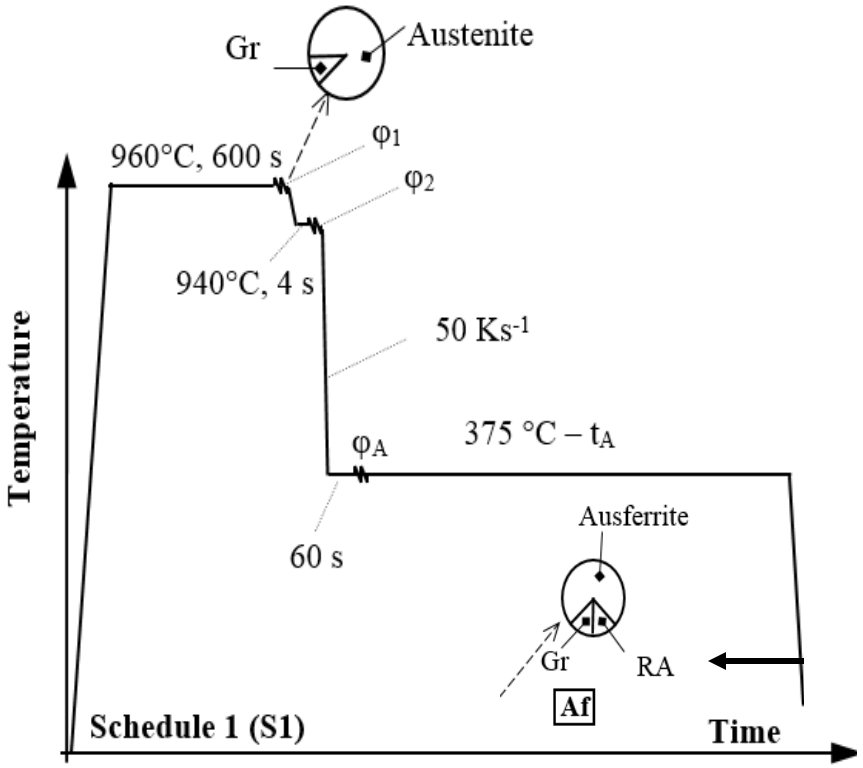
- For thermo-mechanical processing and dilatometric study, a Baehr Dil 805D thermo-mechanical simulator was used.
- The thermo-mechanical simulation was performed on cylindrical samples of 5 mm diameter and 10 mm length.
- Sheathed type S “Pt/Pt-10% Rh” thermocouples with a nominal diameter of 0.2 mm were individually spot welded to the specimens´ surface in central position.

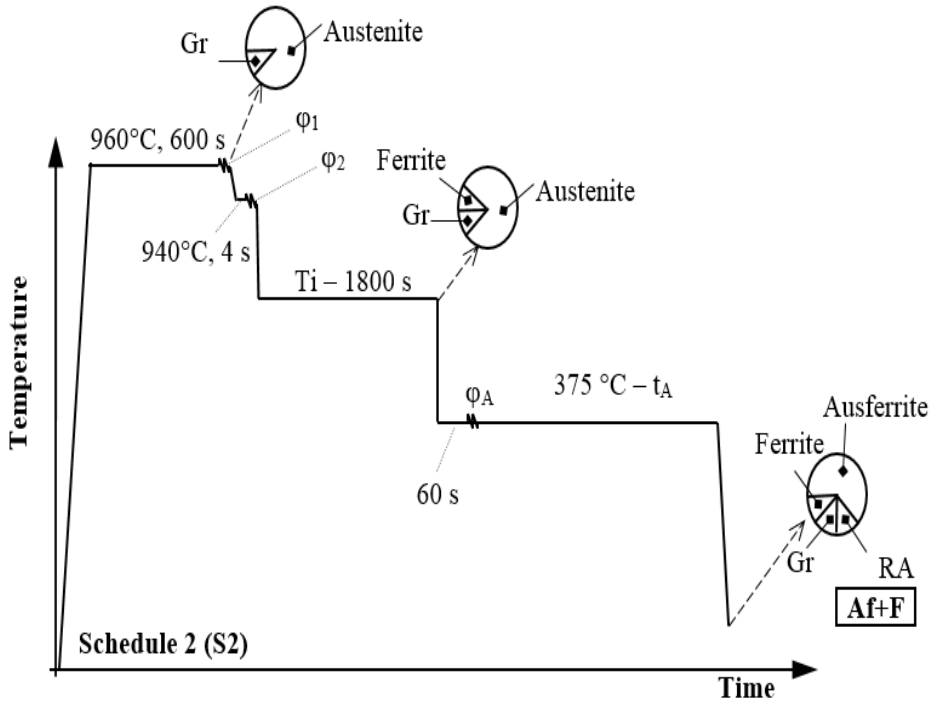
- The sample was mounted horizontally between two SiN stamps.
- The thermal cycles were performed under vacuum of 0.005 Pa by inductive heating using a high frequency (HF) generator. Helium was used for cooling.
- The dimension variations of the specimens during the thermal-deformation cycle are transmitted via a moving quartz pushrod to a LVDT sensor.
- A computer and data acquisition system recorded the dilatometric change, temperature and load as a function of time, and cross correlated the relative change in length as a function of temperature.

Thermo-mechanical schedules applied to the four ductile irons, Gr: graphite, RA: retained austenite and TA: austempering temperature.

- The specimens are subjected to two thermo-mechanical schedules. In these schedules, the specimens were heated up to 960°C and subjected to two deformation steps at 960°C and 940°C.
- The main objective of these deformation steps is to refine the structure through work hardening, recovery and recrystallization effects in austenite.

	φ_1	φ_2	φ_A
without Ausforming	**0.1**	**0.2**	**0**
with Ausforming	**0.1**	**0.1**	**0.1**





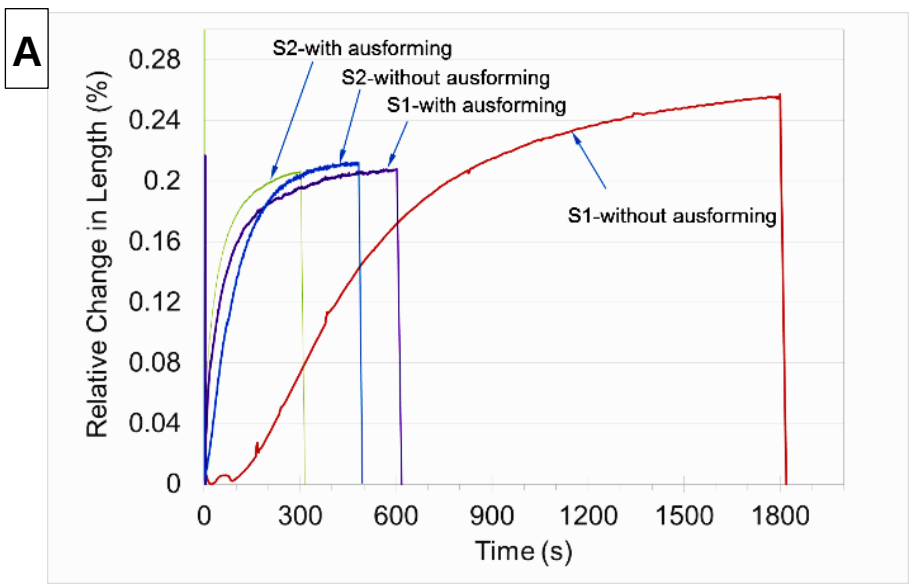
- The very slow deformation rate of 0.5s-1 is adopted to minimize the susceptibility of the specimen to cracking by decreasing the strain hardening effect during deformation.

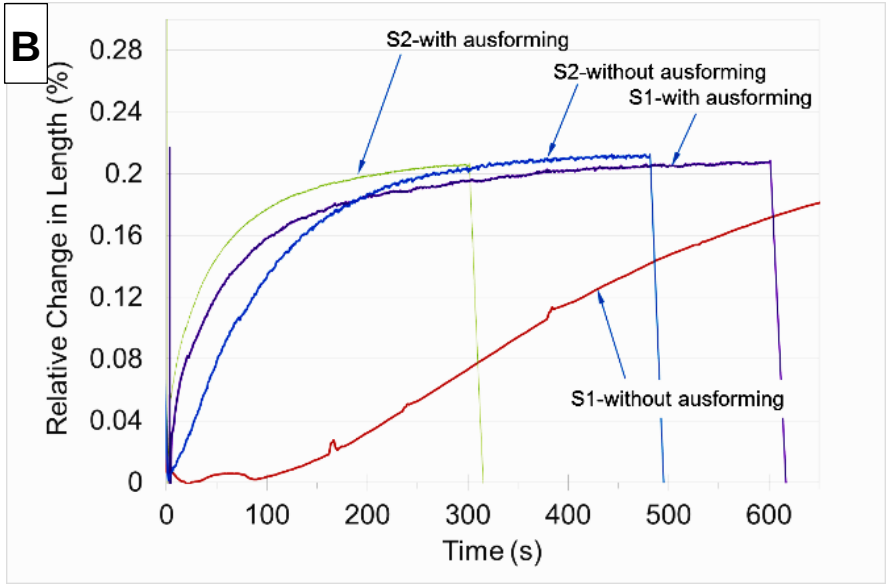
- Two variants of deformations, namely with ausforming and without ausforming are applied .

- For the sake of comparison, the total applied true strain in both variants is φ_t = 0.3. The austempering time t_A corresponds to the time for the end of stage I of transformation, which is processing condition dependent as will be shown.

Results and discussions

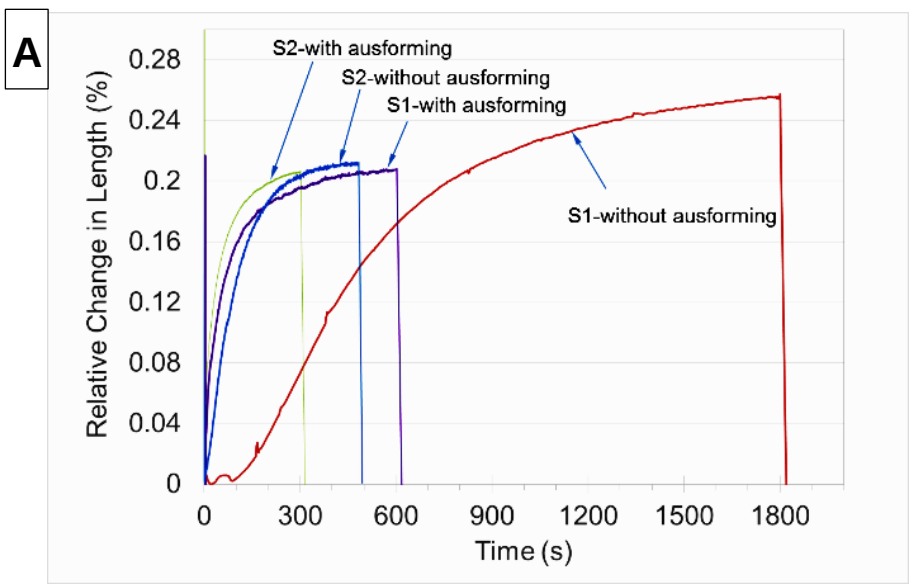
Transformation Kinetics

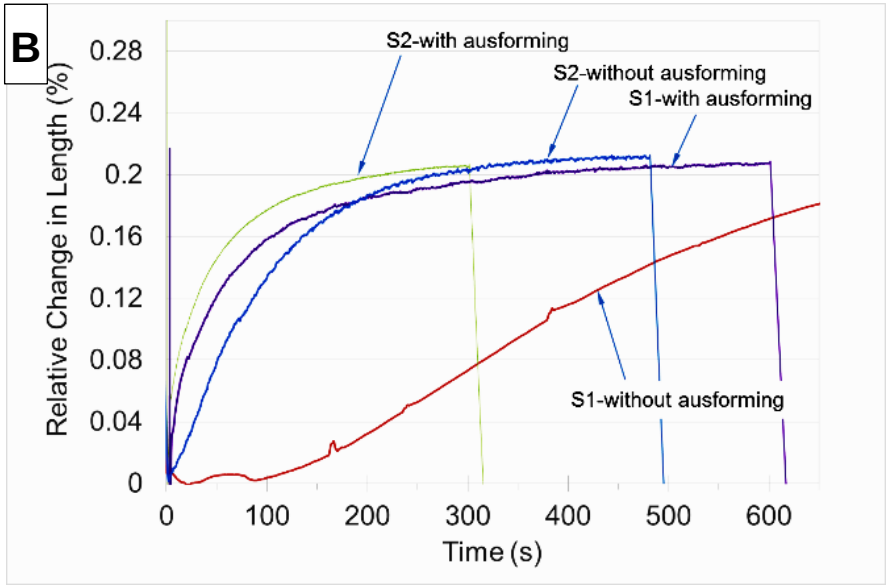




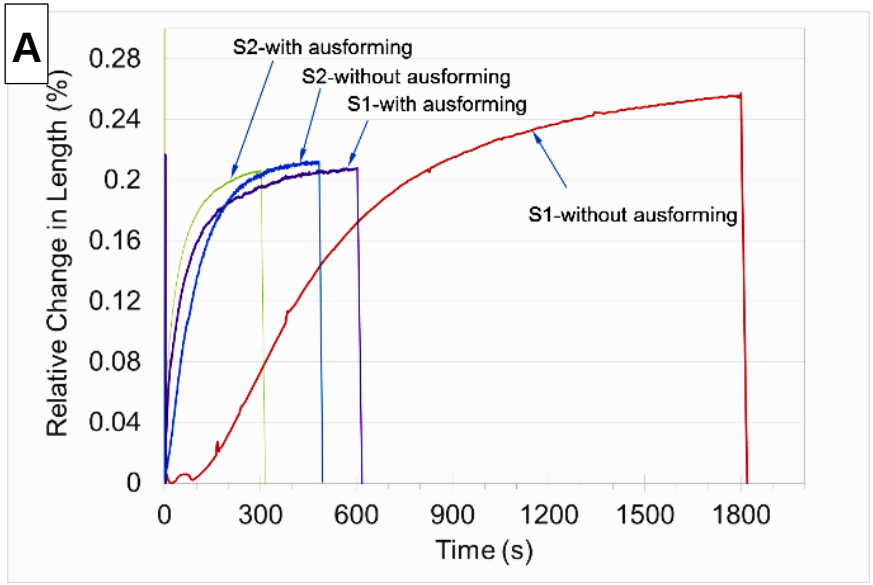
- The samples expansion is due to the transformation of austenite into ausferrite. Both of deforming the austenite prior to the transformation stage I and introduction of ferrite pronouncedly accelerated the transformation kinetics.
- Ausferrite transformation takes place directly after applying φA. For Schedule 1 (S1).

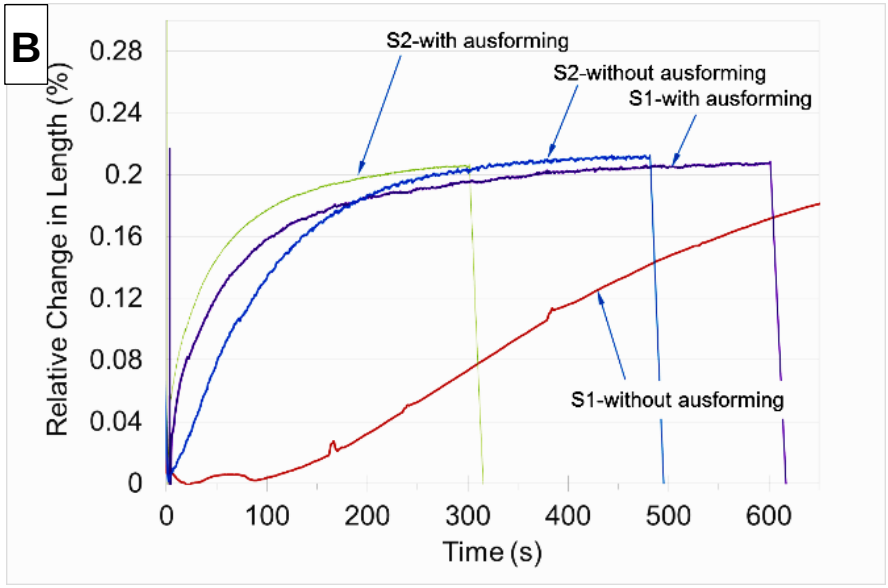
- The transformation requires about 1800 s to reach its saturation when the DI is not ausformed. Ausforming the ductile iron accelerated the transformation so that the transformation saturation is achieved after about 840 s.
- The acceleration of ausferrite reaction due to ausforming is correlated to the much larger number of ferrite particles nucleating on defects (e.g. dislocations, twins, etc.) caused by deformation.





- The higher nucleation rate of ferrite increases the kinetics of ausferrite transformation as the carbon atoms diffusing away from the ferrite will have to migrate for shorter distances within the austenite to establish the high carbon austenite in metastable equilibrium with the ferrite .
- Thus, the times needed for processing following the ausforming step are considerably reduced compared to processing conventional ADI.

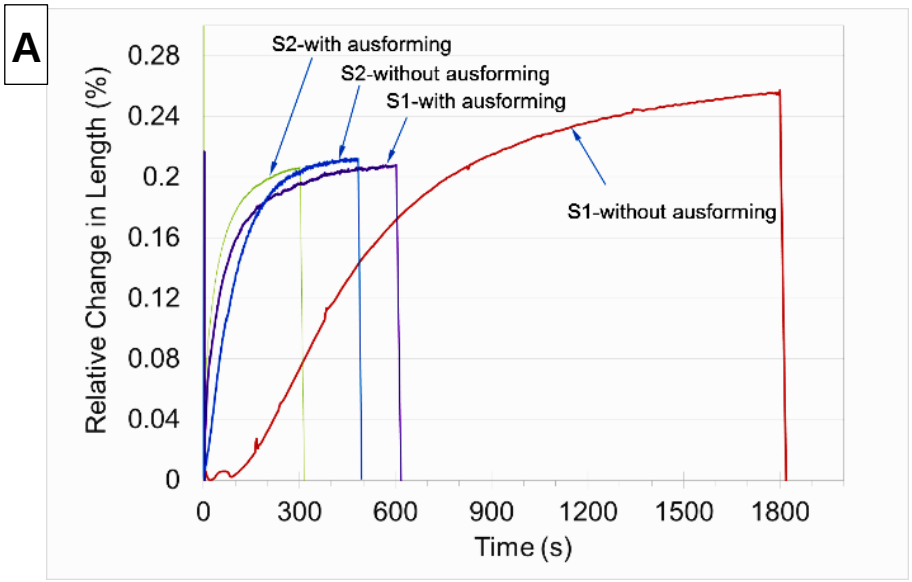


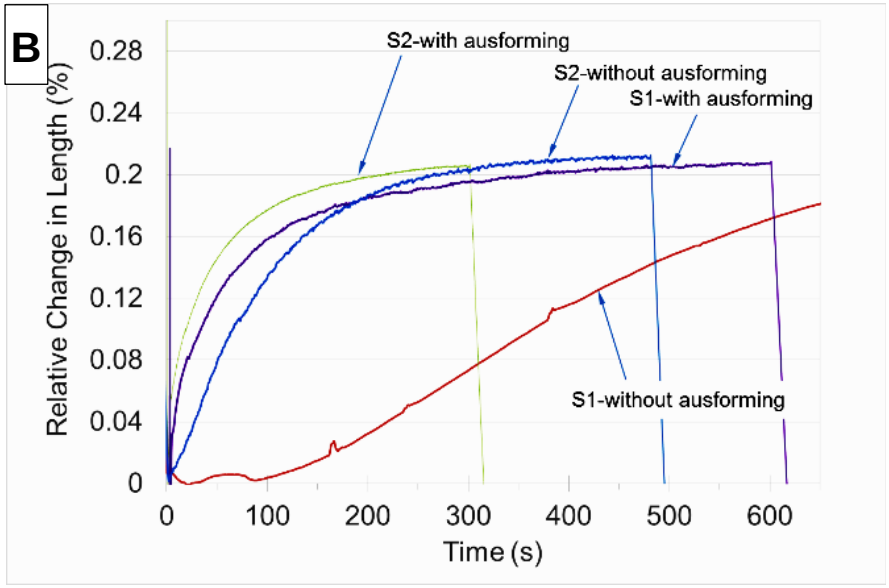


- In schedule 2 the introduction of ferrite to the microstructure, before austempering, has also a pronounced effect on accelerating the kinetics of ausferrite formation and reduction of the incubation period of transformation.

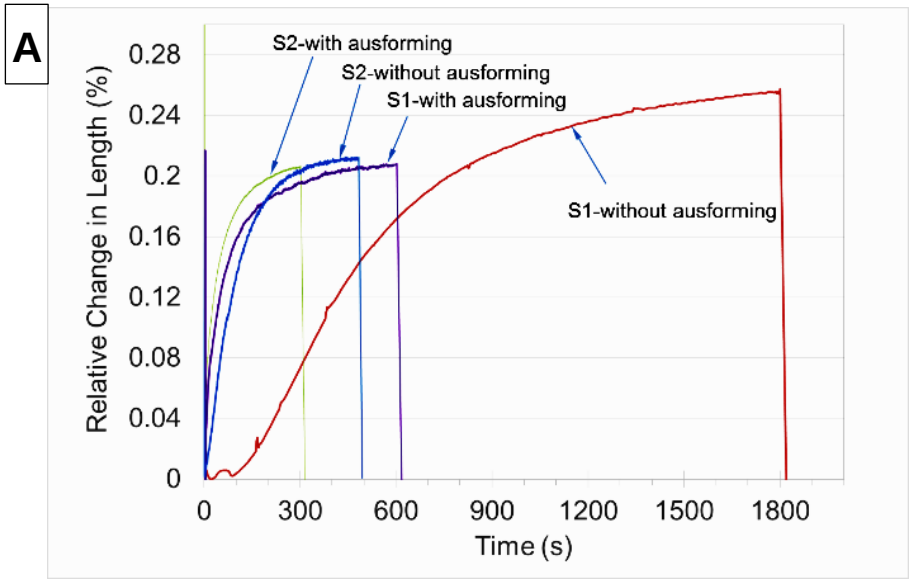
This can be attributed to:

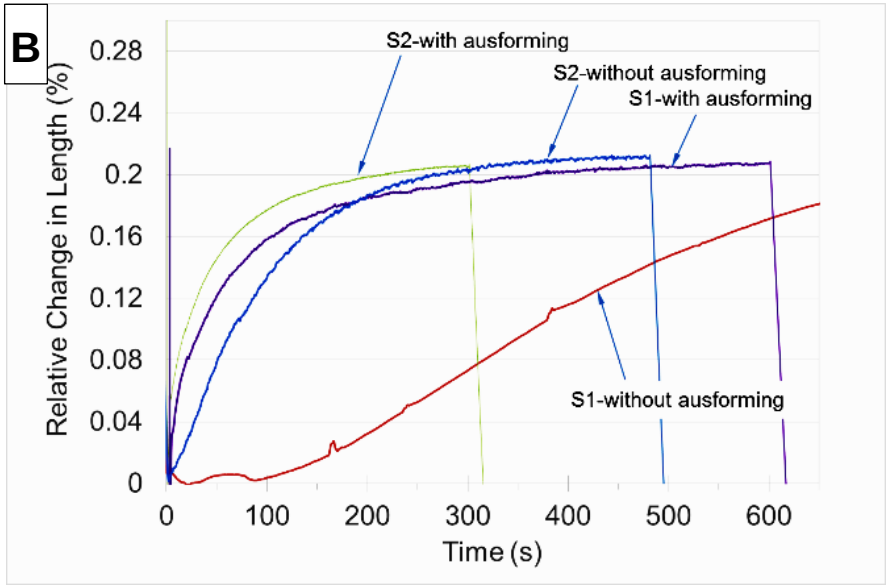
1. The increased number of sites for the nucleation of acicular ferrite at the ferrite austenite interface.
2. The reduced carbon content of the intercritical austenite during the isothermal holding at the intercritical annealing temperature: during cooling to and isothermal holding at Ti, C atoms diffuse from the austenite matrix to the graphite nodules, because the saturation level of austenite with C decreases with decreasing temperature.





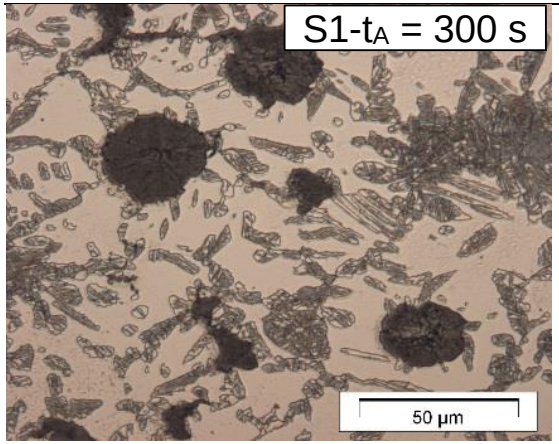
- The introduction of 15 % ferrite to the matrix seems to have stronger effect on accelerating the ausferrite formation than the effect of applying φA = 0.1.
- The introduction of ferrite reduced the time required for transformation saturation to about 500 s which is about 340 s less than the that of the ausformed DI.

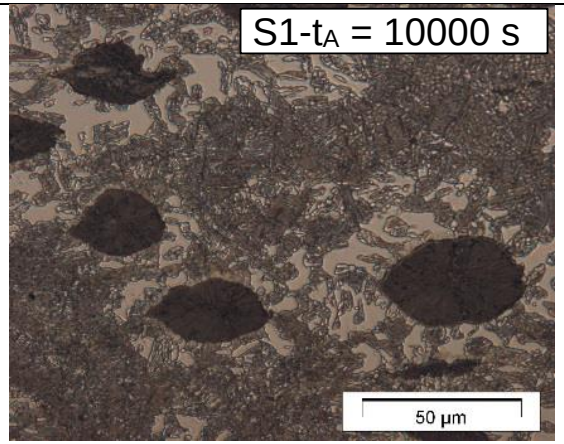


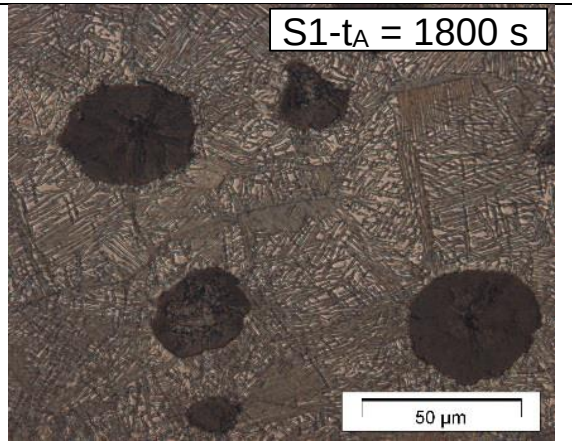


- However the transformation of the ausformed DI starts faster but proceeds at slower rate than the DI with introduced ferrite.
- The ausferrite formation time is reduced to about 300 s in the case of introducing ferrite to the matrix by intercritical annealing and ausforming the ductile iron.

Microstructure Evolution

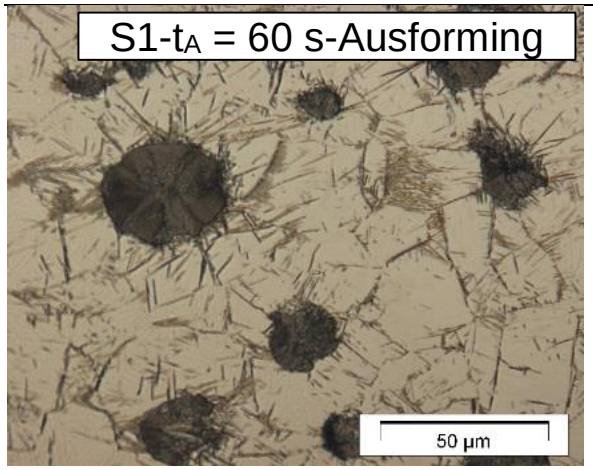


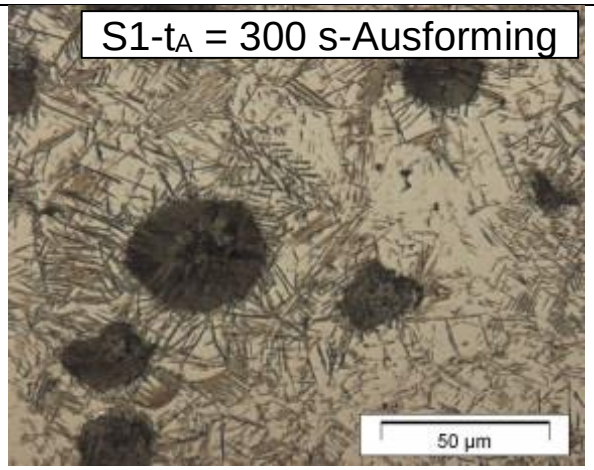


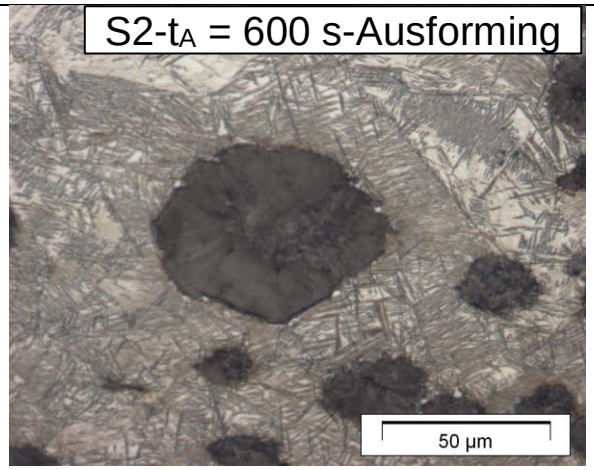


Schedule 1: Without ausforming

- Ausferrite mainly starts to form away from the nodules such that the last formed ausferrite occurs around the nodules.
- During austenitization the carbon diffuses from the nodules to the matrix such that the neighbourhood of the nodules possess higher carbon content and hence higher resistance to transform to ausferrite.
- However, when ausforming the DI, the first formed ausferrite occurs around the nodules.

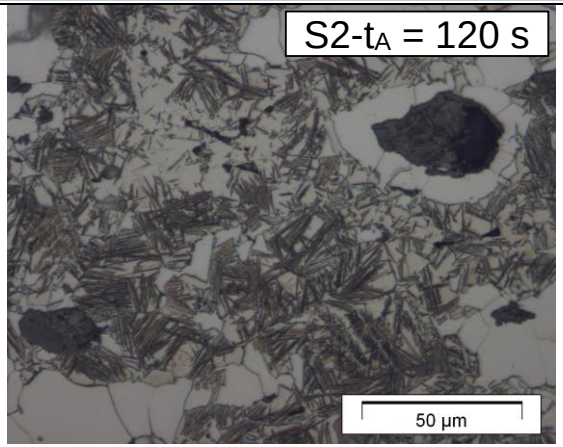


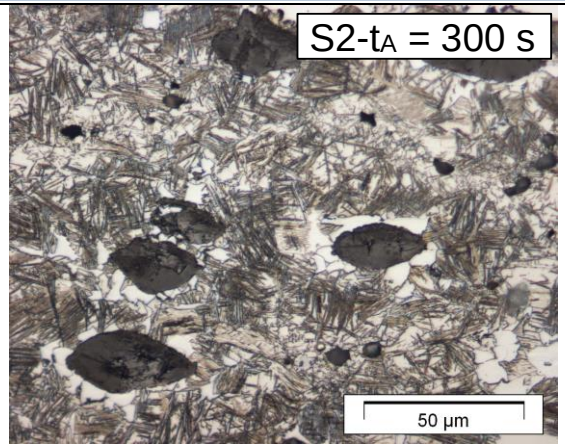


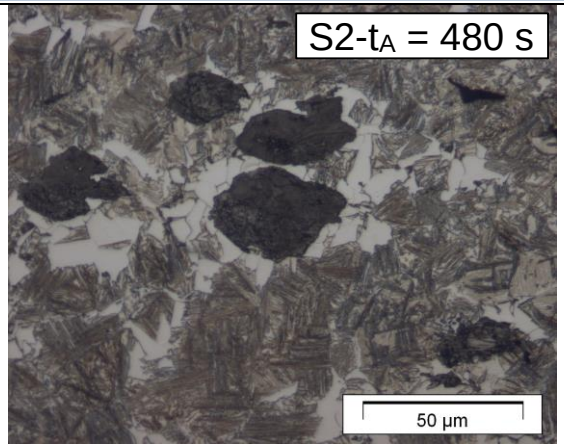


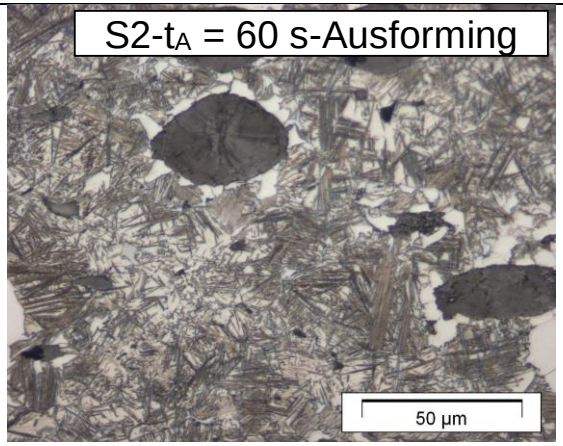
Schedule 1: With ausforming

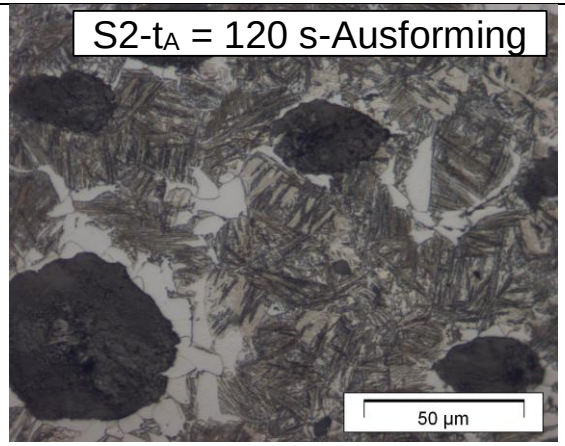
- With ausforming : The ausforming process results in increasing the nucleation sites of ausferrite to a great extent.
- The graphite nodules, which act as a stress concentration would promote localized higher concentration of dislocations around the nodules and hence higher stimulation of ausferrite nucleation. It seems that this stimulation effect is stronger than the retardation effect of ausferrite formation due to the carbon localisation around the nodules, thus the ausferrite starts to form around the nodules in case of the ausformed DI subjected to schedule 1.

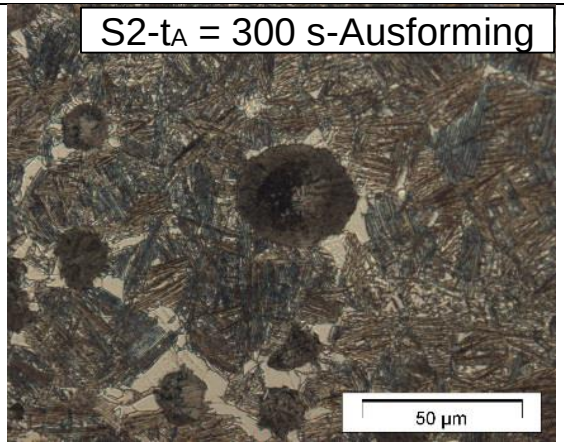










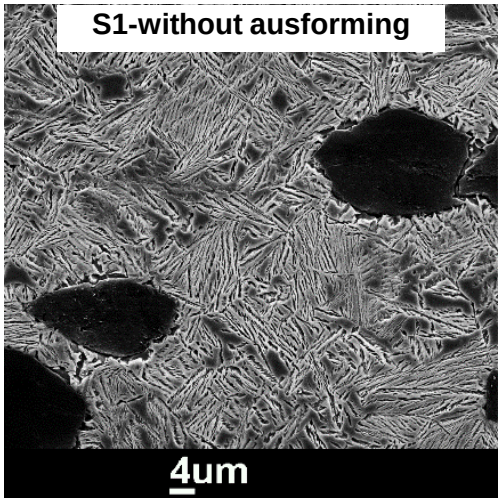


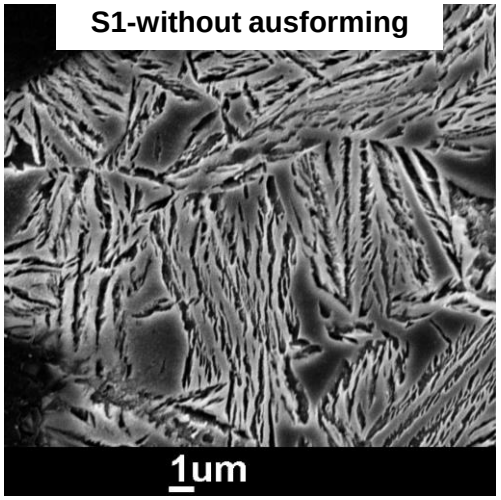
In case of schedule 2,

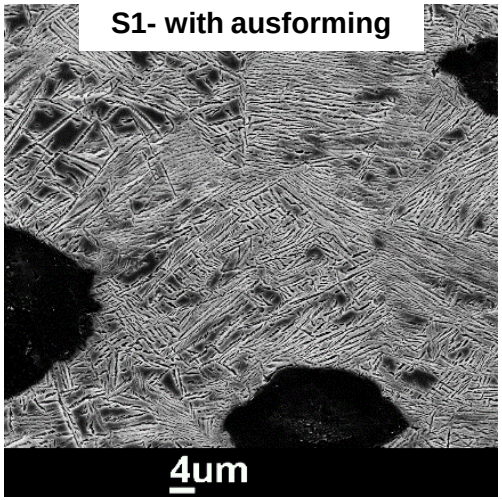
The ausferrite starts to form around the ferrite and the last ausferrite is formed remotely from the nodules and ferrite grains. This is applicable for both the ausformed and non-ausformed cases.

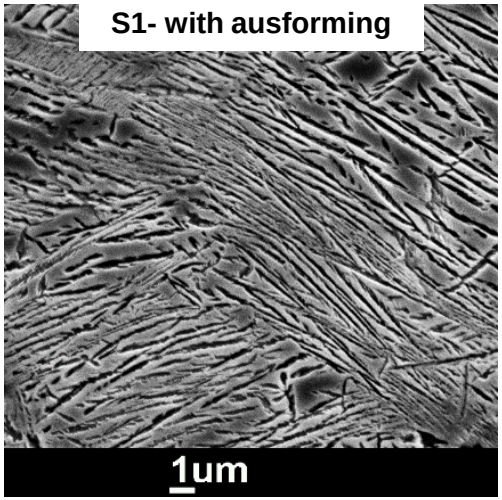
- The samples subjected to schedule II revealed blocky austenite of smaller size and less quantity than that of schedule I.
- Other form of retained austenite that could not be resolved using the LOM is the fine interlath films inside the ausferrite aggregates. In order to distinguish these individual austenite plates within the thin aggregates of the ausferrite, SEM investigations had been conducted.

- The ferrite aggregates are built up from many ferrite plates in the same crystallographic orientation. Myszka et al. reported that isothermal transformation of ausferrite refines the ferrite plates which tend to form a typical feathery pattern indicating the direction of the plate growth.
- The retained austenite is present in a form of homogenously distributed films along ferrite plate boundaries as well as in a form of small isolated austenite colonies.

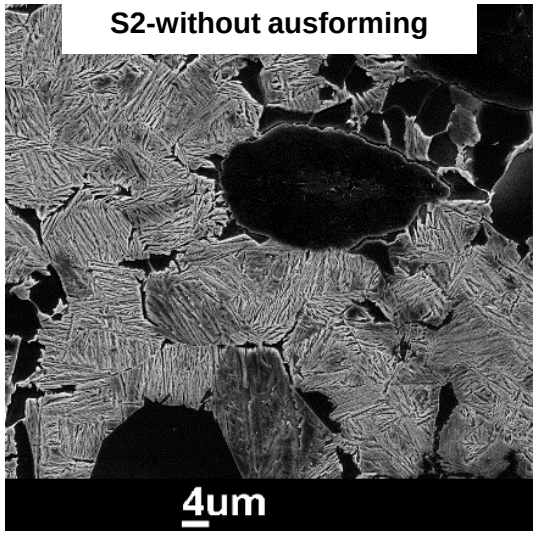


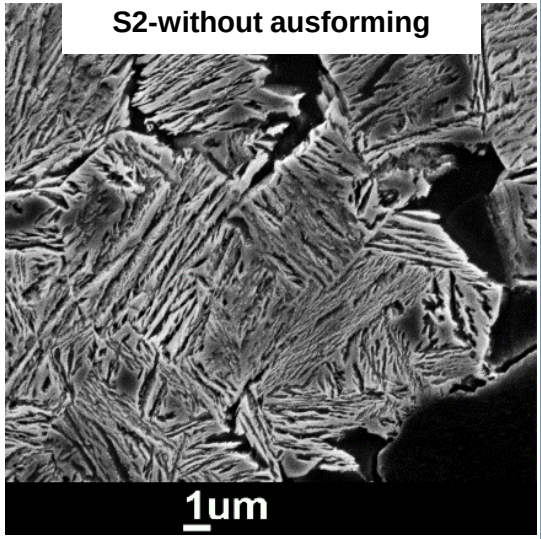


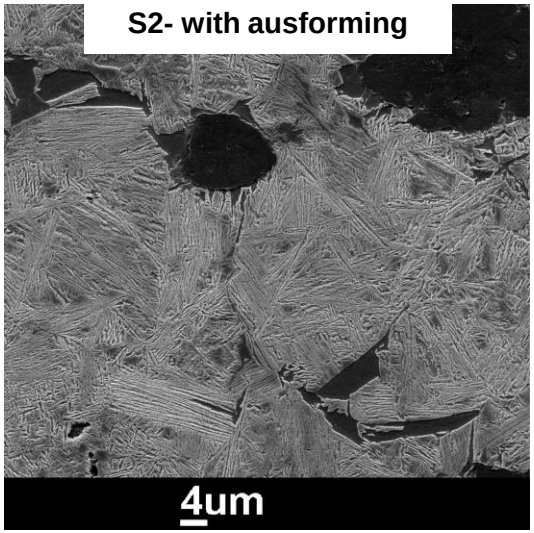


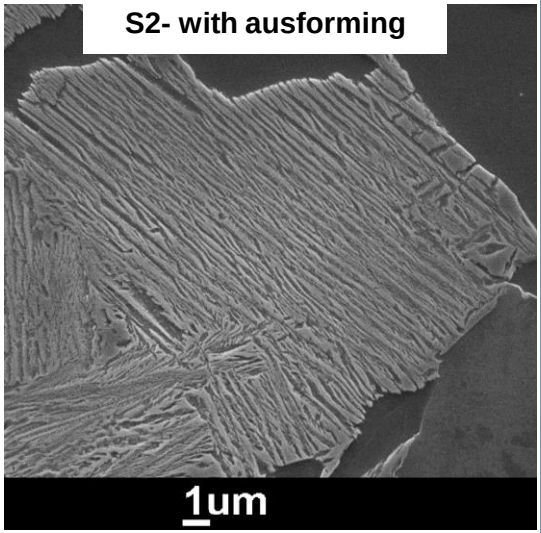


- The polygonal-ferrite phase is easily distinguishable within the structure.
- The comparison of the ausformed ausferrite morphology with the non-ausformed one for both of the applied schedules indicates the impact of ausforming on enhancing the microstructural uniformity and refining the ausferrite platelets.
- The observed refinement is mainly a consequence of the increased nucleation sites of the ausferrite-platelets.









Mechanical Behaviour

Condition		HV20	CS	YS	FS
S1	Without Ausforming	301	1447	689	0.46
	With Ausforming	356	1671	960	0.58
S2	Without Ausforming	274	984	521	0.47
	With Ausforming	282	1008	726	0.45

CS: Compression Strength YS: Yield Strength in compression and FS: Fracture Strength

- The remarkable increase in hardness, strength of the ausformed ductile irons is not only attributed to the structure refinement associated with the ausforming process but also to the increased dislocation density in the bainitic ferrite due to the warm working.

Mechanical Behaviour

- Increasing the dislocation density results in elevated yield and ultimate strengths. It is reported that the increased dislocation density in the bainitic ferrite following warm working of austenite plays a role in increasing the yield strength of steel.

- On the other hand, the impact of ausforming on the mechanical behaviour is stronger when applying schedule 1, i.e. the ferrite free matrix compared to its impact when applying schedule 2 (with introduced ferrite to the matrix).

Conclusions

- This work highlights transformation kinetics, microstructure evolution and mechanical behavior of thermo-mechanically processed ductile irons.
- Two types of matrices were produced in the ductile iron, namely ausferritic and ferritic-ausferritic matrices.
- Furthermore, the ductile iron is deformed applying a total true strain of 0.3 in the austenite region one time and 0.2 in the austenite region and 0.1 during austempering (ausforming) another time.
- Both of ausforming and ferrite-introduction to the matrix accelerate the ausferrite transformation kinetics.
- The ausforming process has its impact on enhancing the microstructural uniformity and refining the ausferrite platelets.
- Such microstructural variations result in remarkable increase in hardness, strength and ductility of the ausformed ductile iron.