Sustainable Plate Manufacturing

Abstract

The current production trend in microalloyed plate is to use increasing slab thickness to provide larger percentage reductions. However, with the use of microalloying elements to retard grain growth and promote the formation of acicular ferrite, large reductions may not be necessary. This will be investigated using the hot deformation technique of plane strain compression testing.

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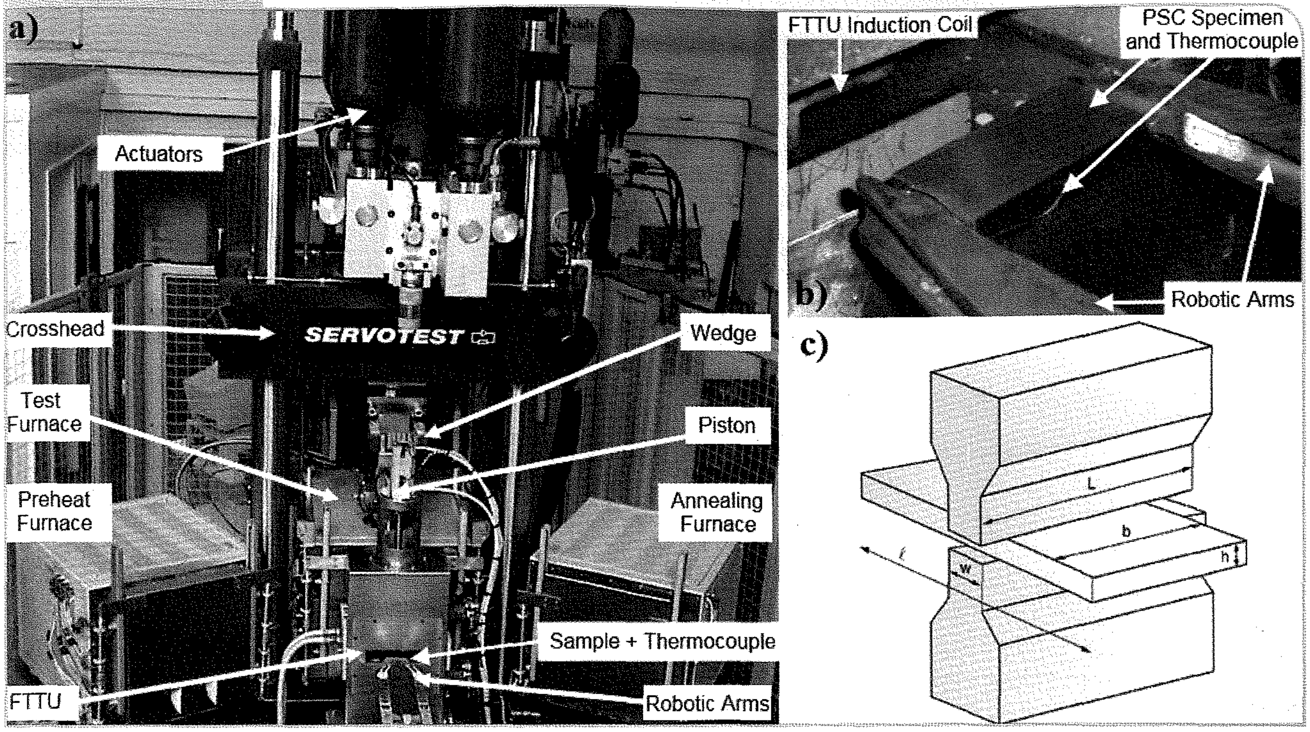
The global iron and steel industry uses more than 21 exajoules (EJ) of energy each year (one exajoule = 1 x 10^{18} Joules, or 23.9 x 10^6 tonne of oil equivalent), which accounts for approximately 12.5–15% of iron and steel production costs.[1–3] Plate manufacturing is essentially a sequence of events, each requiring a change in state and a minimum energy input that cannot be removed but can be reached more efficiently — estimations of these minimum energy inputs have been made.[4,5] An estimated 2.3–2.9 EJ/year of energy could be saved within the industry if best practice technologies with improved energy efficiency were implemented, such as the adoption of near-net-shape casting practices, which would save 0.35 GJ/tonne crude steel (tcs) produced.[1,6]

The trend within the plate rolling industry is for increasingly large mills capable of rolling thicker slabs in order to achieve increasing percentage reductions from slab to plate with the view to achieve improved microstructural and mechanical properties.[7] Within the strip industry, however, the reverse is true, with developments focused on leaner, continuous, near-net-shape processes, initially with thin slab casting and then progressing to direct strip casting (DSC) and the endless strip production (ESP) process.[8–10] In near-net-shape casting, the starting slab thickness is closer to the end plate thickness, thus requiring a less intensive mill schedule to achieve the desired plate thickness, but the plate undergoes less work so that the microstructure and mechanical properties may not be as expected for a conventionally cast and rolled slab. The concept of near-net-shape casting has previously focused on the role of microalloying additions.[11] This paper provides details of a microstructural study into the effect of different theoretical starting thicknesses on the final microstructure and properties of an X70 pipeline steel.

There are 2 million km of pipes transporting hydrocarbon products worldwide.[12] Pipeline steels have three specific requirements: high strength, high toughness and good weldability. As the strength increases, the wall thickness for a particular pipe diameter decreases, reducing material costs. In microalloyed steels, Nb provides strength via the precipitation of ultrafine (<20 Å) particles of Nb(C, N) and Nb-C-N clusters — the amount of precipitation strengthening depends on the amount of Nb in solution at the beginning of rolling and the precipitation rate in austenite, which is reduced by Mo and Mn additions.[13,14] Microalloyed steels have an array of final microstructures, which can be difficult to quantify, and include:

- PF = polygonal ferrite.
- QPF = quasi-polygonal ferrite or irregular ferrite: irregular grain boundaries; high dislocation density.[15]

Figure 1



Servotest TMC equipment at The University of Sheffield Department of Materials Science and Engineering (a) and (b);[27] and (c) PSC test geometry.[26]

- WF = Widmanstätten ferrite: elongated ferrite plates nucleated at austenite grain boundaries.[15]
- BF = bainitic ferrite: fine, non-equiaxed ferrite; retained austenite grain boundary structure (RAGBS).[16]
- AF = acicular ferrite: highly substructured, elongated ferrite grains; a type of BF that nucleates on second phases within the prior austenite grains that requires a coarse prior austenite grain size; no RAGBS.[15,17,18]
- GF = granular ferrite: ferrite with dispersed granular particles and high-C martensite; RAGBS.[15]

Experimental Methodology

Plane Strain Compression Testing — At The Institute for Microstructural and Mechanical Process Engineering: The University of Sheffield (IMMPETUS), plane strain compression (PSC) testing has previously been used to successfully model industrial rolling practices.[19–21] PSC testing is a useful tool for the simulation of plate rolling, where approximately plane strain conditions are observed.[22–24] The technique is detailed in a Good Practice Guide,[25] and allows control over deformation conditions such as temperature, strain, strain rate and number of deformations, resulting in similar stress-strain curves to those produced during plate rolling, creating a microstructure similar to that expected on an industrial scale. During PSC testing, the specimen is held between two robotic arms, as shown in Figure 1, and enters the fast thermal treatment unit (FTTU), where it is heated to the desirable testing temperature. It then enters the test furnace and is deformed between two tools such that strain is limited to one plane, and deformation to two planes. This process may be repeated to build up a number of deformations, each representing one industrial roll pass.

Samples of an API 5L X70 specification 19-mm-thick plate with composition as detailed in Table 1, supplied by Tata Steel Europe, were homogenized at 1,250°C for 2 hours, then sectioned into specimens with dimensions of 60 mm x 30 mm x 10 mm in

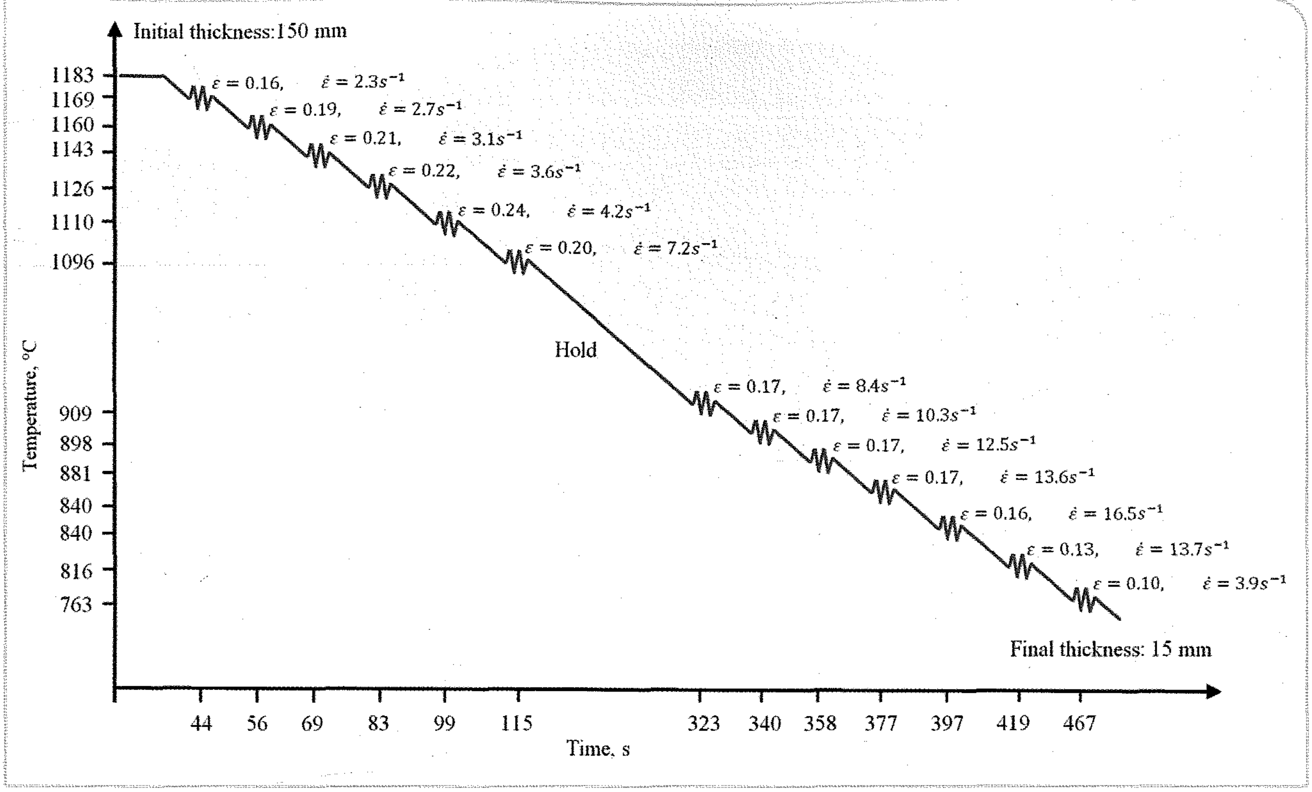
Table 1

X70 Plate Composition

C*	Si	Mn	P	S	N	Al†	Cu	Mo	Ni	Cr	V	Nb‡	Ti
0.035	0.32	1.6	0.005	0.0007	0.004	0.033	0.16	0.002	0.18	0.17	0.004	0.038	0.015

* Carbon equivalent: 0.3595
† Al-to-N = 8.25
‡ NbVTi = 0.057

Figure 2



Industrial rolling mill schedule that provided the basis for the PSC test design. The PSC tests use temperatures and strain rates that are representative of this mill schedule such that the tests are a simplified version of the industrial plate rolling process.

preparation for PSC testing. A mill schedule for the rolling of 150-mm X70 slab down to 15-mm plate, as shown in Figure 2, was used to design the PSC testing regimes shown in Figures 3 and 4. After testing, the specimens were cut, mounted in conductive Bakelite, ground through a succession of SiC grinding papers, polished using 6-µm, 3-µm and 1-µm diamond suspensions, etched in picric acid to reveal the prior austenite grain boundaries and imaged in an optical microscope. The grains were measured using the linear intercept method.[27]

The PSC testing had two aims:

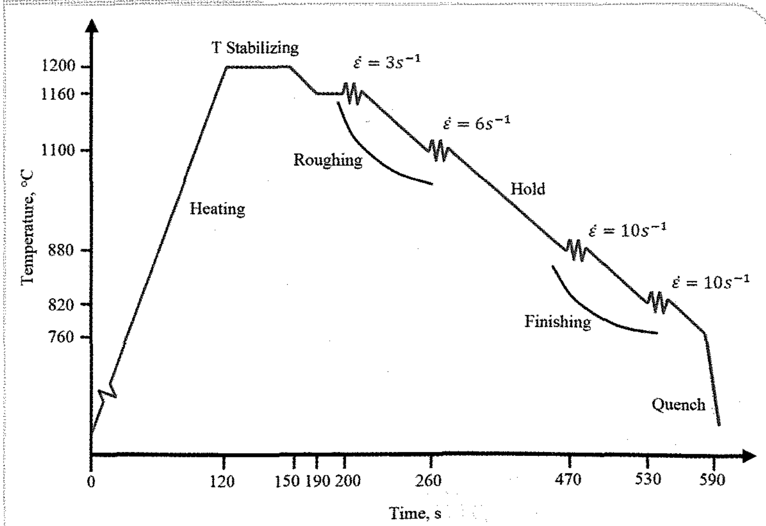
1. Investigate the effect of the starting plate thickness on final properties by altering the total amount of reduction via a series of 4-hit PSC tests to a total strain of 1.8.
2. Investigate the effect of the percentage of the total deformation that was achieved in the roughing and finishing stages, in a series of 2-hit PSC tests, to a total strain of 1.2. For example the 1-to-3 mill schedule consists of 25% of the total deformation during roughing and 75% during finishing.

A 6-hit test was also achieved, which will form the basis of further research.

Results and Discussion

The microstructures in Figure 5 show elongation of the austenite grains due to deformation, with the effect becoming more pronounced with increasing amount of deformation, particularly above 60%

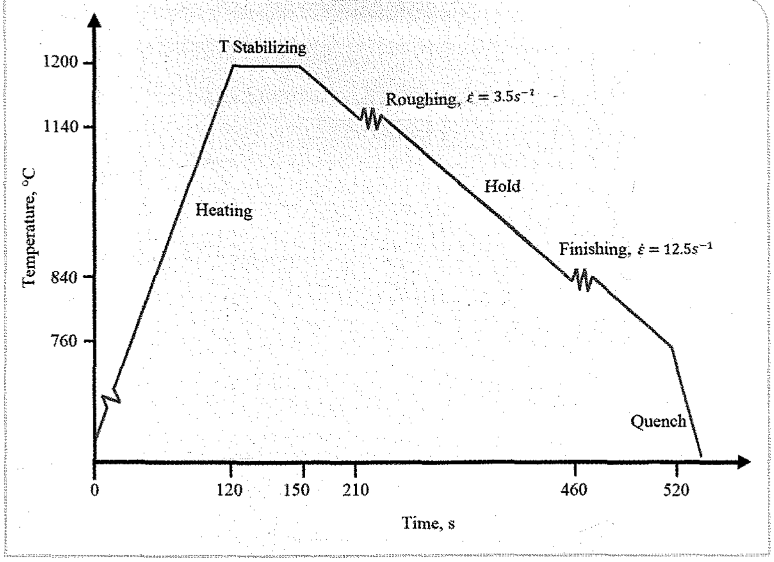
Figure 3



PSC schedule to study the effect of different starting slab thickness by altering the total strain.

deformation, where the grain aspect ratios are >2. This is congruent with plate rolling of microalloyed steels, where carbonitride precipitation during the high interpass times (>10 seconds) causes an effect known as "pancaking."[28,29] Despite all the specimens shown in Figure 6 reaching the same final thickness, pancaking is visible only in the 1-to-1, 1-to-2, 1-to-3 and 1-to-4 ratio microstructures. In those tests, an increased proportion of hot rolling occurs in the finishing stage: within the temperature range of VN precipitation and just above the Ar_3, resulting in strain-induced precipitation of VN precipitates in austenite that act as nucleation sites for intragranular ferrite.[30,31] For the 2-to-1, 3-to-1 and 4-to-1 ratios, the grains become increasingly equiaxed, with an aspect ratio of 1.12 for the 4-to-1 microstructure, which may be due to increased austenite grain growth at the higher deformation temperature.

Figure 4



PSC schedule to study the effect of altering the amount of reduction achieved during roughing and finishing.

The microstructures in Figure 5 suggest a hypothesis that the microstructure remains constant after 60% reduction, and therefore a reduction in starting slab thickness, moving toward a near-net-shape route, may be possible. The microstructures in Figure 6 also support the hypothesis that varying the mill schedule so that a larger proportion of the total strain occurs just above the Ar_3 also causes further grain refinement, so that a reduction of 50% with the new mill schedule may also give the same final microstructure. While the grain size gives an indication of strength, which may be confirmed via microhardness testing, it should be remembered that strength is not the only parameter key to pipeline applications. Fracture toughness is a key factor;

Table 2

Grain Size Measurements in the Longitudinal (L_1) and Short Transverse (L_3) Directions for Different Percentage Reductions

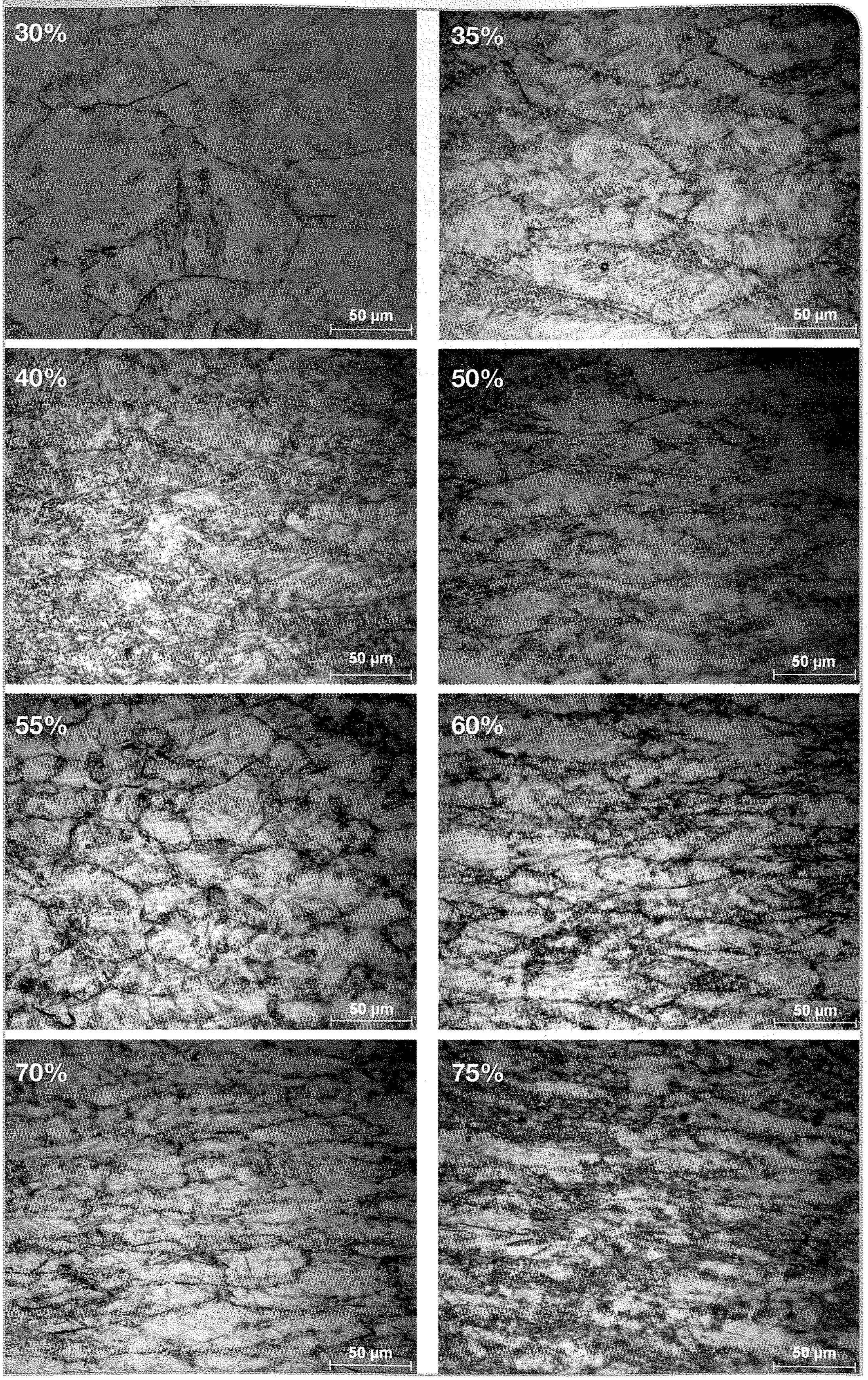
Reduction	30%	35%	40%	50%	55%	60%	70%	75%
Simulated starting slab thickness, mm	21.4	23.1	25	30	33.3	37.5	50	60
Total strain	–0.36	–0.5	–0.6	–0.69	–0.92	–1.1	–1.2	–1.6
Final specimen thickness, mm	7.26	6.55	6.09	5.11	4.47	4.13	3.31	2.51
Grain size: L_1, µm	41.4 ± 25.5	37.0 ± 7.0	27.7 ± 6.7	33.0 ± 3.5	27.4 ± 5.0	29.8 ± 4.0	28.0 ± 4.2	23.8 ± 1.0
Grain size: L_3, µm	27.0 ± 6.2	26.0 ± 6.3	18.9 ± 1.3	17.1 ± 2.8	17.5 ± 2.6	13.8 ± 2.7	11.4 ± 0.7	9.6 ± 0.4
Grain aspect ratio	1.53	1.42	1.46	1.93	1.57	2.16	2.46	2.48

Table 3

Grain Size Measurements in the Longitudinal (L_1) and Short Transverse (L_3) Directions for Different Ratios of Roughing-to-Finishing

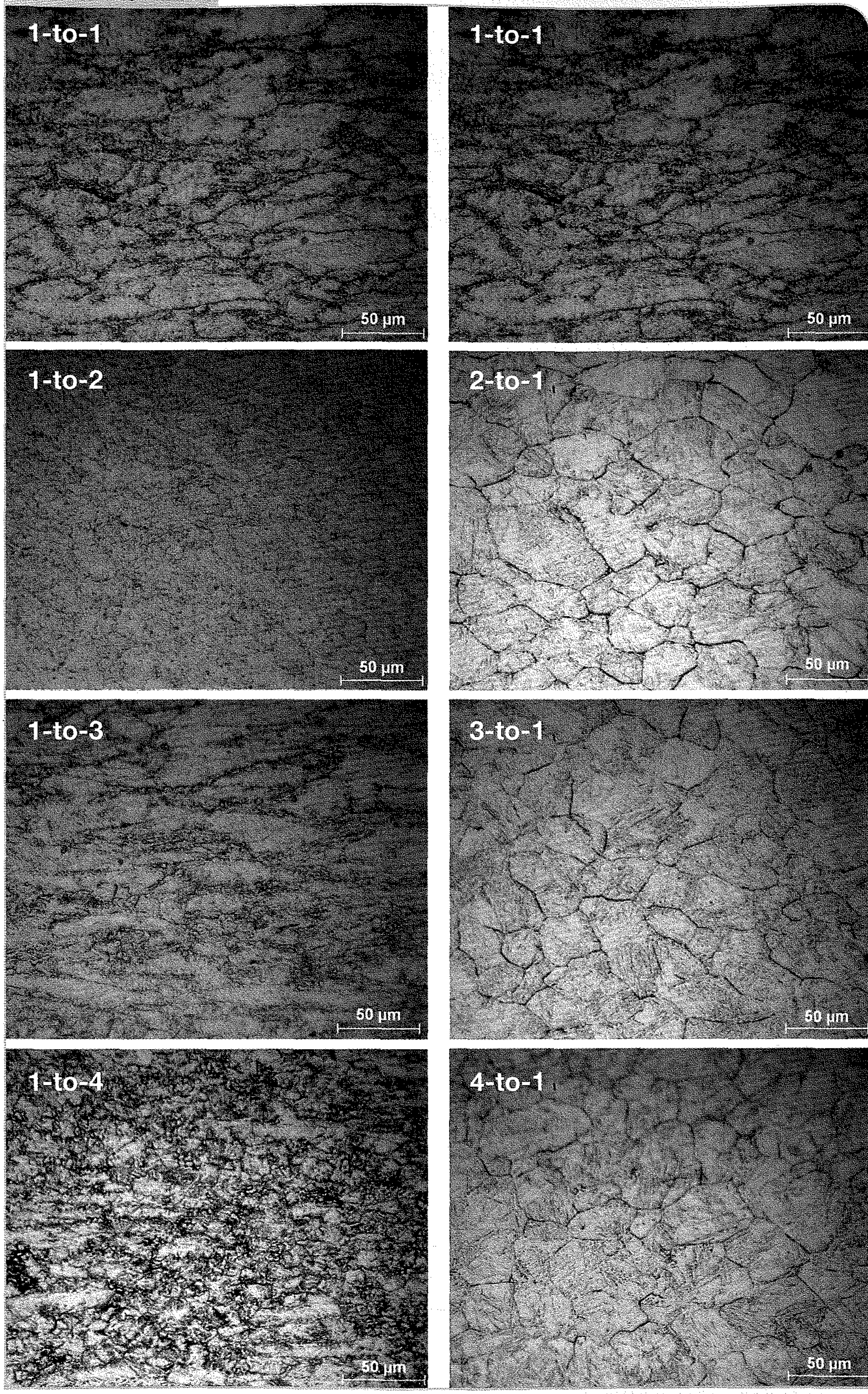
Reduction	1-to-1	1-to-2	1-to-3	1-to-4	2-to-1	3-to-1	4-to-1
Final specimen thickness, mm	2.48	2.91	2.88	3.04	3.09	3.12	2.94
Grain size: L_1, µm	33.1 ± 7.9	—	27.6 ± 2.7	14.7 ± 1.1	31.4 ± 5.1	24.6 ± 3.5	24.0 ± 3.4
Grain size: L_3, µm	12.6 ± 2.0	—	11.4 ± 1.4	8.7 ± 0.8	20.7 ± 1.5	20.7 ± 1.5	21.5 ± 1.1
Grain aspect ratio	2.63	—	2.42	1.69	1.52	1.19	1.12

Figure 5



Optical micrographs from plane strain compression 4-hit tests to different percentage total reductions.

Figure 6



Optical micrographs of plane strain compression 2-hit test specimens with varying ratios of reduction in the roughing and finishing sections of the test, before and after the hold. Greater reduction at higher temperature, for example the 4-to-1 ratio, results in a larger prior austenite grain size, whereas a greater reduction at lower temperature results in a pancaked structure.

therefore, a grain size analysis alone is not enough and further work is required.

Specimens obtained from industry already have a prior grain structure. To create a virgin microstructure, model alloys are based on an austenitic Ni – 30 wt. % Fe alloy with similar stacking fault energy and hot deformation behavior to austenitic steel alloys.[32–35] The use of a model Fe-Ni-Nb alloy would remove the effect of transformation, allowing the deformed structure to be retained upon quenching to room temperature without transformation into martensite so that the hot worked microstructures and precipitation events in the austenite matrix, for example of VN and Nb(C,N), may be studied.[36]

Conclusions

PSC tests conducted on the TMC equipment at IMMPETUS are a useful method in simulating industrial rolling parameters within the laboratory.

The tests investigating the effect of starting slab thickness require further investigation; but as a microstructural study, they suggest that the trend in ever-increasing rolling reductions may not be necessary to achieve the desired qualities for pipeline grade plate.

The investigation into the effect of a higher percentage of the total rolling reduction occurring in the roughing or finishing stages confirms what is already well known — that the effects of temperature and strain rate on final microstructure are large. The next step in this investigation would be to observe the ferrite grain structure and confirm the hypothesis that the microstructure for the 4-to-1 ratio is due to strain-induced precipitation and deformation just above the Ar_3.

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