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Mechanical and structural aspects of high temperature deformation in Ni alloy

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Properties

ABSTRACT

Purpose: Experimental results on hot deformation and dynamic structural processes of nickel based alloy were reviewed. The attention was given to the analysis of dynamic structural processes which operate during hot deformation of the material.

Design/methodology/approach: Hot compression tests were performed on solution treated precipitations hardenable nickel based superalloy of Inconel 718 within a temperature range of 720-1150°C at constant true strain rates of 10^{-4}, $4x10^{-4}s^{-1}$. The flow stress curves and microstructure of deformed nickel based superalloy were presented.

Findings: During hot compression of solution treated material, highly localized flow was observed at relatively low deformation temperatures 720 - 850°C. The particle distribution and their morphology were not found to be affected by localized flow within the investigated strain range. At low strain rate the shear banding and intergranular cracks and cavities growth were found to be responsible for the observed flow stress decrease at 720, 800 and 850°C and might result in a sample fracture at larger strains.

Research limitations/implications: In spite of intense strain hardening due to deformation and phase transformation overlapping, light optical microstructure observation of deformed samples did not reveal significant effects of heterogeneous distribution of the phase components. Therefore, in order to complete and confirm obtained results it is recommended to perform further analysis of the alloy by using transmission electron microscopy technique (TEM).

Practical implications: An interaction between dynamic precipitation and flow localization may become an important feature of high temperature performance and may also allow producing specific structures of materials.

Originality/value: The contribution of flow localization to the strain hardening or flow softening and the flow stress-strain behavior during hot deformation of precipitation hardenable alloys is still a subject of extensive researches. The interaction between the flow localization and dynamic precipitation process was a subject of a very limited research works only.

Keywords: Working properties of materials and products; Plastic forming, Dynamic precipitation

1. Introduction

The ability of the material to undergo plastic deformation is one of the most exceptional characteristics of metals and alloys. Such ability has been utilized in most forming operations to obtain the required shape of many products. Obtaining the suitable microstructure that guarantee appropriate properties of final products is the main target in many forming operations. Cold and hot-working are the most commonly used techniques in forming metals and alloys. During cold-working, intermediate annealing is regularly required to remove the work hardening effect through recovery and recrystallization of the material. Both processes were observed to operate not only under static conditions but under dynamic conditions in addition, i.e. during high temperature deformation. During the last decades the mechanisms involved in hot-working of metals and alloys were widely investigated. The most common softening mechanisms include dynamic recovery (DR) and dynamic recrystallization (DRX). At relatively low strain rates a precipitation process may develop during hot deformation of solution treated age hardenable alloys. Such phenomenon is known as the dynamic precipitation (DP), and defined as a precipitation during deformation of solution treated alloys below the solvus temperature. DP process may interact with other structural processes during hot deformation and has an effect on both the flow stress value and the final structure and properties of the material. Contribution of DP in general, increases the total hardening of the material due to retardation of both DR and DRX by dispersive particles growth. The degree of strengthening during hot deformation which results from dynamically precipitated particles depends on their morphology, strength and distribution within the matrix. During hot deformation of age hardenable alloys the change of particle distribution and their morphology may also affect the structure and material properties. In particular the particles morphology may be affected by the dynamic coarsening of precipitates which might operate during hot deformation of some alloys.

A crucial important feature of plastic deformation is the homogeneity of strain distribution. It is commonly accepted that at low temperatures and high strains, flow localization may develop and affect the material ductility. However, hot-deformation at intermediate temperatures may also result in localized plastic flow and nonhomogenous deformation of the material. Flow localization, as a result of substructure instability and collective motion of a large number of dislocations is typical for a coarse slip, shear banding, Luders bands development and Portevin-LeChatelier effect. Kink bands and mechanical twins may also be considered as a special form of flow localization. The coarse slip is usually used to describe the localized flow within individual grains, whereas shear bands traverse many grains very often without any remarkable relation to the position of easy glide systems plane. In pure metals and single phase alloys the shear bands were found to be preferential sites for the nucleation of both static and dynamic recrystallization.

It is commonly believed that in age hardenable alloys, the shear bands and dislocation substructure produce preferred sites for nucleation of precipitates and increase the nucleation and particles growth rate during hot deformation as a result of higher vacancy concentration produced by intensive straining as well as increased dislocation pipe diffusion. The analysis of structural processes which are associated to dynamic aging of supersaturated solid solution during hot deformation may become very complicated because of the mutual interaction between dynamic precipitation process and the material structure which results from the deformation process.

The stress-strain curves for metals and alloys obtained during hot deformation are usually characterized by an initial hardening range followed by either steady-state flow, single-peak or multi-peaks behavior depending on the material, deformation temperature and strain rate. It has been reported that for materials that exhibit steady-state flow after an initial hardening range the flow stress level was controlled by sole DR process. It is a common believe that single and multi-peak σ-ε characteristics are associated with DRX. It is worth to mention that the change of particles morphology and/or the material texture may also result in the flow stress peak development. The localized plastic flow was also found to be responsible for the observed flow softening after the initial peak in some hot deformed materials. Thus, the flow softening can not be used for a simple DRX detection and careful structural observations should always be performed to analyze structural processes which are responsible for the material softening during hot deformation.

The contribution of flow localization to the strain hardening or flow softening and the flow stress-strain behavior during hot deformation of precipitation hardenable alloys is still a subject of extensive researches. The interaction between the flow localization and dynamic precipitation process was a subject of a very limited research works only [1-13]. Such an interaction may become an important feature of high temperature performance and may also allow producing specific structures of materials.

There is a shortage of data which are referred to specific features of phase transformation processes in precipitation hardenable alloys. Moreover, existing data do not allow generalizing structural features of DP and simplifying structural description of the process. The experiments on hot deformation of age hardenable alloys and the analysis of DP process have got a practical meaning. This is the reason to perform further experiments on other alloys.

The present work has been inspired by researches performed on Cu and Al alloys undergoing multi-step phase transformation during high temperature deformation. There is a considerable amount of experimental evidence that interaction of complex phase transformation and deformation process in Cu-Ti and CuNiSiMg alloys leads to flow localization and shear bands development [1-3, 6]. Non uniform deformation may accelerate precipitation and stimulate a growth of the precipitates within areas that possess large misorienations with respect to the surrounding matrix, which facilitates further flow softening along these coarsened particles. Thus, one may assume that in nickel based superalloy deformed during precipitation of hardening phases in particular, the effect of localization of the phase transformation alike of this observed in Cu alloys, should also occur. The most interesting purpose of experiments describe bellow was to study the mechanical behavior and related structural changes that take place during hot deformation of supersaturated Ni alloy below (dynamic precipitation conditions) the solvus temperature. Emphasis was placed on the interaction of precipitation process with structural inhomogeneties that may develop during hot deformation.

2. Material and methodology

The uniaxial compression tests at different temperatures and strain rates were performed on solution treated precipitations hardenable nickel based superalloy Inconel 718 in order to investigate the effect of the hardening phases on hot deformation behavior. The flow localization and shear bands development can be expected during hot deformation of the alloy and the flow localization may affect both mechanical behaviour and structural features. The similarity of precipitation sequence, during static aging of Cu-Ti and Cu-Ni-Cr-Si-Mg alloys make them suitable for studying the interaction of flow localization and dynamic precipitation process. In order to intensify an interaction of phase transformation and deformation processes, hot compression tests were performed at low constant strain rate (10^{-4}, $4{\cdot}10^{-4}s^{-1}$) within the temperature range corresponding to temperatures of precipitation of hardening phases. Long compression test allows to reach large enough deformation value and long enough deformation time which was required for diffusion controlled process to develop during deformation test The cubicoidal samples (20x10x20mm) were deformed by means of computerized Gleeble test equipment. The flow stress value under different low strain rates and different deformation temperature being examined. Additionally, the properties were explained through observation of the microstructure using standard optical microscopy technique.

3. Description of achieved results

The effect of deformation temperature on the true stress-true strain curves for the alloy deformed at strain rate: 10^{-4}; $4{\cdot}10^{-4}s^{-1}$ and temperature of 720-1150°C are shown in figures 1 and 2.

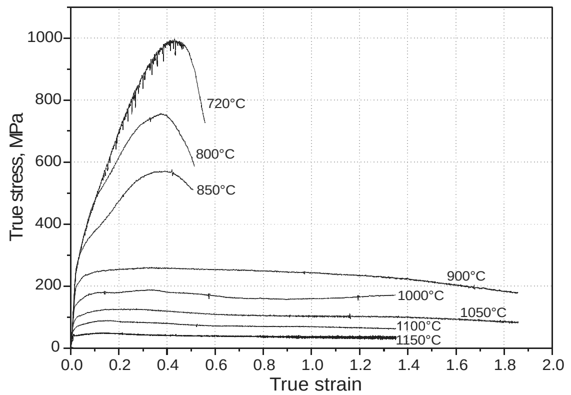

Fig. 1. True stress-true strain curves for Inconel 718 alloy deformed at different temperatures and a strain rate of 10^{-4} s^{-1} (the deformation temperature was indicated in the figure)

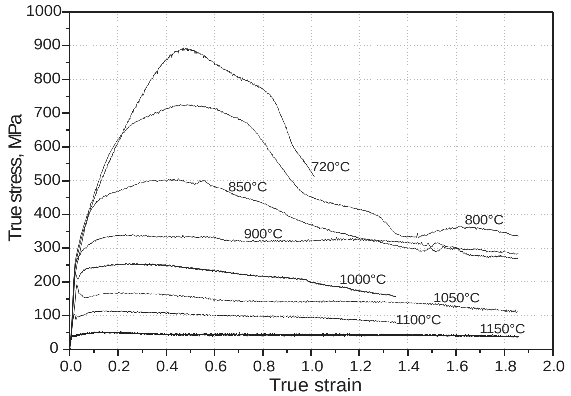

Fig. 2. True stress-true strain curves for Inconel 718 alloy deformed at different temperatures and a strain rate of $4{\cdot}10^{-4}$ s^{-1} (the deformation temperature was indicated in the figure)

The sample fracture within flow softening range was also observed at these deformation temperatures, yet the effect was not large enough to cause a fracture of the sample before reaching its imposed maximum strain, as it was in case of the samples deformed at these temperatures at lower strain rate (Fig. 4). Non-uniform deformation was found to operate during the test, suggesting that the softening might be ascribed to the flow localization (Fig. 4, 5).

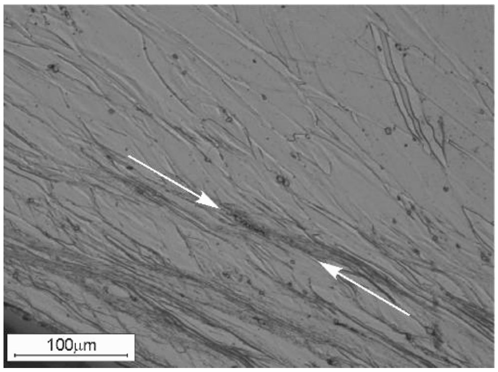

Fig. 3. Microstructure of the sample deformed at 720°C, strain rate of $10^{-4}s^{-1}$

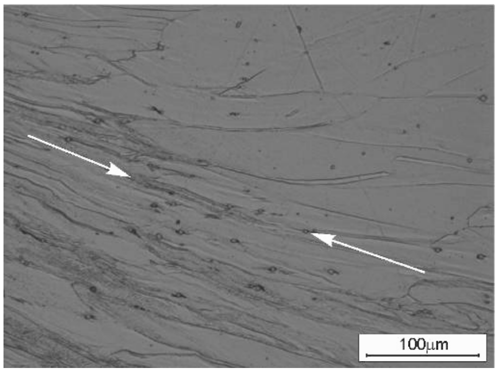

Fig. 4. Microstructure of the sample deformed at 720°C, strain rate of $4{\cdot}10^{-4}s^{-1}$

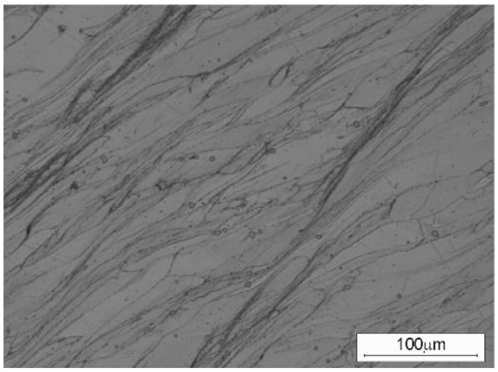

Fig. 5. Optical micrograph for the sample of In718 deformed at 850°C, strain rate of $4{\cdot}10^{-4}s^{-1}$

Investigations of the samples evidenced a few effects of a structural components localization that might result from preliminary flow localization. Microstructure of the hot deformed alloy exposed columnar carbides particles distributed along shear bands (see regions marked with arrows in the figures 3 and 4).

The microstructure of the solution heat treated sample deformed at both strain rates within the range of temperature 900-1050°C revealed meaningful strain localization effects. However any arrangement of precipitations due to heterogeneous form of deformation could not be clearly detectable (Fig. 6).

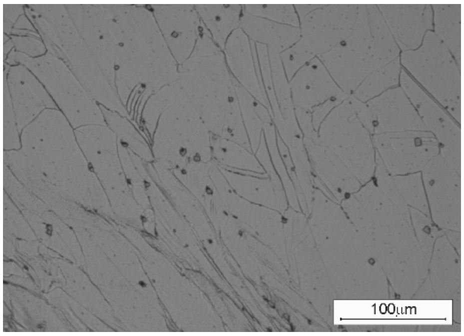

Fig. 6. Optical micrograph for the sample of In718 deformed at 900°C, strain rate of $10^{-4}s^{-1}$

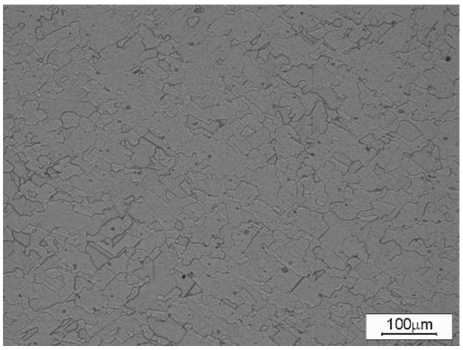

Fig. 7. Optical micrograph for the sample of In718 deformed at 1050°C, strain rate of $4\cdot10^{-4}s^{-1}$

Flow curves for the samples deformed at higher temperatures (above 850) at both strain rates are characterized by initial hardening range followed by steady flow until the end of the test, suggesting that the flow stress value was controlled by dynamic recovery. However, microstructural observations showed clearly that dynamic recrystallization had also an effect on the flow stress value (Fig. 7). The sample fracture was not observed within flow softening range. Slightly marked flow softening was probably resulted from lamellas fracture and coarsening of some particles. Flow localization, in the form of coarse slip and shear bands was practically not observed for these samples (Fig. 7).

4. Conclusions

The maximum flow stress value at high temperatures of deformed samples was found to decrease with increasing deformation temperature and might be attributed to the increased dynamic recovery and dynamic recrystallization rate as deformation temperature increases. The effect of dynamic precipitation can be recognized as an increase of maximum flow stress at low deformation temperature. Shear banding and integranural cracking was intensified within the temperature range of 720-900°C. Microstructural observations suggested that intergranular cavities growth was responsible for load decrease and the fracture of the material. Localization of carbides within shear bands was observed for the samples deformed at 720-850°C.

Acknowledgements

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